Spring 2021

Design for Additive Manufacturing (3D Printing)

Michael O'Donnell
mmo38@zips.uakron.edu

Michael J. Levy
University of Akron, mjl117@zips.uakron.edu

Topology Optimization for Additive Manufacturing

Authors:
Michael Levy & Michael O'Donnell
Advisor: Jae-Won Choi

Dept of Mechanical Engineering
University of Akron
Spring 2021 Capstone Project Report

Abstract

The purpose of this project is to study and explore design for additive manufacturing, an emerging research area dealing with functionality, manufacturing, materials savings, and other improvements made possible by the technology of 3D printing. Topology optimization is a method to optimize a design based on loading and boundary conditions to reduce weight while maintaining functionality. For this study, a mechanical part was designed, analyzed, optimized, and tested. Since the purpose of this part is to explore the process of topology optimization, it was specifically designed for testing in mind. What this means, for the scope of this project, is that the part should have a geometry complex enough to display the capabilities of additive manufacturing compared to traditional subtractive manufacturing. Our design is a simple bracket that could be mounted to a wall or any vertical surface, with two arms that reach out at an angle to hold weights. Finite Element Analysis (FEA) was performed on the part, so that stress could be analyzed and compared to the strengths of 3D printing filaments intended for use, ABS (Acrylonitrile butadiene styrene) and PLA (Polylactic acid). A topology optimization software called nTopology was then used to topologically optimize the part, with a subsequent FEA on the optimized model to again verify the part's strength regarding the design load. Parts were then printed with both materials and tested.

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1. Introduction

Design for additive manufacturing, also known as 3D printing, is a massively expanding area of research with nearly endless possibilities of technologies and applications to be explored. One such application is known as topology optimization. Topology optimization is the process of taking a mechanical part model, using a computer program to apply a load case, and minimizing the mass and geometry of the part to what is necessary to support the load case. The purpose of this project is to explore and study the process and performance viability of topology optimization in design for additive manufacturing.

We developed the following plan to execute this project: First, a mechanical part had to be selected or designed to conduct this study. Next, the part was designed in CAD, and different methods of 3D printing were researched and considered for use. Finite element analysis was performed on the part to establish a baseline for the topology optimization. Then, topology optimization software was used to optimize the part. After that, the original part was printed along with samples of the optimized version to be tested and compared.

1.1. Engineering Standards

If this study were to be conducted in a professional environment, there are many standards for additive manufacturing that should be considered in order to comply with the industry standards. For example, as 3D printing can be a very abstract concept, there are standards for terminology defined in ISO/ASTM 52900-15, "Standard Terminology for Additive Manufacturing" [1]. It defines standard terminology used in describing additive manufacturing processes, build space, printing parameters, and other geometric and functional variables. Another standard that would be important to consider is ISO/ASTM 52902-19, "Test artifacts — Geometric capability assessment of additive manufacturing systems" [3], which describes benchmarking test piece geometries in order to assess performance of additive manufacturing systems' capabilities and calibration. The document provides many different test geometries that showcase multiple performance metrics of the printer, which would be important to demonstrate in a professional additive manufacturing environment.

Another potential standard to consider is ISO/ASTM 52910-18, "Additive manufacturing - Design - Requirements, guidelines, and recommendations" [3]. As the name suggests, the document provides requirements, guidelines, and recommendations for using additive manufacturing in product design. It provides general guidance and identification of issues for three intended audiences: designers designing products to be additively manufactured, students learning mechanical design and CAD, and developers of additive manufacturing guidelines. A final standard that would be important to consider is ISO/ASTM 52915-16, "Standard Specification for Additive Manufacturing File Format (AMF)" [4]. It addresses the problem of the current industry standard file format, stereolithography (STL), of only consisting of a surface mesh, and does not consider material properties, substructures, et cetera. This new file format has many benefits and is designed for future needs. It represents objects in such a way that it is technologically independent, allowing any machine to build it to the best of its ability. It is also backwards and future compatible, meaning existing STLs can be converted, and new features can be added into it in the future. All of this flexibility makes it easy to understand how useful this new format can be in a professional setting.

1.2. Constraints

We had multiple constraints to consider in this study, as our goal was to demonstrate the advantages and capabilities of topology optimization in design for additive manufacturing. Namely, we had to balance manufacturability, weight, and performance.

- Part Design
  - Traditionally manufacturable original part
  - Simple load case for testability
  - Complex geometry for optimization utility
- Simulation
  - Low FEA stress to predict parts passing
  - High weight removed to demonstrate optimization
  - Additively manufacturable output part
- Testing
  - Design reliable and measurable application of force
  - Create optimized parts that pass under design loading
  - Print multiple sample to compare results

2. Design

2.1. Design Procedure

2.1a. Part Selection

The first step was to choose a mechanical part to be studied. Several considerations were taken in the selection of this part. The first consideration was the location of the part on a spectrum of complexity that would allow it to be worth topologically optimizing. If the part was too simple in its geometry and/or load case, then it could likely be optimized simply through hand calculations to minimize the dimensions. However, if the part is too complex in its function, then it would be difficult to test accurately and reliably. We initially designed a basic car pedal and began using Soldwork's topology optimization tool. All of the loaded points and fixed points were on the same plane which led to a somewhat simple shape when optimized. The optimization could easily be used as a guide to manually remove material to create an easily machinable part. We felt a part like this might not be the best way to show off the capabilities of additive manufacturing with this technology due to its simplicity. We decided to design a new part with conditions that would lead to a more complex optimized part with which subtractive manufacturing methods would be far less feasible. We also began to search for a program that was purposefully built for these types of optimization simulations. After contacting nTopology, we were provided with licenses to use their program which specializes in optimization simulations.

