Generative Design: An Explorative Study

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Abstract. Generative design tools have recently become an interesting solution to tackle design problems in several technical fields. This article takes into consideration the specific field of mechanical design and aims at describing available generative design solutions capable of dealing with structural optimization problems. The study provides a practical description on the workflow and performances of a specific software system implementing a generative approach for the generation of a set of alternative solutions for a static structural design problem. The software analyzed is Autodesk's Generative Design, hosted in Fusion 360. The article discusses the functioning of the software and its performances; an enhanced focus on the features oriented to the generation of manufacturable shapes is provided in the text. In order to provide a practical and effective procedure, a literature case study was selected to test the software.

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1 INTRODUCTION

Generative approaches are recently becoming more and more applied in a variety of technical fields. By implementing artificial intelligence tools, they can elaborate and propose to a human user a series of plausible solutions for a design problem. That is, a number of alternative configurations that i) satisfy a set of imposed design constraints and ii) try to maximize a goal function passed to the algorithm. The proposed alternatives are the result of an iterative exploration of the related solution space that is guided by an artificial intelligence.

Thanks to the significant increase of computing power available, these tools have recently observed a growing interest in the design community. Generative Design (GD) has taken its first steps in the architectural field [7,8][13] and has generally been first applied in open-problem scenarios characterized by large design spaces. In this context, the term "Generative Design" refers to a series of tools, implementing artificial intelligence methods and algorithms, applied to solve design problems. From a practical point of view, GD tools essentially seek for a solution of a problem expressed with a mathematical formulation; this often results in an iterative optimization process that tries to minimize an objective function. Accordingly, GD has proven itself useful to identify uncommon solutions that do not fall within the typical set of shapes or configurations used (consider, for instance, Figure 1). As a result, GD tools have been first exploited mainly to encourage divergent thinking and creativity. This remains a distinctive aspect of the technology that has brought to its application in areas where aesthetics and innovativeness are important in the product development process, such as product design [3][14] or the automotive sector (e.g. [1][9]).

Figure 1: Philippe Starck's A.I. chair for Kartell [14].

More recently, GD has been applied in the mechanical field to pursue performance-driven design [4][11][16]. In this case, research focused on the development of AI tools to deal with structural optimizations; in this case, the part's plausible topologies are coupled with their FE-simulated structural behaviors to identify the most performing shapes. As in Topology Optimization (TO), which shares many features to GD, parts can be optimized according to compliance or minimum weight while maintaining a safety factor or a deflection. While the application of this kind of GD resources as everyday tools is still a distant target, their use is being encouraged by the development of more reliable and easy-to-use tools. Simultaneously, the functionalities offered by such software systems have been continuously improved, especially considering the ranges of possible design constraints and load conditions offered.

One of the companies who has arguably invested more in the development of GD tools and in their integration within traditional CAD environments is Autodesk. The software company has launched its Dreamcatcher project [12], dedicated to the development of GD tools back in 2014; five years of development have brought to the release of the first version of GD commercial software. Autodesk's tool is called "Generative Design" [15] and is hosted within Fusion 360 [5], a parametric CAD modeler. Autodesk's GD (AGD) is essentially a suite of the CAD application that optimizes the shape of a component to comply with a static structural load condition. Cloud computing functionalities are exploited to run multiple FE analyses and obtain a result in an acceptable time window.

While TO analyses have become a standard tool, GD potentialities have not been fully explored, as AGD is the first tool that can be applied without a heavy tuning and setup phase. These features have brought GD tools within everyone's reach, but the skills required for a conscious application are not yet fully formed and widespread. Moreover, there is not much information on the performance of the technology and the benefit that its application could guarantee, especially in the industrial context. Considering AGD, its implementation details, its framework and the features offered by the software have not been fully discussed yet.

