Comparative Analysis of Topology Optimization Platforms for Additively Manufactured 6 DOF Robot Arms

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***Abstract* - Topology optimization (TO) is increasingly integrated into commercial CAD environments due to the ease and cost-effectiveness of manufacturing complex freeform geometries using additive technologies. Although the underlying TO theory is well-established, various topology optimization systems yield different results. This paper conducts a systematic evaluation and cross-analysis of five representative TO platforms using elements of a six degrees of freedom (6 DOF) robotic arm as a case study. To assess the practical implications, the most successfully optimized components are 3D printed and assembled into a functional robotic arm. The evaluation criteria, including postprocessing requirements, energy efficiency, price, and manufacturability of optimized vs. unoptimized parts, are discussed. The platforms are then ranked based on these criteria. Keywords – Topology optimization; 3D printing; robotics; optimization**

I. INTRODUCTION

Topology optimization has been a significant tool to help when designing a part thereby looking to reduce the mass with a constraint set on the stiffness of the part [1]. Robots are no longer produced only in highly structured industrial environments; a simple robotic hand can be manufactured using an off the shelf available additive manufacturing process almost in any circumstances. This drives and opens a new opportunity for designers to experiment with geometry of robotic parts to save material, but on the other hand enables unprecedented design freedom directly related to aesthetics and mechanical properties. Lighter robots not only save energy during manufacturing and later operation phase, but also result in increased safety and potential harm caused by collision [2-4]. These concepts, widely recognized as design automation processes [5] are nowadays becoming an integral part of commercial CAD environments used to design a wide range of mechanical components [6]. Additional benefits of topologically optimized parts compared to their unoptimized counterparts comes in form of time savings [7] needed to print the parts, energy and material savings which are all discussed later in the paper. Although both topology optimization and in recent time, but to a much lesser degree, generative design have both been successfully applied to design of robots [8-14], there is a lack of comparative studies between different options available for topology optimization especially in the domain of robotics design. In this paper, five CAD environments with integrated topology optimization modules are compared. We use real manufactured parts to experimentally confirm savings estimated through simulation given by topology optimization environment. We outline advantages and disadvantages of each. The platforms were tested while using parts of a six degree of freedom robot as a test scenario. The chosen parts were later manufactured using additive manufacturing, precisely Fused Deposition Modeling (FDM) and assembled into a fully operational 6 DOF robotic arm.

II. TOPOLOGY OPTIMIZATION IN COMMERCIALLY USED CAD SOFTWARE

Topology optimization has become a common addition to widely used commercial CAD software giving the opportunity to designers to significantly improve their models with majority of work transferred to the design automation process performed automatically. In this study we want to show that the topologically optimized parts don't just have interesting designs but are also functional just as before the optimization with additional benefits. When choosing the software for this paper only those for which we could get a student license were used. The five software platforms that were used are SolidWorks, Fusion 360, Creo Parametric, Altair Inspire and Ansys Discovery. When setting up the parameters across the platforms, parameters were kept as similar as possible to achieve comparable end results.

The main parameter, mass reduction percentage was always set to 20%. This ensures stability of printed parts and enables end results to be comparable. The diagram below shows the step-by-step process to setup and carry out a general topology optimization process. Figures 2. – 6. show forearm optimized in each software.

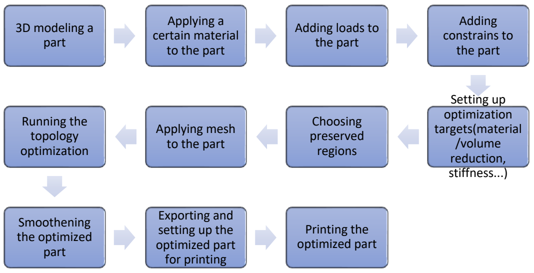


Figure 1. Generic procedure of topological optimization process

A. *SolidWorks*

- All the parts that were optimized were initially designed in SolidWorks.
- The set up for topology optimization follows the flow chart shown in Figure 1.
- When setting up the part for the optimization there is an option to optimize the part in a way it could later be used as a positive in a mold making process.
- One of the downsides is that to see the result, the optimized part must be saved as a separate file and after that allow the smoothing option to see the final product.