2.1b. Part Design

In our research, we saw that parts with fixed points and loads on different planes resulted in more complex geometry, which demonstrates more strengths of additive manufacturing. We also wanted a part that could be easily tested. The part we designed is a simple, vertically loaded bracket that consists of two arms at a 60° angle from each other protruding from the mountable base. At the end of these arms was a connection point for our vertical loads to be attached.

2.1c. Selecting a Printing Process and Material

Although there are many different possibilities with the University's resources when it comes to which method of 3D printing to use as well as which material, this was another decision where COVID-19 restrictions weighed in heavily. Due to this, it was decided that the printing for this project would be done on our home FDM printers. This also narrows down the material selection to common FDM plastics. PLA and ABS were chosen as they have somewhat dissimilar properties and are two of the most common and readily available materials for home 3D printing. PLA is known to be relatively brittle, while ABS is much more ductile, and it could be interesting to analyze the two potential failure modes.

In the simulations, the parts are assumed to be completely solid structures. We were very interested to see how the layer lines of the prints would affect the part strength. Material and printing conditions affect layer adhesion, and reduce part strength along these lines.

2.2 Design Details

2.2a. Finite Element Analysis

After the initial part was designed in SolidWorks, we applied a specific load force and obtained finite element analysis results. An arbitrary design load of 14 N (split between the two mounting points), about 3 lbs, was chosen for two reasons. First, taking at-home testing into considerations, it would be easier to find sets of relatively lower weight increments to use. Second, with a lower design weight, a larger portion of the material should be able to be removed, allowing for maximum topology optimization to be studied. SolidWorks' material library has a preset material for ABS, but properties needed to be added manually for PLA. The mechanical properties were taken from the research paper "Mechanical Property Optimization of FDM PLA in Shear with Multiple Objectives" [5].

Table I. Material properties of bulk polylactic acid as found via literature review[1–3]

Material property	Units	Value
Density (ρ)	g/cm^3	1.24
Elastic modulus (E)	MPa	3500
Shear modulus (G)	MPa	1287
Poisson's ratio (ν)	–	0.36
Yield strength (σ_y)	MPa	70
Ultimate tensile strength (S_{ut})	MPa	73
Elongation	%	~7

Figure 1: Mechanical Properties of PLA assumed for this study.

Property	Value	Units
Elastic Modulus	2000000000	N/m^2
Poisson's Ratio	0.394	N/A
Shear Modulus	318900000	N/m^2
Mass Density	1020	kg/m^3
Tensile Strength	30000000	N/m^2

Figure 2: Mechanical Properties of ABS assumed for this study, via SolidWorks

The inner surfaces of the mounting holes were selected as "fixed geometry" and the downward design load was applied to the hole's surfaces as a bearing load.

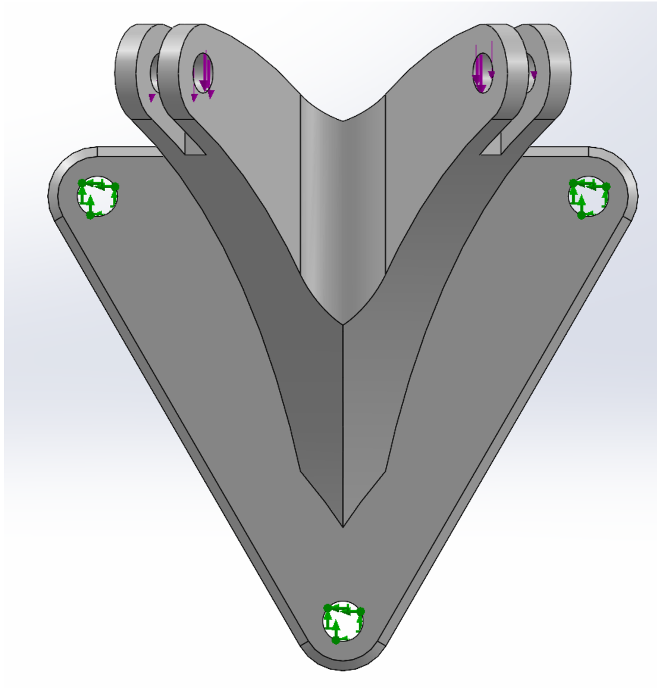

Figure 3: Load case applied to the bracket model.

As seen below in Figure 4, the maximum calculated stress in the PLA version of the bracket is approximately 4.1 MPa, which is well below the yield strength of PLA, 70 MPa.

