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Comparative Analysis of Topology Optimization Platforms for Additive Manufacturing of Robot Arms

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Abstract: Recently, CAD environments have integrated topology optimization (TO) tools, enabling rapid development and manufacturing of parts with optimized mechanical properties. However, different CAD platforms incorporate TO differently, making a comparative analysis necessary. This study aims to systematically compare the efficiency, material usage, and design quality of five commonly used CAD/TO platforms when applied to the topology optimization of a six degrees of freedom robotic arm. The objective is to identify the key differences in how these platforms influence the final design and manufacturing outcomes. Practical validation of results is provided by printing and assembling optimized components into a fully functional robotic arm. Our findings indicate differences in optimization efficiency, material usage, and print time between analyzed platforms. Strengths and weaknesses of each platform are indicated and recommendations for optimization parameters are provided.

Keywords: topology optimization; CAD; 3D printing; robot design; optimization; CAM

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1. Introduction

Integration of topology optimization (TO) tools and CAD environments is becoming increasingly important recently, allowing engineers and designers to conveniently create, control, modify, and optimize 3D geometries using computational algorithms. TO is a performance-based design tool that finds the most efficient material distribution for a given objective, initial volume, and set of constraints. This enables the design of lightweight yet stiff structures. At the same time, the design optimization process is transferred from the designer to the computational domain.

These optimized structures are often characterized by elegant, organic forms built of free-form voids in continuum structures [1]. Moreover, as shown in [2], structures with optimal stiffness designs favor very complex microstructures. This limits the direct transfer of optimized designs to manufacturing environments, especially in the case of conventional manufacturing technologies. To be manufactured conventionally, these structures must often be redesigned and adapted to meet manufacturing constraints [3,4]. This is a time-consuming process, prone to errors while reconstructing a parametric model from the topology-optimized part, thus generally limiting the potential of design optimization [5].

On the other hand, additive manufacturing has opened a vast space to natively materialize complex geometries. The integration of TO and additive manufacturing can make the most of their advantages and potentials and has wide application prospects in modern manufacturing [6–8]. This beneficial interaction has facilitated the expansion of TO beyond niche software environments, making it accessible as a tool in commonly used CAD software. This way, these advanced algorithms are becoming available to a very broad audience, starting with high school students. The potential of full integration of additive manufacturing, CAD, TO, is yet not reached and is expected to grow in the future.

A comprehensive list of currently available CAD environments with integrated TO tools can be found in [9]. The authors also evaluate three TO platforms: SolidWorks, Ansys

Mechanical, and Abaqus, and run comparative analyses on three common case studies. Simulation results are given, and platforms are ranked accordingly. In this study, we adopt a similar approach but run simulations on a real technical product, a robot arm, and go beyond simulation, printing the components to shed additional insights into the geometry and materializing and assembling it into a final product.

The basic idea behind TO is that the portions of the structure that do not contribute significantly to the compensation of external forces through elastic deformation can potentially be removed from the structure. This way, the total mass of the structure is iteratively reduced while the constraints set are not violated. The stress-constrained optimization problem is formulated to find a minimum weighted structure that satisfies the stress constraint and is, at the same time, in equilibrium with external loads [10]. The design problem takes the following form:

$$\min V(\rho), \rho \in [0,\ 1] \tag{1}$$
$$K(\rho)u(\rho) = F$$
$$\sigma_{VM}(\rho) \leq \frac{\sigma_e}{f}$$

where

- K is the global stiffness matrix.
- σ_{VM} and σ_e Von Mises and material yield stress, respectively.
- f is a safety factor.
- u and F are displacement and load vectors.

In the above equation, ρ is for the material density of each element used as a design variable and varying continuously between 0 and 1. For such a formulated problem, the end structure usually contains many intermediate densities, or grey values, which is not practically meaningful. A solution to this problem is the so-called solid isotropic material with penalization (SIMP) method, which was introduced by Bendose [11]. This method, by using power law, penalizes intermediate densities and promotes binary material distribution. This way, a binary solid–void structure can be more reliably achieved.

$$K(\rho) = \rho^p \cdot K^0, \rho > 1 \tag{2}$$

where

- K^0 is the stiffness matrix for the given isotropic material.
- p is the penalization exponent, usually in the range of [1,3,12]

The first implementation of the SIMP method was by O. Sigmund, 99 lines of Matlab code [13]. This simple implementation is the foundation of many later applications, which are built upon it. The SIMP method can be applied to a wide range of TO problems, i.e., a continuous compliance optimization problem (CCO), and a discrete compliance optimization problem (DCO).

An important problem from an engineering perspective, the continuous compliance optimization problem is formulated as follows:

$$\min F^T u(\rho),\ \rho \in [0,\ 1] \tag{3}$$
$$K(\rho)u(\rho) = F$$
$$K(\rho) = \rho^p \cdot K^0$$
$$\int_\Omega \rho < V$$

where V is the volume constraint that defines the maximum amount of distributed material. The objective function measures stiffness by compliance, which is a preferred approach in TO due to the direct relation of compliance to structural stiffness. Namely, compliance is defined as the inverse of stiffness, so by minimization of compliance, the optimization process effectively maximizes stiffness. This approach is also aligned with the finite element method and the minimization of elastic strain energy of the structure related to the external work of the loads [14]. Therefore, minimizing compliance is a standard and efficient approach in structural optimization, which leads to stiffness maximization of the optimized structure.

From an engineering and application perspective while using TO environments, the availability of a desired objective function, being mass or compliance minimization, is essential. The set of available optimization and manufacturing constraints is also of high importance. Constraints can include fundamental properties such as a targeted fraction of material distributed in optimized structure, maximally allowed deflection, and targeted eigenfrequency, but they can also be related to the manufacturing process, forcing symmetry, preserving regions, defining pulling directions, etc. The most common case is that stiffness maximization (or compliance minimization) is selected as the objective function. Usually, only a single optimization objective can be selected. In the case of multiple selected criteria, the problem becomes multi-objective, which makes it complex to solve using gradient-based methods. This can be overcome by using weights to transform the problem into a single objective optimization. Another option is using heuristic algorithms, i.e., evolutionary algorithms to explore the multidimensional space for optimal results [15]. It is important to note that weight selection for the multi-objective case influences the result of optimization since there is more than one combination of weights, with the consequence of individual solutions for every weight combination, which forms the Pareto front of non-dominated solutions. To explore the Pareto front, an exhaustive search between various weight combinations is thus necessary.

Although the TO theory is well established now, wider incorporation of TO add-ons has been more recent, with the majority of applications analyzed in this study starting around 2018 [16]. Of the five analyzed environments, the first one to introduce TO is Altair Inspire, back in 1994 with its OptiStruct package and General Motors as the first customer [17].