Figure 2. Topologically optimized shoulder in SolidWorks

B. *Fusion 360*

- Offers a quick and easy set up for the topology optimization of a certain part.
- The topology optimization is run on the Fusion 360 cloud.
- The topology optimization option is not free to use however students get infinite free coins (v.2.0.18477) which can then be used for the topology optimization.
- Fusion 360 also accepts parts designed in other CAD environments.
- Here also the process to getting the part optimized follows the flow chart shown in Figure 1.
- Fusion gives additional options considering the region preservation process.

Figure 3. Topologically optimized shoulder in Fusion 360

C. *Creo Parametric*

- Topology optimization set up in this software is more complex comparing to other four platforms.
- Before the 2nd step in Figure 1, certain regions that are to be preserved must be separated as individual body parts.
- The rest of the flow chart corresponds to the setup process in Figure 1.
- Once the parts are optimized, they must be saved in separate folders otherwise the next optimized part will overwrite existing ones.
- Meshing in Creo is also less automated compared to other platforms and requires manual fine tuning of the mesh. For the wrist part the optimization could not be proceeded because satisfactory mesh could not be generated.
- The end results are comparable to other four platforms tested in this study.

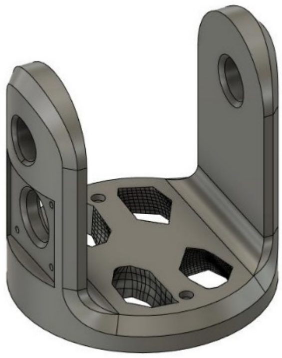


Figure 4. Topologically optimized shoulder in Creo Parametric

D. *Altair Inspire*

- This software also follows the flow chart shown in Figure 1.
- Altair has falls behind on variety of load types compared to other four platforms.
- Before the 2^{nd} step in Figure 1, certain regions that are to be preserved must be separated as individual body parts, similarly to Creo.
- The smoothing option in Altair is the most intuitive, robust, and fast.

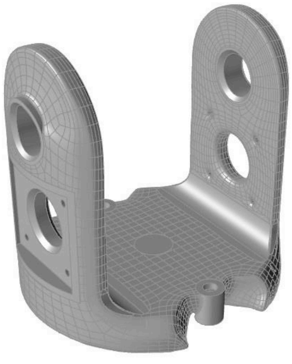


Figure 5. Topologically optimized shoulder in Altair Inspire

E. *Ansys Discovery*

- This software alongside Fusion and SolidWorks also follows the flowchart outlined in Figure 1.
- When setting up the part for the topology optimization the software offers a large variety of materials and types of loads.
- When selecting areas which will be excluded from the optimization, it is possible to select whole surfaces and only adjust the depth of the excluded areas.
- If parts designed in another software are optimized, i.e. SolidWorks, the part must be saved as Ansys Discovery file. Otherwise, the part would not open.
- Even though Ansys offers a student version it prevents the optimized parts to be saved. For that reason, although the parts were optimized, they couldn't be 3D printed and experimentally verified.

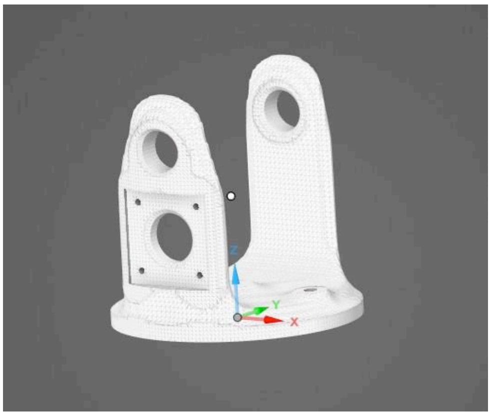


Figure 6. Topologically optimized shoulder in Ansys Discovery

III. SELECTING THE PARTS FOR 3D PRINTING

As the Ansys files could not be exported we excluded those results at the start from printing. For the printing, to check the actual printability and potential hidden problems, we selected one part for printing from every platform, besides Ansys. The chosen parts were manufactured using a 3D printer. Specifically, the technology that was used was FDM.