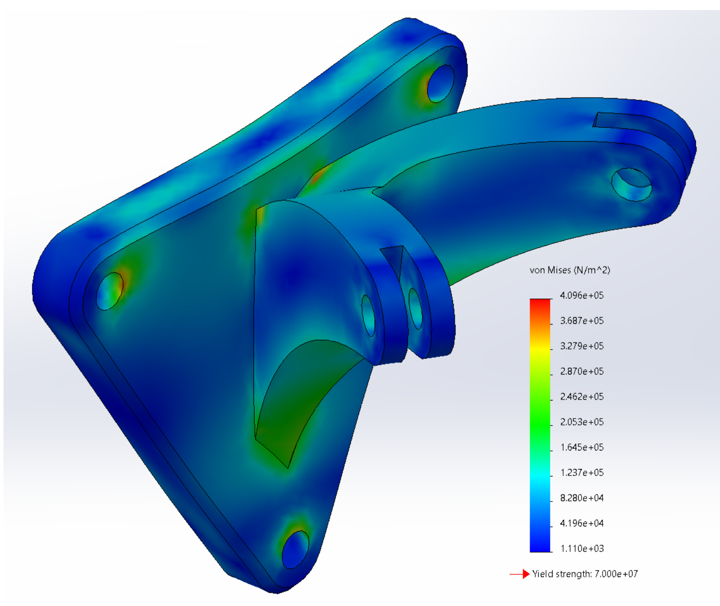

Figure 4: PLA unoptimized part FEA.

The same finite element analysis was performed with the material changed to ABS, and the results are shown below in Figure 5. The stress was very similar at about 4 MPa, however, this is much closer to the yield strength of ABS, which is approximately 18 MPa at worst.

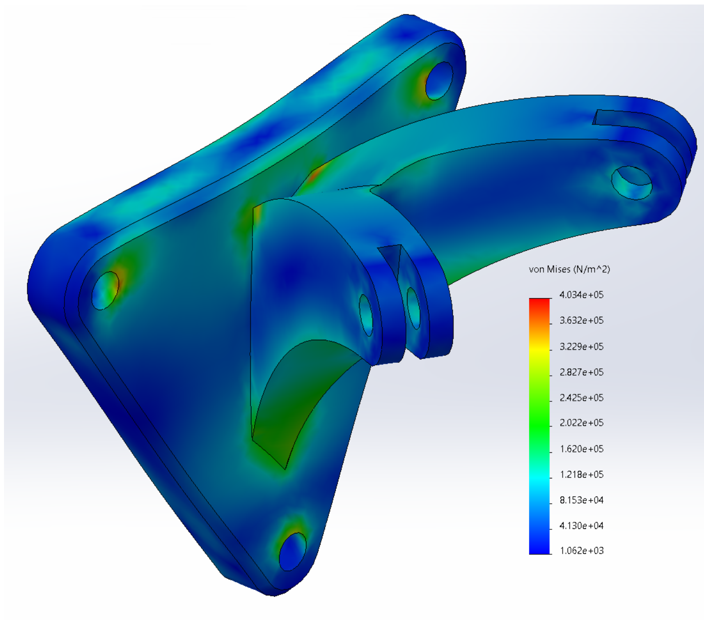

Figure 5: ABS unoptimized part FEA.

Once the parts were optimized using nTopology, the resulting models were also subject to the same FEA. The nTopology process will be explained in Section 2.2b, but the FEA results are shown here below in Figures 6 and 7. The stresses are again considerably low: approximately 5.6 MPa and 5.7 MPa for PLA and ABS, respectively. So, the parts are expected to withstand the load case when they are printed and tested.