The TO community, both open source and commercial, is very active now and will be even more in the future [18]. Thus, there is a clear motivation to analyze the current possibilities of five commonly used TO platforms: namely, SolidWorks, Altair Inspire, Creo, Ansys Discovery, and Fusion 360. It is important to note that software selection is based on the principle of being able to acquire a free academic version of the software. The other criterion is to keep a set of analyzed platforms not too extensive and, also, to analyze a set of representative software packages, the ones that will give useful feedback to interested communities.

As a test case, we decided to go beyond a single, isolated case study and to go not only through simulation but also through the materialization of optimized components and their assembly to the final product. A six degrees of freedom robotic arm is chosen as a test case. Robots are no longer manufactured 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 circumstance. This drives and opens a new opportunity for a broad audience to experiment with the geometry of robotic parts to save material. This also enables unprecedented design freedom directly related to aesthetics and mechanical properties.

In addition, lighter robots not only save energy during manufacturing and later operation phases but also result in increased inherent safety and potential harm caused by collision [19–21]. Additional benefits of topologically optimized parts compared with their unoptimized counterparts come in the form of time savings [22], energy savings, and material savings, which are all discussed later in this paper. TO also has the potential to find globally valid optimized robot designs for a given set of trajectories [23], which is an important finding since most TO applications are conducted on a set of typical load cases and configurations [24]. Both TO and, in recent times but to a much lesser degree, generative design have been successfully applied to the design of lightweight robots [25–30]. These applications follow the general principle of topology optimization and show that lighter structures, which, at the same time, satisfy stress constraints, can be successfully designed and used in robotics design.

Despite promising applications of TO in various problems, there is a lack of comparative studies between different TO environments and their experimental comparison. Existing studies primarily focus on simulations and isolated case studies, often neglecting the experimental validation of these designs in functional products. Furthermore, there is a lack of comprehensive side-by-side comparisons of multiple TO platforms using a consistent test case, which is crucial for understanding their practical applicability and performance differences. Finally, most of the studies focus on analyzing the optimization procedure of individual components rather than complex, real-world assemblies.

In this paper, we build upon our previous findings [31] to shed additional light on five CAD/TO environments with integrated TO modules. We use physically manufactured parts assembled into a functional robotic arm to experimentally confirm savings estimated through simulation given by the TO environment. A discussion on energy savings for robot manufacture and operation is presented. The optimized parts were manufactured using additive manufacturing, fused deposition modeling (FDM), and assembled into a fully operational 6 DOF robotic arm for final experimental verification. The differences in how TO tools are implemented and the impact this has on the end design of optimized components of robotic parts across platforms suggest that a systematic comparison is necessary. To evaluate these hypotheses, we employed a systematic approach to test each TO platform under identical conditions.

The rest of this paper is organized as follows: Section 2 describes the materials and methods used in this study. Section 3 presents the results of the TO process and their experimental validation. In Section 4, a discussion on savings achieved through TO is presented. Section 5 discusses the findings and compares the performance of different platforms. In Section 6, the conclusion and future research directions are given.

2. Materials and Methods

TO has become a common addition to widely used commercial CAD software, providing the opportunity for designers to significantly improve their models with the majority of work transferred to the design automation process performed automatically. In this study, we want to show that the topologically optimized parts are characterized not only by their interesting designs but are also functional just as before the optimization with additional benefits. When selecting the software for this paper, only those for which we could get an academic-free license were used. To achieve the objective of comparing TO platforms, five widely used software environments were selected: SolidWorks (Waltham, MA, USA), Fusion 360 (Singapore), Creo Parametric (Boston, MA, USA), Altair Inspire (Troy, MI, USA), and Ansys Discovery (Canonsburg, PA, USA). Each platform was assessed based on the ability to optimize the mass and maintain the structural integrity of the robotic arm components, as well as the ease of use and processing time.

A fully functional robotic arm is initially designed in 3D using SolidWorks, as illustrated in Figure 1A. This model will be used to compare optimization software by comparing optimized designs of the same components across analyzed software platforms. In Figure 1B, an optimized robot hand is presented. Components that were optimized are colored red.

The objective of TO was to reduce the mass; at the same time, a constraint was set on the safety factor. The mass reduction percentage was always set to 20%, while the safety factor was set to 5. This ensures the stability of printed parts and enables the end results to be comparable. Initially, a higher percentage of mass reduction was used, but this resulted in disconnected geometry, which was divided into separate and unconnected regions. This revealed the problem that although constraints were not violated, the TO process resulted in infeasible designs. Experimentally, 20% mass reduction was found to reliably generate feasible designs. This problem is discussed in more detail in Section 4.