The material from which the parts were made is PET-G. The optimized parts also required supports and in some places, we had to increase the supports in comparison to the same non optimized part because during optimization, while removing material the software created new holes and overhangs. Due to the complexity of the parts, support removing can become cumbersome, and postprocessing of the parts takes additional time from a human operator. One solution to this would be to print complicated optimized with a printer that supports multi material printing and then using for example PVA as a support material which is dissolvable in water.

It is also important to consider material used for print because some filaments warp more than others during print and thus create deformations in parts that have thin areas. In the case presented in this study, the parts were printed with PET-G, and besides of stringing, no other major problems occurred. If i.e. ABS was chosen, which tends to warp during print it would be a tough task to successfully print the chosen optimized forearm. The same goes to the wrist optimized in Fusion 360 which is the most interesting in design but would be harder to print because the part would be problematic to stick to the print bed due to a lot of small surfaces that were generated while optimizing the part.

The chosen shoulder yields a very interesting design and shoves the perfect example of symmetry in topology optimization. This part wouldn't make any problem to print with any material.

IV. COMPARISON BETWEEN OPTIMIZED AND NON OPTIMIZED PARTS

After the optimized and non-optimized parts were designed, a comparison between them was performed.

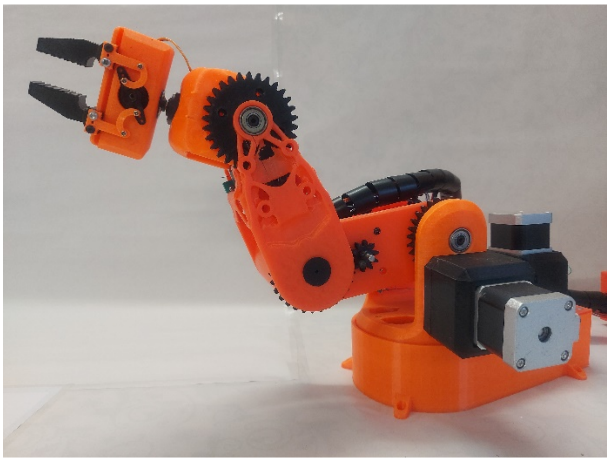


Figure 7. Complete functional robot with optimized components

Considering the design of the optimized parts compared to the design of the nonoptimized ones, it is notable that the optimized parts are shaped in a way that is not intuitive, and these parts consists of complex curves which indicate an optimization process was used for design. Figure 7. shows the robot assembled of optimized parts and connected to a completely functional robotic hand.

All the parts that were printed were prepared in a software called Cura. Cura allows to see the estimated print time and material consumption. This gives an opportunity to see many differences between optimized and nonoptimized parts.

The main advantage in topology optimization after material saving is time saving. For every optimized part a slight decrease in print time is noted. The below part names in the first column of Table 1 are named after arm parts for convenience. The estimated mass consumptions in column four of the Table I also includes the mass for the needed supports during print. Therefore, the mass savings are less than expected because some of the optimized parts need supports in areas they didn't need before optimization. this is a consequence of the optimization process, during which additional overhangs and other design details are created.

These features to be printed need additional support structures what means addition to the overall mass consumption.

TABLE I. ESTIMATED PRINT TIME AND MASS CONSUMPTION OF OPTIMIZED AND NONOPTIMIZED PARTS

Robot parts	Estimated print time for nonoptimized parts	Estimated time for optimized parts	Estimated mass consumption for nonoptimized parts	Estimated mass consumption for optimized parts
Shoulder	12h 29min	11h 43min	102g	91g
Forearm	15h 44min	14h 25min	107g	75g
Wrist	9h 8min	8h 58min	69g	61g

V. COSTS AND SAVINGS WITH TOPOLOGY OPTIMIZATION

For this section of the paper the robot forearm will be used as an example to see all the costs and savings when using topology optimization. The forearm used for calculation was optimized in Altair Inspire, but similar analysis hold also for the parts optimized in other platforms.