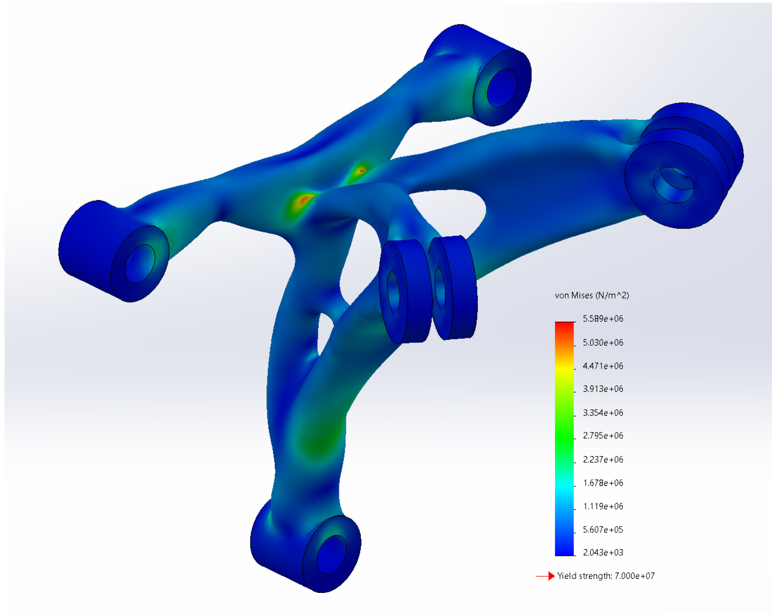

Figure 6: Optimized PLA part FEA

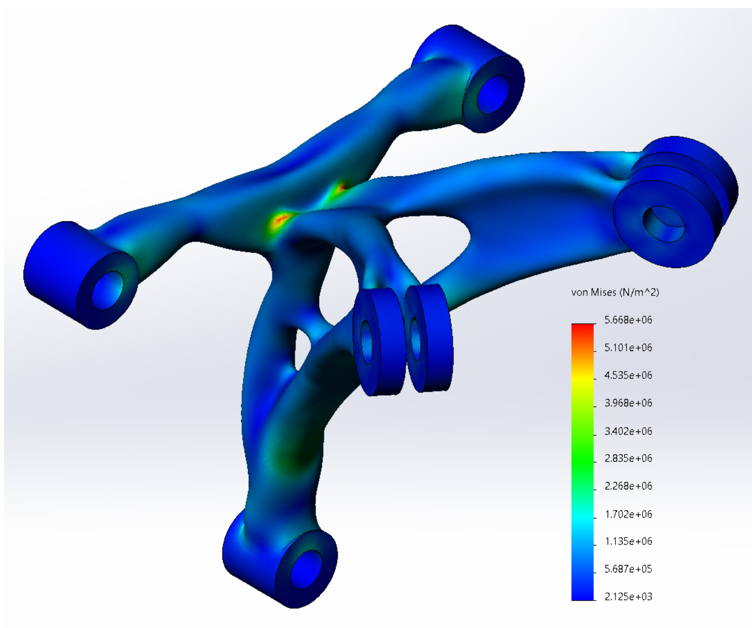

Figure 7: Optimized ABS part FEA

2.2b. Topology Optimization

Initial topology optimizations were done inside SolidWorks. We decided to search for more purpose-built software that could provide more functions. We came across nTopology which specialized in the types of optimization simulations we were looking for. We reached out and were provided with licenses to their software.

We found nTopology to have excellent in-depth guides to learn many of the software's features. Below is a review of the general steps we took to perform a topology optimization and post-process the part for export. nTopology uses a system of blocks, where each block performs a task and can be nested within other blocks as inputs. Within nTopology we first imported our CAD files for both our original part as well as a part file containing the preserved regions. Preserved regions are areas we specified should not be altered, thus allowing a better surface for hardware to mount flush. Originally, the optimization process modified the material around the mounting holes, but the preserved regions will replace these areas in the final model. The 'Finite Element Model' block contains other nested blocks which define the properties of the model needed for the simulation.

We created lists of faces for both the 'Force Faces' (mounts where force will be applied) and the "Fixed Faces" (simulates the mounting points fastened to the test stand).

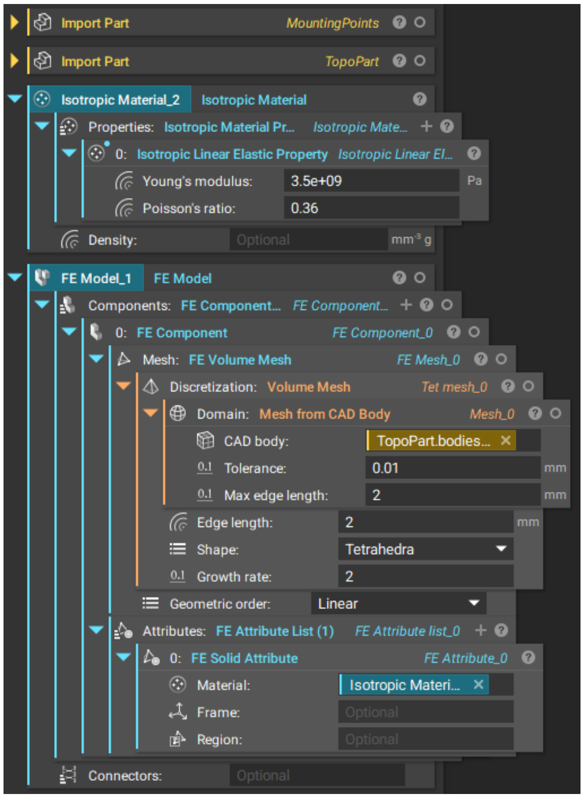

Figure 8: Importing Part Files

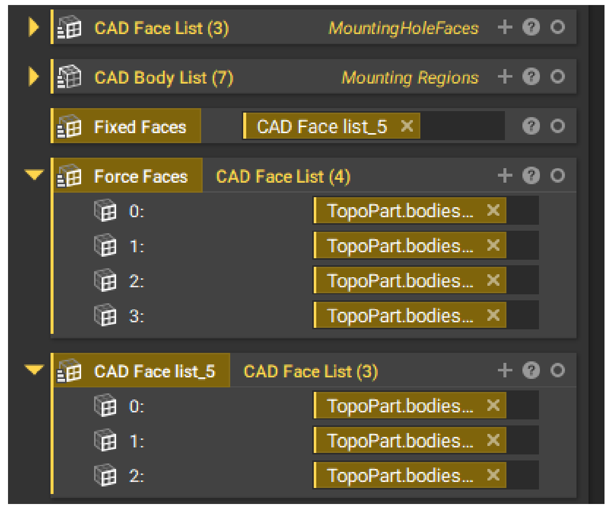

Figure 9: Defining Face Groups

Our displacement restraint block is what takes our list of mounting faces and defines them as fixed faces for our simulation. The 'Volume Mesh' and 'FE Volume Mesh' seen in many of the blocks used our solid part and mapped it out using tetrahedral elements. During the optimization, there will be calculations done at each connection point or 'node'.