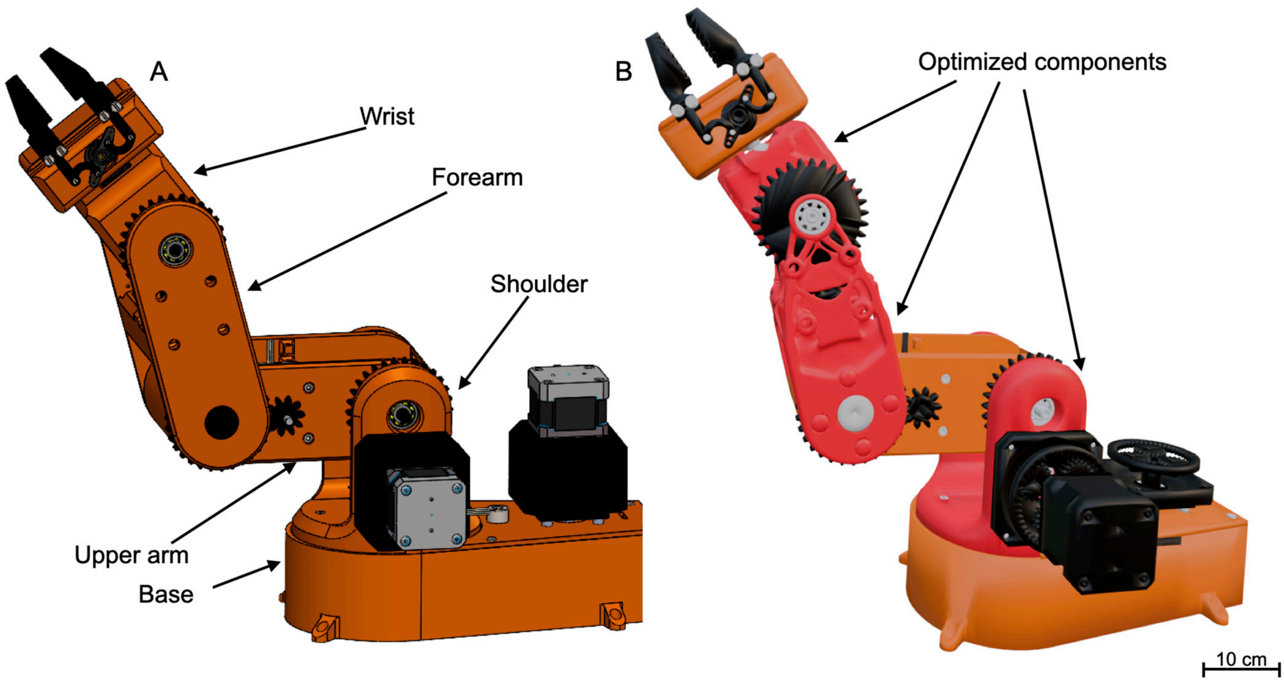

Figure 1. CAD model of the robot arm used as a case study (**A**). Model of the robot arm after optimization of shoulder, forearm, and wrist (**B**).

The diagram in Figure 2 shows the step-by-step process to set up and carry out a general TO process adopted in this study. As previously mentioned, a CAD environment must be selected to design the initial 3D geometry of the part for optimization. Material constants such as elastic modulus and Poisson's ratio are defined in the next step through a selection of materials. Software platforms analyzed in this study have a large database of applicable materials and these libraries were obviously designed with 3D printing procedure in mind.

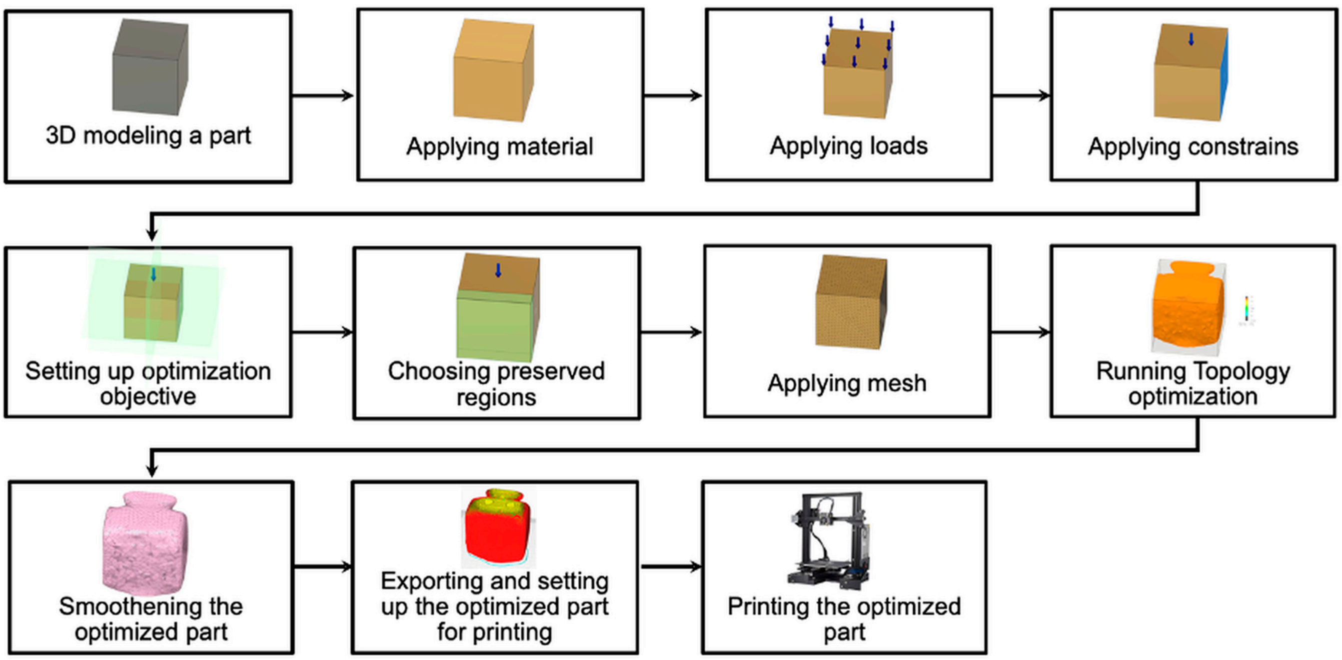

Figure 2. The procedure of topological optimization process.

The next two steps are related to defining loads that act on the part and appropriate constraints, which can be either a clamp that prohibits motion in all three axes or lower-order contact constraints, allowing for specific translations and rotations. The next step defines the objective of the TO process.

Some parts of geometry must be preserved since they present contact points for other parts of the assembly. This is achieved in the sixth step. The meshing of geometry is used to discretize the parts into finite elements. Mesh size has an influence not only on the processing time but also on the result of the optimization. There are some general rules on the tetrahedral mesh size, such that the dimension must be less than the thickness of the preserved region. However, experimental fine-tuning of the mesh is almost always necessary. After the optimization ends, postprocessing is performed to smoothen out the surface and remove small artifacts. This makes parts ready for export and sending to the 3D printer. In this step, we decided to keep the unchanged topologically optimized geometry received from optimization. In some cases, optimized geometry is used as a template to recreate a 3D model with simplified geometry, especially if the manufacturing process requires doing so.

Although the process of topology optimization is, in general, similar to all the software presented here, there are differences, which will be discussed in Section 5. It is important to note that to ensure a fair comparison of TO platforms, identical conditions should be defined in terms of loads and boundary conditions, along with the optimization objective.

The loads and constraints used for the optimization of the components were identical across all the platforms and are presented in Figure 3. The forearm (A) was clamped at the surface connected to the upper arm. Distributed force of 200 N is applied vertically downward at the surface connected to the wrist. In addition, a torque of 100 Nm was applied at the same location to balance the torques propagated from the gripper up to this point. For the wrist (B), a vertically distributed force of 100 N is applied to the interface between the wrist and the gripper. The opposite end of the wrist is clamped. For the shoulder (C), there are two openings on the bottom surface where it attaches to the base, and these are clamped, preventing any movement. A vertical distributed force of 300 N is applied on the surface connecting the shoulder to the upper arm of the robot. In addition, a torque of 200 Nm is applied to balance the torque propagating from the gripper up to this point. It is important to note that the actual values of the forces are significantly below those used in simulation. The exact magnitude of the forces is not of critical importance for comparative analysis as long as the boundary conditions and forces are kept identical across the platforms. The material used for all the analyses is PET-G with tensile strength of 45 MPa, Young's modulus of 2 GPa, and Poisson's ratio of 0.4.