Accordingly, this article aims at a practical and effective description of the design workflow offered by AGD. The study has been carried out applying AGD to a static structural optimization problem and carrying out the entire design phase using the tools offered by the AGD suite. As explained in the remainder of the paper, the case study was selected from the literature in order to be able to compare the results with those obtained by means of traditional tools.

2 CASE STUDY

The case study selected to test the functioning of the AGD is the design challenge proposed at [2]. The component to be designed is a gripper arm that is part of a robot deputed to the handle meteors. The overall shape of the part is assigned and depicted in Figure 2; the areas to be maintained intact are marked in red in the figure. The overall goal consists of the reduction of weight of the component within the limits imposed by the design requirements summarized in Table 1. The load case is characterized by a static load of 20000 N applied orthogonal to the gripping surface (see Figure 2), while the part is constrained on two cylindrical surfaces that interact with the rest of the robot. A maximum deflection of 8mm is allowed while guaranteeing a safety factor of 3.

Parameter	*Value*
Force applied to gripping surface	20000 N
Max deflections	8 mm
Safety factor	>3
Material	ASTM A36

Table 1: Design requirements of the challenge.

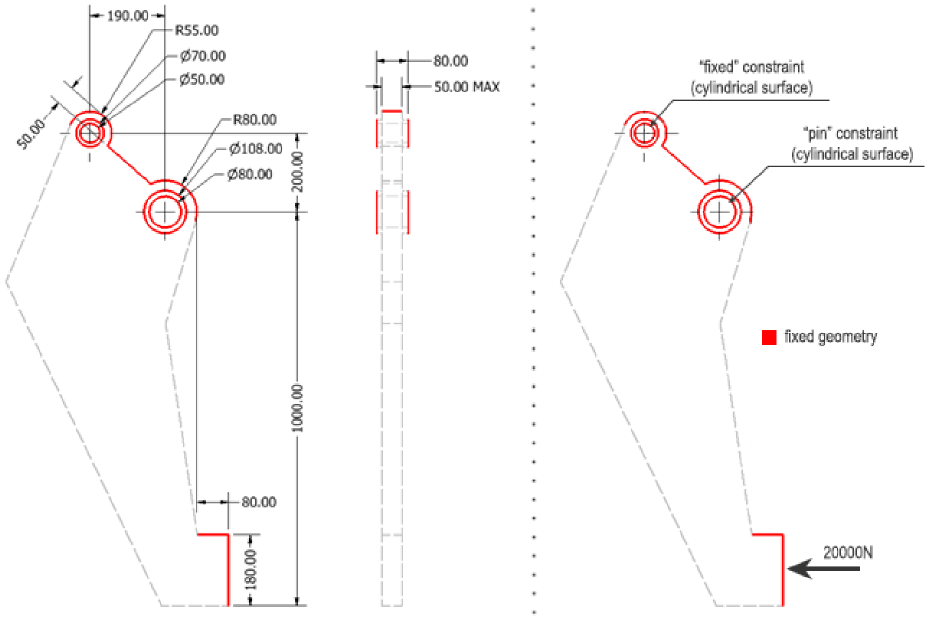

Figure 2: Design constraints of the part to be optimized.

3 AGD FRAMEWORK

The framework proposed by AGD heavily relies on cloud-computing: while most phases are carried out by the user on its personal workstation, all the optimization and the analyses are performed in external servers. The phases composing the AGD's framework are similar to those that can be found within a TO analysis. The main difference is the generation, at a first level, of a series of shapes that need to be "explored" to identify the most effective solution. The overall framework can be schematized in the following phases, depicted in Figure 3:

- Objectives – two options ("Minimize mass" and "Maximize stiffness") can be selected as goal for the analysis. In both cases, a SF is required. If the second option is selected, the user should provide also a target mass that the optimization should achieve.
- Geometry – the user defines the areas that should be left intact by the optimization (Preserve regions) and the volumes that must remain empty (Obstacle regions). One of the great differences w.r.t. the classic TO approach is that AGD does not require the definition of a starting volume (Design space) to be progressively hollowed. The optimization can be initiated with a plausible Starting Shape (SS) that can guide the optimization, but this choice is optional.
- Load cases – AGD supports forces, pressures and bearing loads. Gravity can be included in the analysis as well. Available constraints are identified as fixed, pinned and frictionless. Multiple load cases can be considered by the solver; dynamic conditions, on the other hand, cannot be introduced. All the loads and constraints need to be applied to preserve regions.
- Manufacturing constraints – they can be provided by the user to guide the analysis towards shapes that can be manufactured using a specific process (additive manufacturing, 5-axis milling, 3-axis milling), hence reducing the production costs for the part fabrication. This advanced feature is being introduced also in some TO software.
- Material –only linear-elastic models can be used up to this moment. AGD allows the concurrent selection of up to ten materials in a single analysis.
- Input Check & computation – AGD checks if the required information is provided. In case of a positive answer, Cloud-computing is performed after the payment of a fixed fee (cloud credits).
- Results – once that the results are downloaded on the local machine, these are available to the user; depending on the setting of the optimization, the results may be in the order of dozens.
- Exploration – AGD has a dedicated environment that offers visualization tools to map the results in an ordered manner to help the user to identify the best possible solution. Results can be plotted according to their mechanical and physical properties.
- Selection – the user identifies the design that best fits the desired behavior and exports it from the visualization environment.
- Export – the design is isolated and made available for further modifications to the user; the CAD geometry of the part is imported within the modelling environment of Fusion 360. This phase is associated with a cost, as the software requires an extra payment for every design exported from the visualization environment.
- Modification – once that the design is exported, it should be edited with traditional CAD tools to amend defects that are typically present in complex shapes, characterized by multiple B-REP surfaces. This is required also in TO applications, where the tessellated shape produced by the optimization need to be edited and beautified to allow fabrication.
- Validation – The performances of the exported shape need to be validated by performing an additional set of FE analyses. Independently from the modifications introduced in the previous phases, some discrepancies can be found by comparing FE results obtained in the exploration phase and the final design. Accordingly, a validation is usually recommended to assess the final mechanical properties of the part.

The user is facilitated in the execution of all the steps by a simplified GUI that proposes the steps in a chronological order. Moreover, a series of automatic intermediate controls indicate to the user the possible lack of data essential to perform a subsequent task.

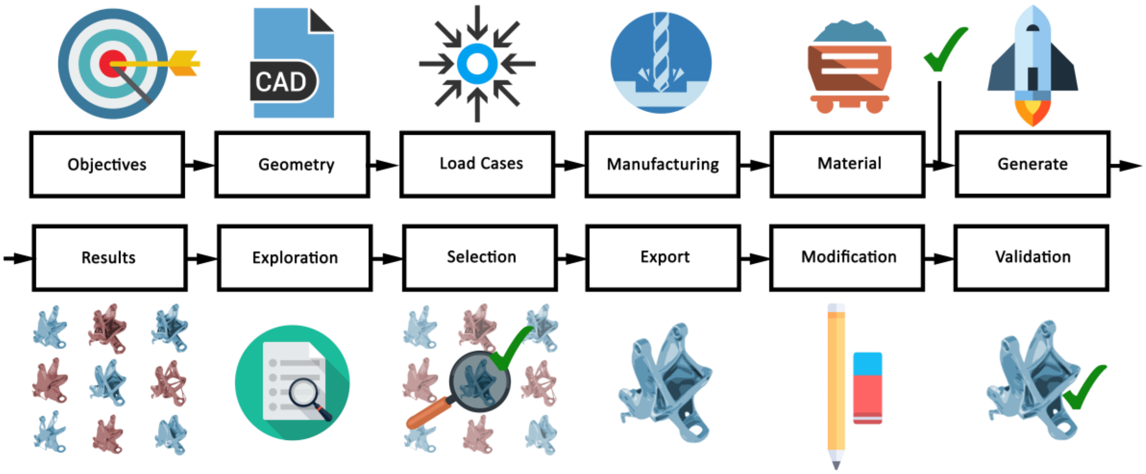

Figure 3: Autodesk Generative Design Framework.