For our optimization constraints, we first added 'Planar Symmetry' to ensure our model is symmetric across our defined plane. We set our 'Volume Fraction' constraint to 0.3, so the optimization will target a volume of 30% of the original part. The 'Passive Region' constraint ensures that the separate CAD of just the mounting points will not be affected.

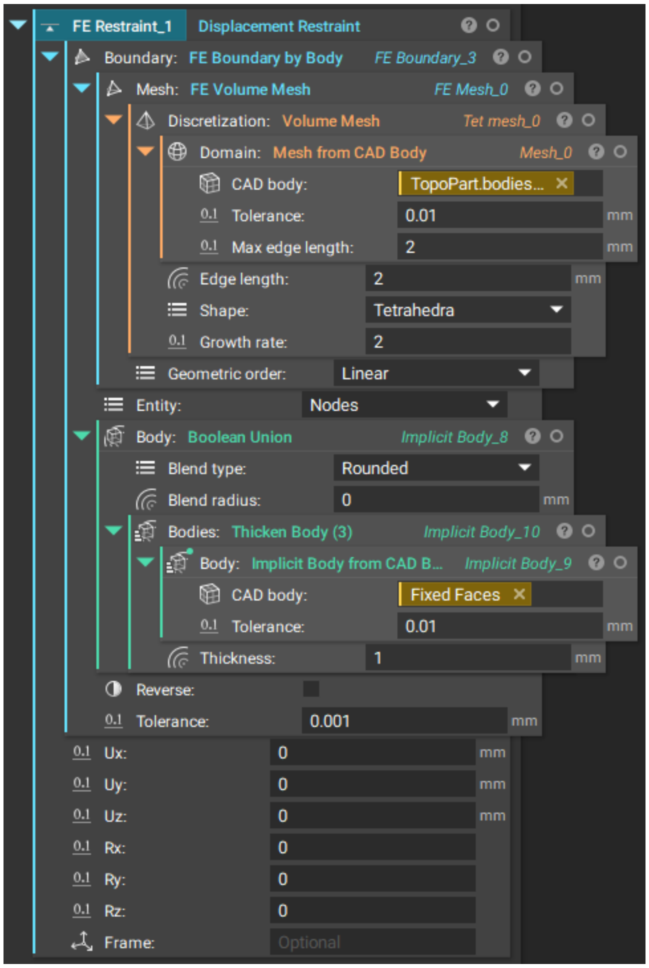

Figure 10: Displacement Restraint

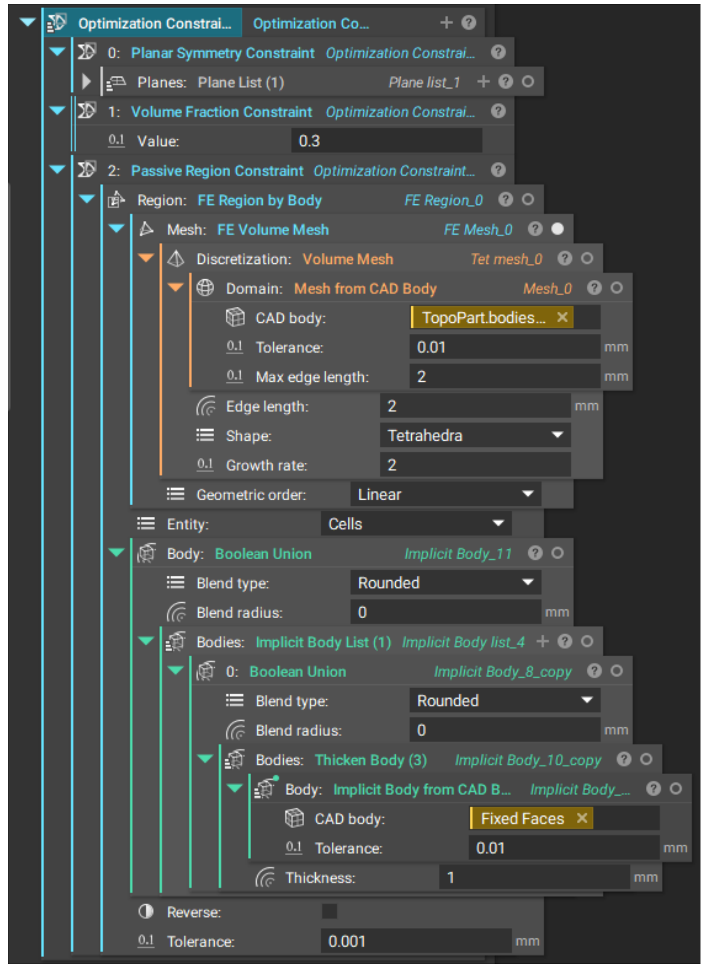

Figure 11: Optimization Constraint

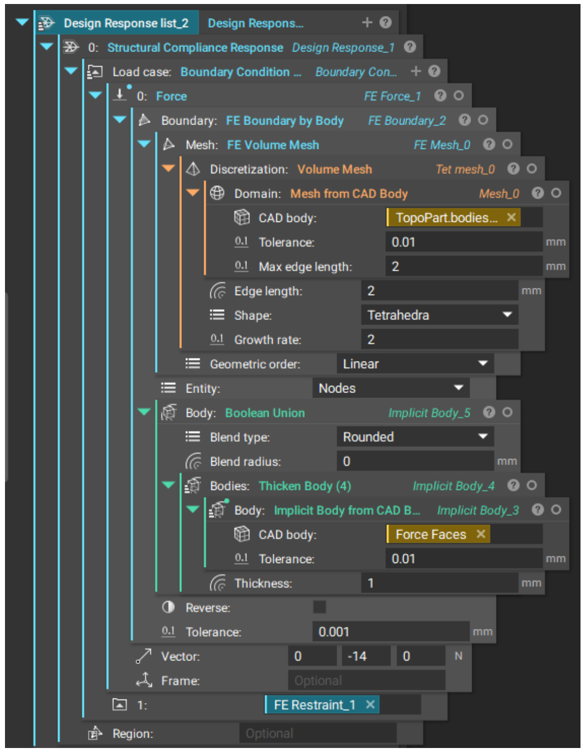

Figure 12: Design Response Constraint

The previously configured blocks can be nested inside a 'Topology Optimization' block. Once the optimization is complete you will see a 'Topology Optimization' box with some sliders. Adjusting the threshold slider allows you to visualize which elements are most important to the structural integrity of your part given the loading conditions.