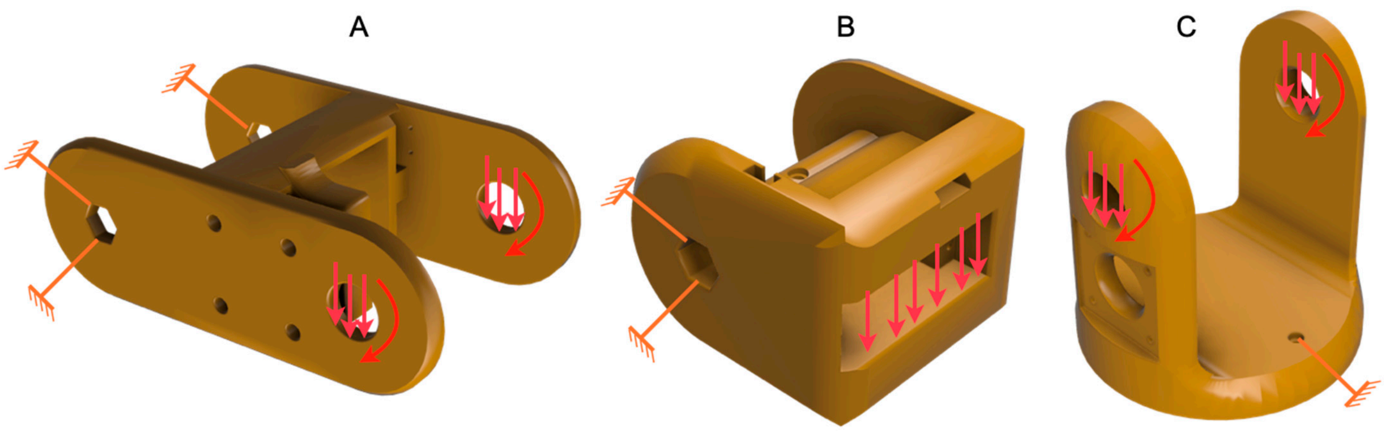

Figure 3. Loads applied to the optimized parts: (**A**) forearm, (**B**) wrist, and (**C**) shoulder.

Regarding the mesh element size, each of the analyzed platforms uses a built-in meshing algorithm. To keep the results comparable, we limited the parabolic second-order tetrahedral global element size to 2 mm in each platform and excluded local meshing. Experimental fine-tuning of mesh to achieve satisfactory results is necessary. Lower values allow for generating finer structures but come at an increased cost of processing time.

To assess the potential for optimization of robotic components, initial FEM analysis is performed for every component of the robot. This revealed significant potential for material removal, based on safety factor analysis. The example of the FEM analysis of the forearm in its original, unoptimized state is illustrated in Figure 4. The safety margin is very high: >200 for the above-given parameters used in the study for every component of the robot. This was a clear indicator that parts would benefit from optimization.

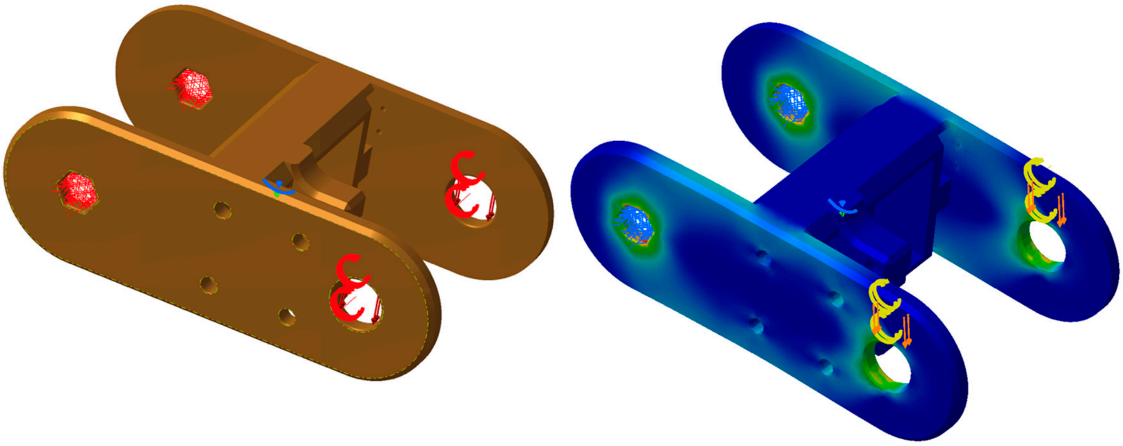

Figure 4. FEM analysis of the unoptimized forearm component.

The following section presents the results of the comparative analysis of selected TO platforms for chosen robotic components, under described conditions, highlighting the specific advantages and limitations of each platform.

3. Results

We used each software platform to make the initial optimization of every robot component. Based on these results, a set of components for the final optimization is reduced to the shoulder, forearm, and wrist of the robot since these components exhibited promising results in terms of stability and material savings—generally, their design resulted in meaningful changes and improvements when compared with the original parts. The results of optimization across the analyzed platforms are illustrated in Figure 5. Original parts prior to optimization are shown in the first column, and their optimized counterparts associated with the optimization platform are in the remaining columns. The results demonstrate significant variability in how each TO platform optimizes the robotic arm components, directly addressing the research question of this study regarding the optimization efficiency of different CAD/TO platforms. Generally, parts optimized in Creo Parametric in our study had the fewest changes in the design, resulting in conservative geometry. An example of this is the shoulder part in the fifth column, bottom. Four symmetrical openings are located on the bottom surface, whereas side walls remain unchanged. In the case of Creo, the wrist was not optimized satisfactorily. Optimization results with divided regions were consistently obtained under the same boundary and load conditions and with the same mesh properties as those used in the optimization of the wrist in other environments. Altair Inspire resulted in complex geometries, with delicate internal structures, for which an example is the forearm in the second column, top. In the case of SolidWorks, there are some critical components with thin substructures, i.e., a forearm in the third column. Fusion 360 successfully optimized all the components, and the change in the design was not significant as in the case of Altair but still more pronounced compared with Creo.

Figure 5. Topologically optimized robot parts per platform. **First** row: forearm. **Middle** row: wrist, **bottom** row: shoulder.