A. *Energy savings for the robot*

To calculate the energy savings while using the optimized forearm the moment of inertia is needed which can be seen in figure 8. If coordinate system of the robot is adjusted so that it is equal to the coordinate system of the forearm, the y-axis will be used as the axis of rotation of the forearm. The moment of inertia is equal to $I_{YY_O} = 134{,}633403\ \mathrm{kgmm}^2$. The rotation speed is set to 30 rpm which in angular velocity is equal to π rad/s. Therefore, the kinetic energy is equal to:

$$E_{K_O} = \frac{1}{2}\omega^2 I_{YY_O} = \frac{1}{2}\pi^2 \cdot 0{,}00013463 = 0{,}0006644\ \mathrm{J}.$$

As the nonoptimized forearm was designed in SolidWorks the moment of inertia will be taken from there which can be seen on Figure 9. We can see that the moment of inertia is equal to:

$$I_{YY_N} = 443{,}03\ \mathrm{kgmm}^2 = 0{,}00044303\ \mathrm{kgm}^2.$$

The rotation speed is the same as for the optimized part. The kinetic energy of the nonoptimized forearm is then equal to:

$$E_{K_N} = \frac{1}{2}\omega^2 I_{YY_N} = \frac{1}{2}\pi^2 0{,}00044303 = 0{,}002186\ \mathrm{J}.$$

If we consider the robot arm as a closed system thereby ignoring friction and temperature losses, we can then write

$$\sum E_{uk} = E_K + E_E = konst.$$

which means that we then have a direct conversion from a electric energy to a kinetic one. To make things more convenient we can say that the energy consumption with the optimized part is equal to:

$$E_{E_O} = 0{,}0006644\ \mathrm{Ws} = 2{,}39184 \cdot 10^{-9}\ \mathrm{kWh}$$

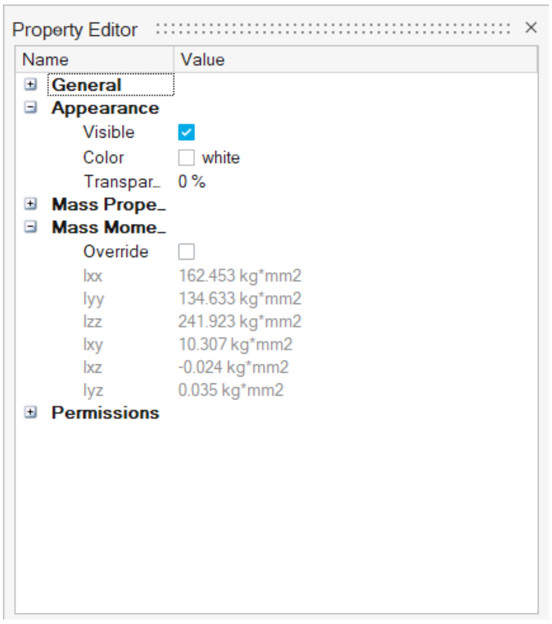
and the energy consumption when using the nonoptimized forearm is then equal to:

$$E_{E_N} = 0{,}002186\ Ws = 7{,}8696 \cdot 10^{-9}\ \mathrm{kWh}.$$

We can then see that the energy savings with the optimized forearm are equal to

$$E_{E_U} = E_{E_N} - E_{E_O} = 0{,}002186 - 0{,}0006644 = 0{,}001522\ \mathrm{Ws} = 5{,}4792 \cdot 10^{-9}\ \mathrm{kWh}$$

or we can say that there is a saving of 69,62%.



Property Editor

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Figure 8. Properties of the optimized wrist in Altair Inspire

B. *Electrical energy savings in manufacturing*

The power consumption of the printer is approximately 120 W. The estimated printing time of the optimized forearm is 14,42 h which gives an energy consumption of 1,7304 kWh. The nonoptimized forearm takes about 15,73 h to print which costs 1,8876 kWh of energy.

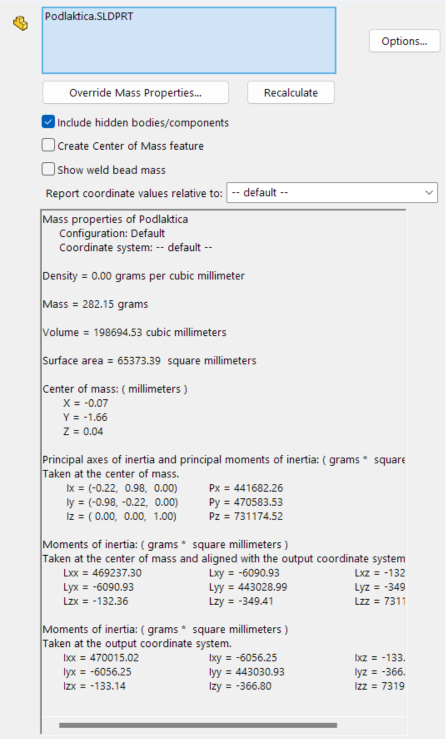
The energy saving is then equal to 0,1572 kWh or 8,3280% and the saved time is 1,31 h.