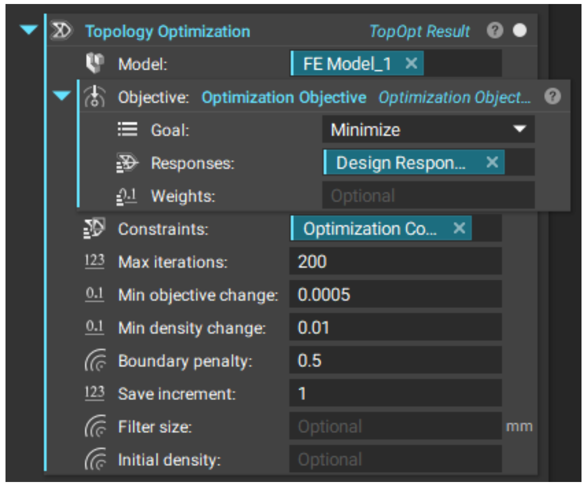

Figure 13: Topology Optimization

The output of the optimization has a somewhat rough surface quality and a 'Smoothen Body' block is used to smooth this surface. There are many 'Boolean Union' blocks throughout the steps which combine two separate implicit bodies. This is used in the following step to incorporate our original mounting point CAD with our optimized part.

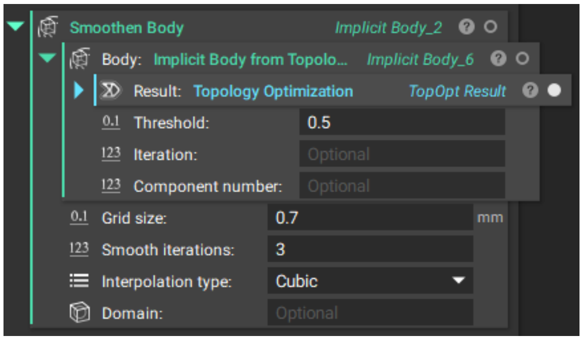

Figure 14: Smoothing the Optimized Part

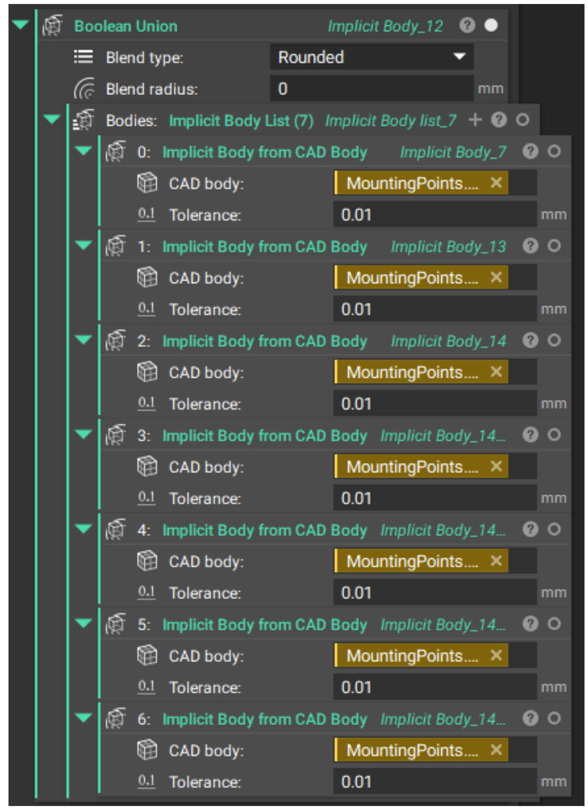

Figure 15: Merging Original Mounting Points

‘Refine Mesh’ is used to prepare the model for the ‘Export Part’ block which saves our optimized model to a specified folder as a parasolid that can be imported by CAD programs.