Finally, since the Ansys-optimized models could not be exported due to restrictions of free academic license, we excluded those results at the start from printing and further analysis. For printing, we selected one component—from Creo Inspire, the shoulder; from Altair Inspire, the forearm; and from Fusion 360, the wrist. These components were selected for print based on the extent of mass reduction, symmetry of design, absence of thin edges and structures, and general appearance and design complexity. A typical example is the forearm optimized in Altair, which exhibits an organic appearance, meets all the optimization criteria, follows symmetry, and is aesthetically appealing. The parts were printed on an FDM desktop Prusa i3 printer (Prague, Czech Republic), and the prints are presented in Figure 6.

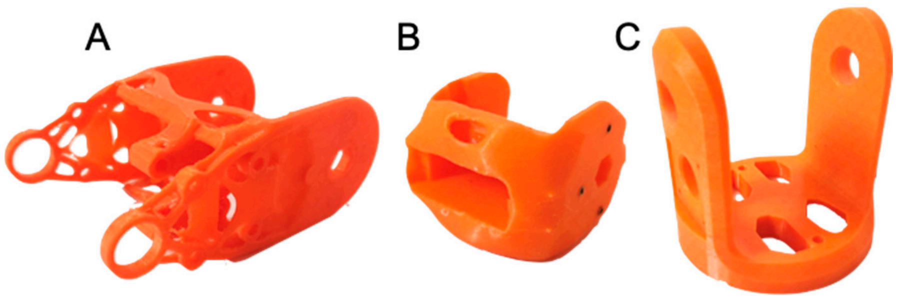

Figure 6. Optimized components selected for 3D printing. Forearm—Altair Inspire (**A**). Wrist—Fusion 360 (**B**). Shoulder—Creo Parametric (**C**).

The material used for printing is PET-G. The optimized parts also required supports and, in some places, we had to increase the supports in comparison to the same nonoptimized part because during optimization, while removing material the software created voids and overhangs, which made the printing process more demanding.

Due to the complexity of the parts, support removal can become cumbersome, and postprocessing of the parts takes additional time. One solution to this would be to use a printer that supports multi-material printing and then use, for example, PVA as a support material, which is soluble in water.

It is also important to consider the material used for the print. Some filaments warp more than others during printing and, thus, create deformations in parts, which contain thin and delicate structures. In the case presented in this study, the parts were printed with PET-G, and besides stringing, no other major problems occurred.

Forearm in our case consists of a complex, fine structure, for which warping could become a problem. In the case of ABS filament, which is prone to warping, printing the selected forearm would be problematic.

Considering the design of the optimized parts compared with the design of the nonoptimized ones, there is a notable difference in complexity in favor of optimized designs. These parts contain complex outer geometry with included voids, which were not present in the original parts.

In Figure 7, the robot assembled of optimized parts and connected to a completely functional robotic hand is presented. All the parts that were printed were prepared in the UltiMaker Cura preprocessor. Cura is an open-source slicer, which also allows for the estimation of print time and material consumption.

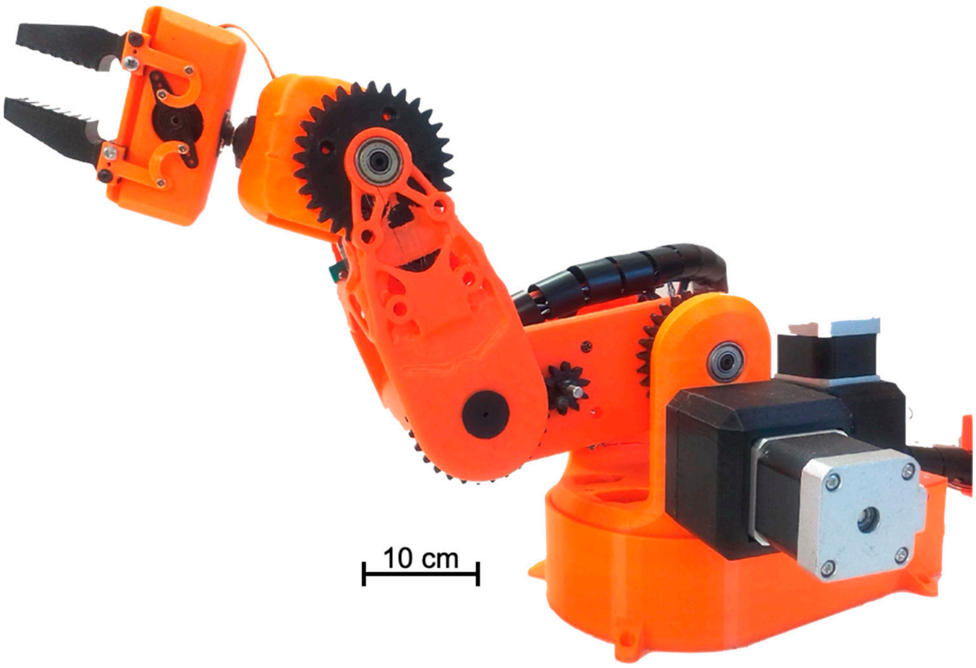

Figure 7. Complete functional robot with installed optimized components.

4. Costs and Savings Using Topology Optimization

Costs for printing the parts are related to filament consumption and printing time. The difference in printing time and filament used for optimized and unoptimized parts of the robot are presented in Table 1.

Table 1. Estimated print time and filament consumption for optimized vs. unoptimized parts.

Part Name	Print Time Original	Print Time Optimized	Filament Original	Filament Optimized	Support Original	Support Optimized
Shoulder (Creo)	12 h 29 min	11 h 43 min	94 g	83 g	8	8
Forearm (Altair)	15 h 44 min	14 h 25 min	89 g	75 g	18	25
Wrist (Fusion 360)	9 h 8 min	8 h 58 min	50 g	35 g	19	26

4.1. Energy Savings for the Robot Operation

Robot forearm will be used to illustrate savings achieved through topological optimization in more detail. Similar analysis can be performed for all the optimized components and correspondent platforms. To calculate the energy savings while using the optimized forearm, the moment of inertia is required, which can be calculated in Altair Inspire where the forearm was optimized (Figure 8).

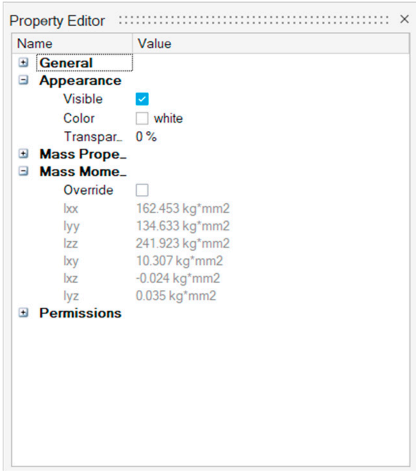

Figure 8. Properties of the optimized forearm in Altair Inspire.