4 RESULTS

The AGD framework has been applied to the selected test case in order to test the functionalities of the software. It's important to note that the scope of this paper is to evaluate the features offered by the AGD tool rather than carry out a mere design activity of a component. As a consequence, while the part optimization will be carried out following the indication provided at [2], a more general perspective will be maintained to try to understand how the tool can be used beyond the individual case study.

In order to consider as many aspects as possible, four different materials and production technologies were introduced in the analysis, regardless of the requirements imposed by the case study. The materials were selected from Fusion 360 library, starting from materials similar to the A36 steel required by the challenge and including also high-performance ones (e.g. Ti6Al4V, AISI304). Four possible alternatives were selected as possible production technologies: 5-axes milling, 3-axes milling, additive manufacturing and unrestricted. Each technology introduces some design constraint to allow manufacturing of the produced part. Milling, for example, requires the definition of a tool geometry to compute volumes to leave empty to allow tool access. Additive manufacturing considers the generation of overhang surfaces. The unrestricted modality, on the other hand, corresponds to an unconstrained optimization. Two separate analyses have been carried out: a first one, without any starting shape used to guide the optimization, and a second one that uses the shape visible in Figure2 as starting configuration.

Each analysis brought to the generation of 28 shapes that the user can consider as plausible solutions. Tables 2 and 3 show that candidate solutions can be divided into categories. AGD differentiates between *converged* and *completed* solutions. The outcomes marked as "*completed*" (5 in the considered application) have either not met the design criteria set during the setup, or the optimization failed to produce a fully converged result. Accordingly, while these results are made available anyway to the user, they should be carefully taken into consideration because they might not be suitable for the application.

Manufacturing constraint	*# Solutions Converged*	*#Solutions Completed*
Unrestricted	4	0
5-axes milling	3	1
3-axes milling	7	1
Additive	9	3
Total	23	5

Table 2: Number of solutions produced by the AGD depending on the manufacturing constraint.

Material	*# Solutions Converged*	*#Solutions Completed*
ASTM A36	6	1
ASTM A572	6	1
Titanium 6Al4V	5	2
AISI 304	6	1
Total	23	5

Table 3: Number of solutions produced by the AGD depending on the material.

The solutions can be explored by means of graphs automatically generated by the software, which allow an efficient mapping of the solutions: the user can select which parameters use on the axes and how to group the solution to identify general trends. Figure 4 shows an example where the solutions generated in the analysis are mapped in terms of mass vs. max displacement. These graphs are functional, as they allow to dynamically compare solutions that differ significantly under multiple aspects (e.g. material, manufacturing technology, macroscopic shape, etc.) this is a crucial step considering the high number of solutions generated by the AGD.