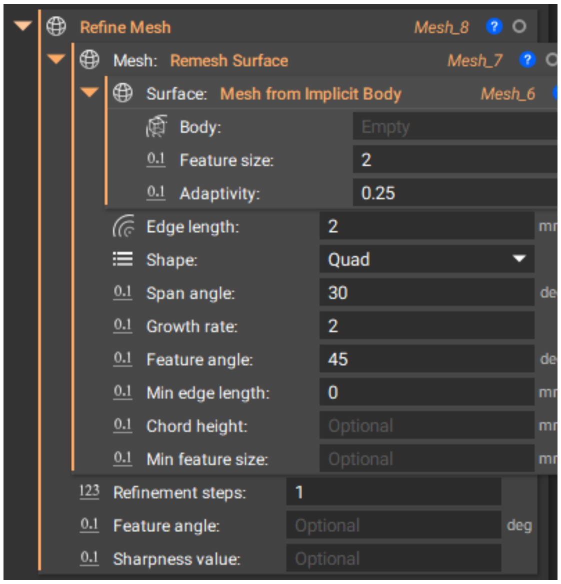

Figure 16: Refining Mesh for Export

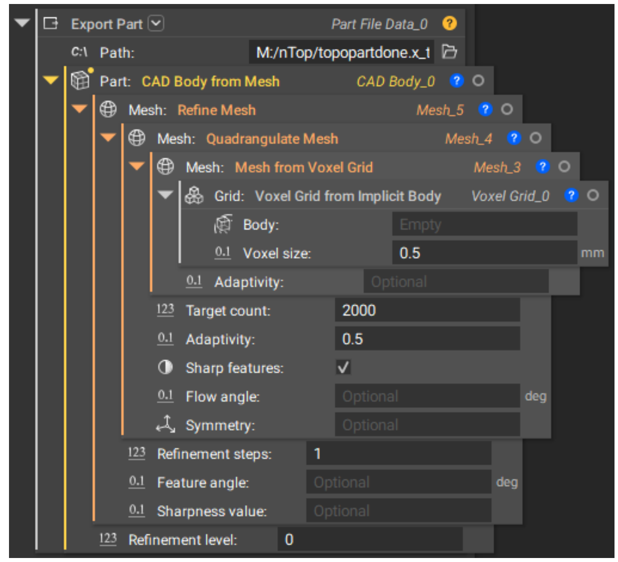

Figure 17: Exporting Model as Parasolid

3. Verification

3.1. 3D Printing

Since two different materials are being considered in this study, one example of each was printed for the original part. Three optimized examples were printed in each material so that their performance could be compared. The parts were printed with the following specifications:

Material	ABS (Zyltech Black ABS)	PLA (Hatchbox Black PLA)
Layer Height (mm)	0.2	0.2
Infill	100%	100%
Nozzle Temperature (℃)	235	215
Bed Temperature (℃)	110	60

Table 1: 3D Printing Specifications for Parts

3.2 Testing

We wanted to test whether the optimized parts could withstand the loads we had specified during the optimization process as well as the points of failure. The test stand's frame seen in Figure 18 was built with 4040 aluminum extrusion. The parts were bolted to the ¼" thick aluminum plate with parallel turnbuckles connected to both of the printed parts' connection points to a bolt with spacers. This setup evenly distributed a vertical load to both points. Our crane scale attaches to this bolt on one side and the other side is connected to a cable that runs down to a pulley that redirects the cable to the front. The position of this pulley ensures that the force is applied vertically regardless of the direction we pull the cable during testing. The testing setup is not meant to give us extremely accurate values, but to show that the parts can withstand the loads defined in our simulation.

We first tested the ABS parts with the unoptimized part failing at 75.61 lbs and the three optimized parts failing at 23.80-29.16 lbs. It is worth noting that these parts all failed at the location of maximum stress predicted in the FEA, on the upper radius where the arms connect to the base of the bracket. They also failed entirely along the layer lines of the parts, which is to be expected with FDM 3D printed parts. All optimized PLA parts withstood over 100 lbs of load without failure. At 100 lbs we felt we could end the test as the parts had greatly exceeded the design load.

Figure 18: Test Bench with Unoptimized ABS Part Attached

4. Costs

Two types of cost analysis will be discussed in this section. First, the overall cost of this study will be calculated, which will include the hours of work spent, the total material cost, and the overall time spent printing the parts. And second, the overall savings due to the optimization of the part will be analyzed.

Labor costs were estimated per the recommended formula by multiplying an ideal hourly rate, the actual number of hours spent working on this project, and a factor of 2.5. Assuming an hourly undergraduate co-op rate of $20.00 per hour and an estimated 60 hours of work spent on this project, labor costs work out to an estimated $3,000. However, a significant portion of the time spent was on learning to use the optimization software, and would not be necessary for optimizing additional parts. Material cost is also another significant factor in 3D printing. A total of eight parts were printed for this study, two of which being the original parts, and six of which were the optimized parts. The unoptimized parts used 186 grams for the PLA part and 175 grams for the ABS part. The optimized parts weighed in at 62 grams each in PLA and 64 grams each in ABS. This makes for a total material cost of 342 grams of PLA and 367 grams of ABS. Both filaments can be bought for a conservative estimate of $25/kg, resulting in a cost of $18.48 for all of the material used to print the parts. A third, more arbitrary, cost metric is print time. Depending on the source, one might be charged anywhere from $1 to $10 or more to commission a 3D print, based on the quality of a contractor's equipment. As these parts were printed at home on hobby desktop FDM printers, an hourly cost of $2 will be assumed for this analysis. The original parts took about 13 hours each to print, while the optimized parts took approximately seven hours each to print. This results in a printing machine time cost of $136.