If the 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 $I_{YY_O} = 134.633403$ 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:

$$E_{K_O} = \frac{1}{2}\omega^2 I_{YY_O} = \frac{1}{2}\pi^2 \cdot 0.00013463 = 0.0006644 \text{ J}.$$

As the nonoptimized forearm was designed in SolidWorks, the moment of inertia will be taken from there, $I_{YY_N} = 443.03$ kgmm^2 $= 0.00044303$ kgm^2.

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

$$E_{K_N} = \frac{1}{2}\omega^2 I_{YY_N} = \frac{1}{2}\pi^2 0.00044303 = 0.002186 \text{ J}$$

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 electric energy to a kinetic energy. To make things more convenient, we can say that the energy consumption with the optimized part is equal to:

$$E_{E_O} = 0.0006644 \text{ Ws} = 1.84661 \cdot 10^{-10} \text{ kWh}$$

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

$$E_{E_N} = 0.002186 \text{ Ws} = 6.0733 \cdot 10^{-10} \text{ kWh}.$$

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

$$E_{EU} = E_{EN} - E_{EO} = 0.002186 - 0.0006644 = 0.001522 \text{ Ws} = 4.22722 \cdot 10^{-10} \text{ kWh}$$

which makes savings of 30.40%.

4.2. Electrical Energy Savings in Manufacturing

The power consumption of the printer used is approximately 120 W. The estimated printing time of the optimized forearm is 14.4167 h which gives an energy consumption of 1.7300 kWh. The nonoptimized forearm takes about 15.7333 h to print which costs 1.8888 kWh of energy.

The energy saving is then equal to 0.1588 kWh or 9.1791% and the saved time is 1.31 h.

4.3. Material Savings

To what extent TO affects the price of printed parts is also an important parameter. At the time of writing this paper, the price of 1 kg of PET-G is around EUR 22.00.

If the forearm is for consideration, the optimized part has a mass of approximately 0.075 kg and the cost is EUR 1.65 and the mass of the nonoptimized one is approximately 0.107 kg, which is around EUR 2.35 in material cost.

Therefore, the forearm optimization results in EUR 0.70 savings.

5. Analyzed Software Differences

In this section the differences among the analyzed TO platforms will be highlighted in the context of available sets of TO tools, meeting the optimization objective, processing speed, and general optimization end results.

5.1. SolidWorks

This is a widely adopted primarily CAD software, offering simulation capabilities for structural, thermal, and fluid flow analyses, along TO.

TO objectives (or goals as referred to in SolidWorks) are the best stiffness-to-weight ratio, maximum displacement minimization, and mass minimization. Constraints available, based on the selected objective, are a mass constraint, maximal displacement constraint, natural frequency constraint, stress constraint, and factor of safety constraint. Simultaneous selection of different constraints is possible. SolidWorks has a built-in automatic mesh smoothing tool, which is very easy to use and intuitive. A set of manufacturing constraints is available for various manufacturing methods, including CNC machining and injection molding.

The results of optimization in SolidWorks meet the optimization criteria consistently. SolidWorks is slower in running optimization, being computationally intensive. Compared with other platforms, optimized surfaces were coarser in SolidWorks and required additional smoothing. Generally, setting up the optimization process in SolidWorks is intuitive, the environment is well integrated and follows the same logic as other SolidWorks tools. Available tutorials and extensive help make understanding the process more reliable and fast.

5.2. Fusion 360

Fusion 360 is built as a cloud-based collaborative environment. It has unique features for real-time simultaneous work on a complex project. It integrates CAD features and TO and allows for a smooth transition from the design environment to the production phase.

Fusion 360 offers two main options related to what is considered TO in this study. The first option is shape optimization under a simulation environment. This option is very limited in terms of functionalities. Target mass and stiffness minimization are available as so-called global objectives. Under global constraints, only a minimum member size is available, which is related to the minimal thickness of the geometry. Since there is no option to directly define a factor of safety, shape optimization was not further evaluated.

The second option is called generative design, which is the focus of Fusion 360 optimization from our experience. As previously mentioned, it runs in the cloud and so-called cloud credits are used to pay for the cloud processing time. For academic licenses, infinite credits are available. This generative design approach is much more like other software packages analyzed in this study. Still, there are some significant differences compared with the other four software platforms. The most significant difference is that for optimization objectives, which are mass minimization and stiffness maximization, it is not possible to set a constraint on mass or volume minimization. Under the limits category, which is used for optimization constraints, the safety factor, modal frequency, maximal displacement, and buckling safety factor are available.

The absence of mass constraint now explains the mass reduction of 32% as seen in Table 2, which is above given threshold of 20% defined for all the other software. Manufacturing constraints are also present and nicely distributed into four categories: additive, milling, 2-axis cutting, and casting.

Table 2. Comparison of tested TO platforms for the forearm of the robot.

	Altair Inspire	Solid Works	Fusion 360	Creo Parametric	Ansys Discovery
Mass reduction	16.12%	17.85%	32.31%	14.21%	16.93%
Processing time	10 min	49 min	60 min	2 min	1 min
Safety factor	54	48	35	49	51
Postprocessing time	<1 min	1 min	<1 min	<1 min	<1 min
Design complexity	Complex	Complex	Complex	Simple	Complex
Print time	14 h 25 min	13 h 51 min	12 h 11 min	14 h 58 min	/

The generative nature of optimization is revealed by the ability to select multiple materials and manufacturing methods at once. It is also possible to leave voids in the structure and let the generative method fill out the free volume, optimizing, at the same time, given objectives and satisfying the constraints. The process is not driven only by the subtraction of initial material as in a regular TO process. On the contrary, the model can be built from a set of predefined, separated bodies, which usually have the role of contact interfaces and load locations and remain fixed through the optimization process. In this case, the outcome is not a single solution but a set of solutions, which have different designs and properties. The designs are differentiated by their minimal safety factor, maximal displacement, material distribution, and volume. Fusion also has a well-organized interactive online help with tutorials, step-by-step guides and video materials. Fusion 360 runs significantly slower compared with other analyzed software in this study.

5.3. Altair Inspire

This is a simulation-driven platform oriented toward conceptual design. It is intuitively built and accessible to a wide range of users. It is optimized for performance, running optimization relatively fast in our study. It has limited CAD capabilities, compared with dedicated CAD environments like SolidWorks or Creo. A multibody concept is usually required for parts being optimized to differentiate regions being unaltered from those being optimized.