C. *Material savings*

How much topology optimization affects price of printed parts is also an important parameter. At the time of writing this paper the price of 1 kilogram of PET-G is around 22,00 €.

If the forearm for consideration, the optimized part had a mass of approximately 0,075 kg and the cost is 1,65 € and the mass of the nonoptimized one was estimated around 0,107 kg which is around 2,35 € in material cost.

Therefore, the forearm optimization results with 0,70 € savings.



☑ Include hidden bodies/components
☐ Create Center of Mass feature
☐ Show weld bead mass
Report coordinate values relative to: -- default --

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Mass properties of Podlaktica
    Configuration: Default
    Coordinate system: -- default --

Density = 0.00 grams per cubic millimeter

Mass = 282.15 grams

Volume = 198694.53 cubic millimeters

Surface area = 65373.39  square millimeters

Center of mass: ( millimeters )
     X = -0.07
     Y = -1.66
     Z = 0.04

Principal axes of inertia and principal moments of inertia: ( grams *  square
Taken at the center of mass.
      Ix = (-0.22,  0.98,  0.00)         Px = 441682.26
      Iy = (-0.98, -0.22,  0.00)         Py = 470583.53
      Iz = ( 0.00,  0.00,  1.00)         Pz = 731174.52

Moments of inertia: ( grams *  square millimeters )
Taken at the center of mass and aligned with the output coordinate system
     Lxx = 469237.30                    Lxy = -6090.93                   Lxz = -132
     Lyx = -6090.93                     Lyy = 443028.99                  Lyz = -349
     Lzx = -132.36                      Lzy = -349.41                    Lzz = 7311