Another metric to analyze is the cost saved as a result of this optimization, both in material savings and print time. Although the original part may likely be manufactured by molding, or machining if it were metal, it is still worth noting the cost saved per part that the topology optimization provided. Looking at a PLA part, the original bracket would cost 186 grams of material and 13 hours to print, for a total cost of $30.65 per part printed. The optimized version would only cost 62 grams of material and seven hours to print, yielding a total cost of $15.55 per optimized part printed. Therefore, the total actual cost of this study of $154.48 resulted in a cost savings of $15.10 per part, a 49% cost reduction. Dividing the cost of performing this study by the cost savings per part, it can be said that it would take the production of eleven parts to make the optimization profitable. Details of the cost analysis can be found in the appendix in Tables 2 and 3.

5. Conclusions

A simple, vertically loaded bracket was designed to study topology optimization for 3D printing. For a design weight of 3 lbs, initial FEA showed stresses well beneath the strengths of the selected materials, ABS and PLA, leaving plenty of room for optimization. Specialized optimization software was requested and granted from nTopology, and was used to topologically optimize the part, reducing the mass of PLA and ABS parts from 186 and 175 grams down to 62 and 64 grams, respectively. One sample of each material was printed for the unoptimized part, and three optimized samples of each material were printed. All samples greatly exceeded the design weight, with PLA parts withstanding over 100 lbs, unable to be broken. With a weight reduction of 63-66%, this results in 49% cost savings per part, with an estimated total cost of $154 to perform this study. It can be concluded that topology optimization is an incredibly viable and valuable process to utilize in design for additive manufacturing.

6. References

[1] ISO / ASTM52900-15, Standard Terminology for Additive Manufacturing – General Principles – Terminology, ASTM International, West Conshohocken, PA, 2015, www.astm.org

[2] ISO / ASTM52902-19, Additive manufacturing — Test artifacts — Geometric capability assessment of additive manufacturing systems, ASTM International, West Conshohocken, PA, 2019, www.astm.org

[3] ISO / ASTM52910-18, Additive manufacturing — Design — Requirements, guidelines and recommendations, ASTM International, West Conshohocken, PA, 2018, www.astm.org

[4] ISO / ASTM52915-20, Specification for additive manufacturing file format (AMF) Version 1.2, ASTM International, West Conshohocken, PA, 2020, www.astm.org

[5] Torres, J. et al. "Mechanical Property Optimization of FDM PLA in Shear with Multiple Objectives." JOM 67 (2015): 1183-1193.

7. Appendix

Table 2: Testing Results

Optimized/Unoptimized	Material	Part	Failure Load (lbs)	Picture of Failure
Unoptimized	ABS	ABS_1	75.61	
Optimized	ABS	O_ABS_1	23.8	

Optimized	ABS	O_ABS_2	24.14	
Optimized	ABS	O_ABS_3	29.16	
Unoptimized	PLA	1	No failure at 100lbs, no further testing required	
Optimized	PLA	1	No failure at 100lbs, no further testing required	
Optimized	PLA	2	No failure at 100lbs, no further testing required	
Optimized	PLA	3	No failure at 100lbs, no further testing required	

Table 2: Labor Cost Calculations

"Labor cost estimates should use the following formula for each partner:

ideal salary (hourly rate) × actual hours spent × 2.5"

Labor	Hours Spent
Part Selection	3
Design	6
Research	4
FEA	10
Topology Optimization	25
Testing	12
Total	60
x $20/hr x 2.5 [$]	3000

Table 3: Printing Cost Calculations

		PLA	ABS	Total
Original Part	Material [grams]	186	175	361
	Print Time [hours]	13	13	26
	Quantity	1	1	2
Optimized Part	Material [grams]	62	64	126
	Print Time [hours]	7	7	14
	Quantity	3	3	6
	Material Price [$/kg]	25	25	
	Print Time Cost [$/hour]	2	2	
	Material Cost [$]	9.3	9.175	18.475
	Printing Cost [$]	68	68	136
	Total Cost [$]	77.3	77.175	154.475

Topology Optimization for Additive Manufacturing

Michael Levy & Michael O'Donnell

Department of Mechanical Engineering

Honors Research Project

Submitted to

The Williams Honors College
The University of Akron

Approved:

Jae-Won Choi

Date: 4-20-2021
Honors Project Sponsor (signed)

Honors Project Sponsor (printed)
Jae-Won Choi

Alper Buldum

Date: 4/21/2021
Reader (signed)

Reader (printed)
Alper Buldum

Gopal Nadkarni

Date: 4/27/2021
Reader (signed)

Reader (printed)
Nadkarni R Gopal

Accepted:

Scott Sawyer

Date: 4/30/2021
Honors Department Advisor (signed)

Honors Department Advisor (printed)

Scott Sawyer

Sergio Felicelli

Date: 4/27/2021
Department Chair (signed)

Department Chair (printed)
Sergio Felicelli