Besides topology, Altair has options for topography, gauge, and combined topography and gauge optimization. Optimization objectives in Altair are stiffness maximization, frequency maximization, and mass minimization. Optimization constraints available are a mass constraint, stress constraint, and frequency constraint. There are additional constraints related to manufacturing and the minimal element size. All the standard loads and constraints are available across the platforms, i.e., concentrated and distributed forces, moment loads, pressure, centrifugation, and acceleration. Constraints include fixed (clamp), enforced displacement, planar, cylindrical, and spherical constraints. Altair offers excellent online resources to explain all the features available, along with a basic theoretical background, which is very helpful.

5.4. Creo Parametric

This is a dedicated and powerful CAD environment, focusing on parametric modeling, allowing for easy design modifications with precise control over design parameters. It offers wide flexibility in modeling but comes at the cost of being more demanding in mastering compared with Fusion 360 or SolidWorks. It is an integrated environment enabling users to validate and optimize designs seamlessly in the same environment.

In the case of Creo, generative topology optimization, GTO, and generative design extension, GTX, are available. While GTO runs locally, GTX runs in the cloud and offers additional options related to multi-material support. The output is not limited to single design but to a set of design options. Optimization objectives in Creo are stiffness maximization and mass minimization. Optimization constraints available are mass constraint, volume constraint, and safety factor. An option for modal analysis (natural frequency optimization) is available. Online documentation is also available and intuitive for Creo. The parts optimized in Creo Parametric are more conservative compared with other platforms analyzed in this study. Creo performed the second fastest in this study.

5.5. Ansys Discovery

Ansys Discovery is analysis-based software and offers additional options in the section on loads and constraints compared with other analyzed software. It also excels in the materials section, allowing users to perform advanced material modeling. TO objectives available are stiffness maximization, natural (first mode) frequency maximization, balance of stiffness and natural frequency, targeted natural frequency, volume minimization, and stress minimization. Depending on the selected objective, the following constraints are available: a volume constraint, a factor of safety, stress-related constraints for stress minimization, and given natural frequency for targeted natural frequency. Manufacturing constraints are present, both for multi-axis milling and 3D printing processes. Ansys offers live physics simulation, enabling users to get real-time feedback on the optimization process. Ansys Discovery is known for the high accuracy of simulation results, making it a preferred choice for critical engineering applications. Since export to STL was restricted in our academic version, the parts optimized in Ansys Discovery were not considered for printing. Simulations performed in Ansys were the fastest of the five analyzed environments.

To conclude, each platform analyzed in this study is suitable for finding optimized designs under given objectives and constraints. The level of depth and detail with regard to part modeling and optimization is what differentiates the platforms. SolidWorks and Creo excel in integrated CAD and simulation capabilities, making them suitable for detailed design and optimization. Fusion 360's cloud-based approach and collaborative tools are well suited for team-based projects. It is also intuitive and easy to start using. Altair Inspire made the most innovative design for the forearm part in this study. The part is an excellent example of a successful TO, at the same time meeting all the criteria. Ansys Discovery is the most depth-oriented simulation software. It offers the most comprehensive analysis and optimization tools, making it the first choice for critical engineering applications.

In Table 2, a final comparison, conducted for the robotic forearm, among the compared software platforms is presented. The comparisons are made in the category of time consumption for TO processing, safety factor, mass reduction, postprocessing time, design complexity, and print time. As a baseline for comparison, a nonoptimized forearm part would take 15 h 44 min to print.

None of the software achieved the exact target of 20% mass reduction. The closest to the target value was SolidWorks, which achieved a mass reduction of 17.85%. The most distant one was one was Fusion 360. Fusion 360 removes material beyond the targeted value if the constraints are not violated. This reduces the control over the optimization process in the case of Fusion 360.

In Figure 9, the results of the material savings and optimization time are given for each of the analyzed software platforms. They are given in the form of box plots as aggregated values for all the optimized components for a given TO platform. It clearly demonstrates the differences in optimization time with Fusion 360 requiring the most time and Ansys Discovery and Creo running the fastest. Regarding material savings, platforms are comparable, staying close but below the targeted value of 20% mass reduction. The exemption is Fusion 360, as explained above.

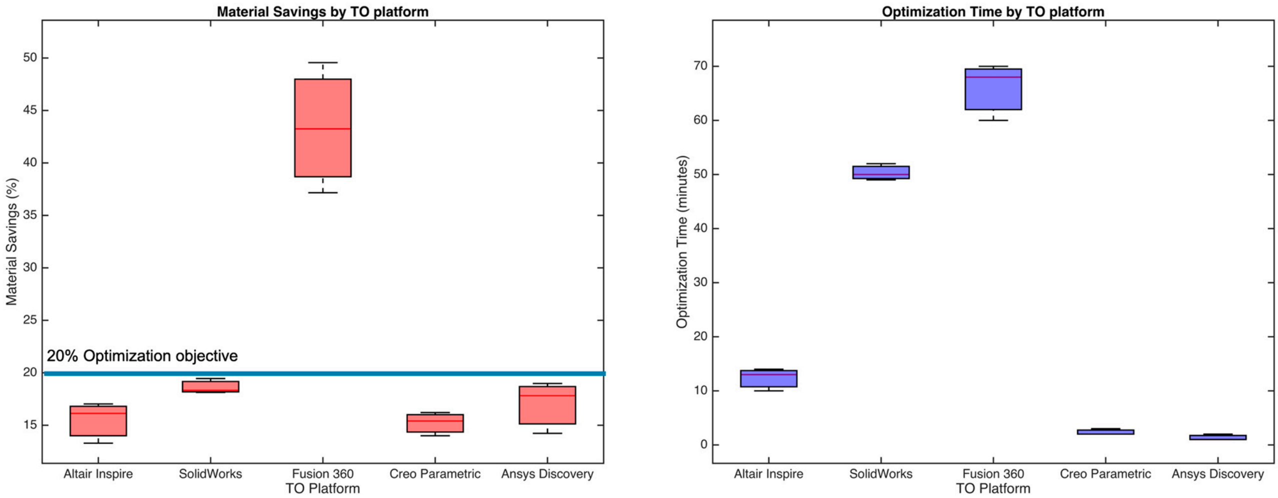

Figure 9. The percentage of material savings and optimization time, per platform.

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

The calculated safety factor is large, >30 for all the parts in all the analyzed TO platforms. It is important to say that the safety factor is considered here only as an indicator and holds only in the simulation. The parts are manufactured using FDM technology, which implies that there are significant deviations from the actual part compared with the material model used in the simulation. Thus, the safety factor can be observed here only conditionally, but it is valuable to indicate the safety margin.