Moments of inertia: ( grams *  square millimeters )
Taken at the output coordinate system.
     Ixx = 470015.02                    Ixy = -6056.25                   Ixz = -133.
     Iyx = -6056.25                     Iyy = 443030.93                  Iyz = -366.
     Izx = -133.14                      Izy = -366.80                    Izz = 7319
```

Figure 9. Properties of the nonoptimized wrist in SolidWorks

VI. SOFTWARE

Considering that many aspects were mentions in this paper and that the optimization platforms are quite different from each other we decided to make comparisons in a few categories and then make a final remark of the software.

A. Desing and overall look of printed parts

This category is subjective, but we focus on design novelty (how original the design is or how explorative certain platform is), design symmetry, and design ability, i.e. is a platform able to achieve satisfactory results for a given part. Each software gave interesting designs and innovative placement of parts surfaces. However, not each software gave at the same time interesting and functional designs. The ranking is in the following order:

1. Fusion 360
2. Altair Inspire
3. Ansys Discovery
4. Creo Parametric
5. SolidWorks

Fusion 360 is put as number one because it gave interesting designs for every part which was optimized and shoved that it performs a topology optimized file without being constrained by original parts shape. Although Altair also gave some interesting results not all parts were as explorative as in the of Fusion 360. Ansys also yields interesting designs, but it lacks the symmetry that the top two had. It comes at the cost of aesthetics. Creo relies heavily on symmetry. It seems like this fact constraints TO engine to generate original parts and limits its exploratory potential. In addition, meshing of the parts in Creo is more complex, and not intuitive. SolidWorks is comparable in designs to the other platforms, but the way it takes material off leaves rugged surfaces and a need for extensive manual smoothing afterwards.

B. Preparation and handling the software

Some of the platforms have been easier and some harder to use and to get started with. the learning curve is dominant criterion on this scale. The ranking is based on an observation of how quickly and easy it is to set up a part for topology optimization and run it in the software. In the case of Fusion 360, despite being intuitive on its own, there is also a very large online library which helps with understanding of all aspects of TO process. The difference between the next three platforms is not significant. In the case of Creo, it is based on our experiment the platform that requires more time to master compared to the other four.

1. Fusion 360
2. Ansys Discovery
3. Altair Inspire
4. SolidWorks
5. Creo Parametric

C. The available options and what the software offer

Although all the tested platforms work in a similar way they do have some differences. Some are more and some are less equipped with options. It is important to note here that all the platforms are constantly being developed. For example, Fusion 360 has on average two product updates per month. Here we were led with the fact that of the more options the software has the better. The ranking is shown below.

1. SolidWorks
2. Fusion 360
3. Ansys Discovery
4. Creo Parametric
5. Altair Inspire

As things stand SolidWorks has the most options available to ensure a good preparation for topology optimization. Fusion offers many from the options and materials SolidWorks does but falls behind in the fixture section. Ansys is comparable in number of options and materials to choose from but lacks several options in the load and fixture sections. Between the last two and the top three is a bigger gap. Creo and Altair lack several options on material selection, as well as in the load and fixture section.

VII. FINAL COMPARISON

In the Table II below a final objective comparison, conducted for the robot shoulder, between the compared software platforms is presented. The comparisons are made in the category of time consumption for topology optimization processing, safety factor, mass reduction, post processing time, design complexity, and print time. As a baseline for comparison, a nonoptimized shoulder part would take 10 h 47 min for print.

TABLE II. FINAL COMPARISON OF TO PLATFORMS FOR THE SHOULDER OF THE ROBOT

	Altair Inspire	Solid Works	Fusion 360	Creo	Ansys Discovery
Mass reduction	13,29%	18,13%	37,16%	15,41%	17,82%
Processing time	10 min	49 min	60 min	2 min	1 min
Safety factor	62,3	75	35	66	77
Post processing time	<1min	1 min	< 1 min	< 1 min	< 1 min
Complexity	Complex	Simple	Simple	Complex	Simple
Printing time	11h 39min	10h 46min	8h 40min	10h 44min	/

None of the software achieved the wanted 20% in mass reduction. The closest to the target value was SolidWorks which had a mass reduction of 18,13%. The most distant one was one was Fusion 360. Regarding Fusion 360, when setting up the parameters and the desired mass reduction Fusion works in a way that it reduces the mass to at least the wanted value but if it’s possible it will reduce the mass much more than needed if the safety factor constraint is not violated.

When looking at the processing time surely the fastest ones are Creo and Ansys.

Right behind them is Altair. SolidWorks and Fusion are far away regarding that it takes them almost an hour to optimize the wanted part. Considering the post processing time there is no big difference between the software and the difference in time is too small to be taken under consideration.

The printing time of the parts is also comparable, with Altair component requiring the most tome to finish the print. This cannot be related directly to software; it is a consequence of the complexity pf the optimized part and varies from one component to the other.

VIII. CONCLUSION

The final comparison of the platforms tested in this paper reveals that all the tested platforms are effective for topological optimization of the analyzed parts. Fusion 360 stands out for its intuitive interface and ease of use, requiring the least amount of time to set up for optimization. Additionally, Fusion 360 offers a diverse library of materials for 3D printing, enhancing the realism of simulations. It's important to note that Fusion 360 operates in a cloud-based environment.

While choosing any of the mentioned software options wouldn't be a mistake, if affordability is of highest importance, Fusion 360 and Altair Inspire emerge as top choices for topology optimization.

Fusion 360 and Ansys Discovery also stand out for their user-friendly interfaces compared to other alternatives. If the main criterion is having a wide range of options when performing simulations, Fusion and SolidWorks top the list.

Ultimately, the choice of software depends on individual preferences and existing workflows. Given that the differences among these platforms are not significant, it might be more practical to use the topology optimization feature in the CAD software an organization already employs for other design tasks. This approach avoids the need to purchase additional software solely for topology optimization.

In general, topology optimization is increasingly becoming integral part of various CAD environments, which is expected to become even more pronounced in upcoming period. This will also increase the options for designers to choose from. In addition, these platforms are rapidly developing almost daily, so additional options are expected in all the platforms.

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