The results of optimization are sensitive to mesh parameters and the constraint set. Trial and error and parameter fine-tuning are usually required to find parameters that will allow optimization to find satisfactory results. The results presented in Figure 10 are unsuccessful attempts to optimize the forearm with a 40% mass reduction. Unconnected regions appear, which is not acceptable. In addition, small edges, and thin and delicate structures occur, which is also problematic both for manufacturing and, also, for a later operational phase of the robot.

For that reason, a 20% mass reduction was adopted, which has the consequence of high safety factors obtained in the simulation. Nevertheless, significant savings in material, time, energy, and later in the operational phase were achieved for such defined mass reduction. This confirms the potential for applying TO concepts to efficient robotic designs.

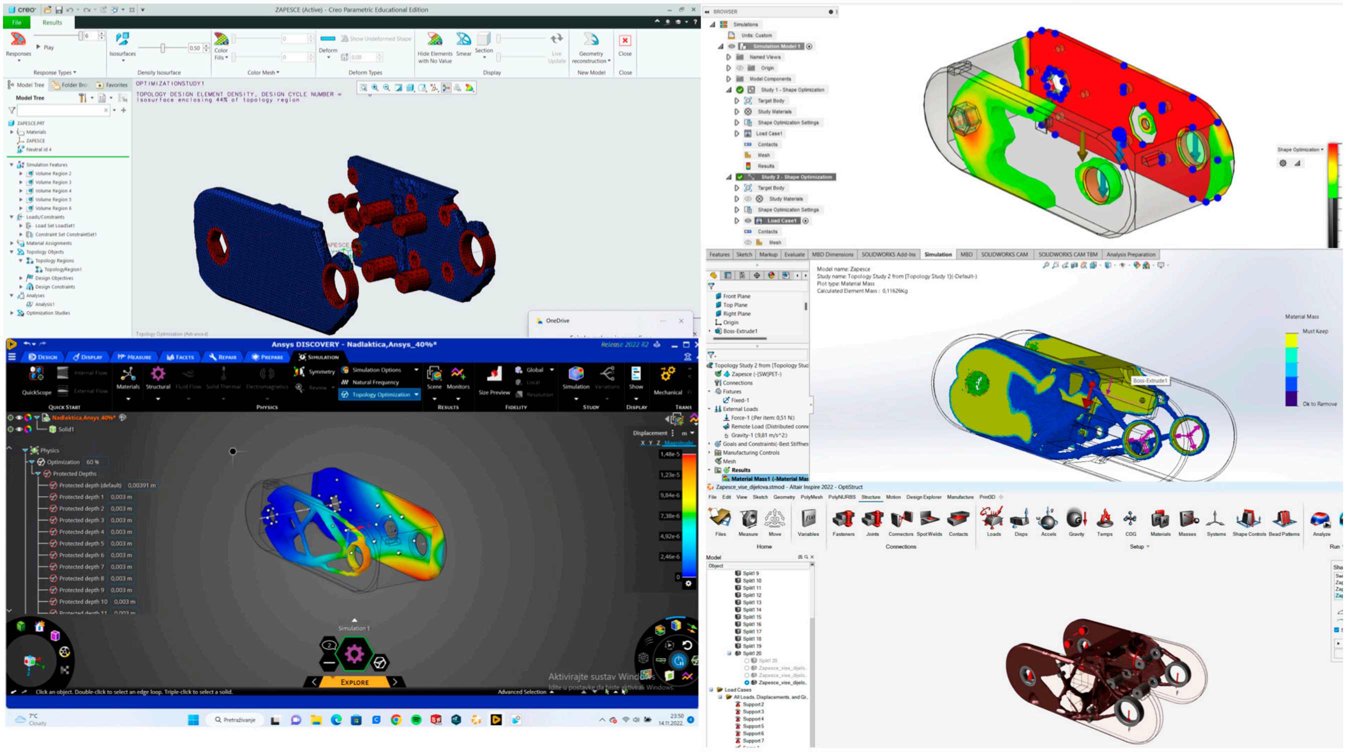

Figure 10. Unfeasible designs for the forearm. **Top left:** Creo Parametric, **Bottom left:** Ansys Discovery, **Top right:** Fusion 360. **Middle right:** SolidWorks, **Bottom right**: Altair Inspire.

6. Conclusions and Future Research

In this study, a comprehensive analysis and comparison of five widely used TO platforms—Altair Inspire, SolidWorks, Fusion 360, Creo Parametric, and Ansys Discovery—was conducted. A six degrees of freedom robotic arm was used as a test case. The objective was to evaluate the performance of TO tools and indicate key differences among them, especially the ability to satisfy the required mass reduction target, the efficiency of the optimization process, the design quality and applicability, and the general applicability of different TO platforms to the optimization of robotic components.

The key findings are the following:

Performance Evaluation of TO Tools: The study revealed significant differences in the performance of the TO tools across the five platforms. Ansys Discovery was identified as the fastest in terms of processing time, while Fusion 360 required the most time.

Material and Energy Savings: All platforms achieved notable material and energy savings through TO. Although none reached the exact target of 20% mass reduction, they consistently demonstrated the potential for substantial reductions in material usage, which directly translates to cost and environmental benefits. Fusion 360 exceeded the target consistently since it is the only platform not able to impose exact mass constraints.

Design Quality and Complexity: The platforms exhibited varying levels of design complexity in the optimized components. Altair Inspire produced the most complex and innovative designs, while Creo Parametric designs resulted in more conservative geometries.

Experimental Validation: The study went beyond simulations by printing and assembling the optimized components into a fully functional robotic arm. This practical validation underscores the applicability of TO tools in real-world scenarios and confirms their potential to enhance the design and manufacturing process in robotics and other engineering fields.

Future research should explore the integration of TO with other advanced manufacturing techniques, focusing primarily on satisfying the constraint set for manufacturing processes, multi-axis milling, or additive manufacturing. This could help overcome current limitations in producing optimized designs that meet optimization criteria and are easy to manufacture.

Another important aspect is the rise of generative design (GD) methods, which are analyzed to a much lesser degree compared with TO, yet offer several comparable benefits. A cross-evaluation of GD platforms, their background theory, current state, and prospective applications are worth researching.

Although the assembled robot is fully functional, a physical stress test of the optimized components is necessary to determine the actual safety margin. This would further enhance the reliability of TO in critical applications where mechanical performance is paramount.

As TO tools and CAD environments continue to evolve, there is a need for continuous evaluation of new features and capabilities. Future studies should focus on assessing the latest developments in TO platforms to ensure that engineers and designers have access to the most efficient and effective tools available.

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Data Availability Statement: Video presentation of the optimized robotic arm: https://drive.google.com/file/d/1U16wDQD-axA2DV-A1HQH8zaEypHbZbQs/view?usp=sharing (accessed on 4 June 2024).

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