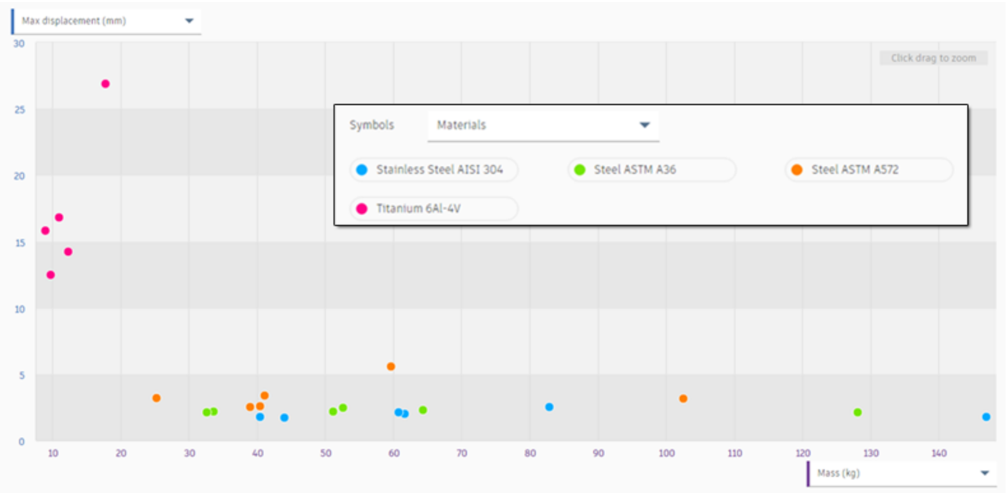

Figure 4: Results dispersion graph produced by the AGD exploration environment, mass vs max displacement, solutions grouped according to the material.

Figure 5 shows a subset of shapes produced in the two AGD studies (with or without starting shape). The introduction of manufacturing constraints evidently influences the type of results produced. Solutions obtained under the same hypothesis (grouped by color or by row in Figure 5) evidently share similarities in the geometry produced by the algorithm, with main features that are maintained constant within each group of solutions. Even considering all the solutions produced with a starting shape (row 2 and row 4 of Figure 5) is possible to identify significant similarities. Specifically, the envelope of all the shapes roughly resembles the starting shape.

However, some limits in the compliance of the imposed manufacturing constraints can be identified. While the global features required by the selected process are verified in the produced results, the software occasionally fails on a local level in the generation of details that are not manufacturable or introducing errors that affect the surface quality. A valid example, with this respect, is represented by the generation of corrugated overhang surfaces in AM parts, as showed in Figure6. As a consequence, a subsequent editing phase is required in order to refine and polish the shapes identified by the AGD analysis.

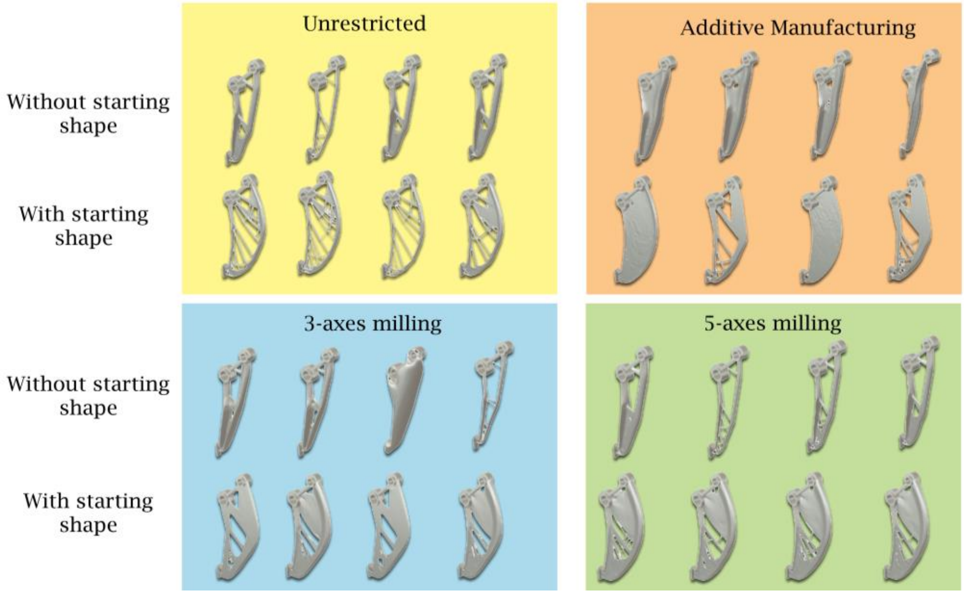

Figure 5: A selection of shapes produced by the two analyses.

Figure 6: Local defects introduced in AM parts.

Table 4 reports a selection of results produced by the AGD. The structural behavior of the generated shape is valid for the selected application, as they satisfy the constraints of Table 1. The mechanical performances of the best solutions produced by the AGD are comparable with the best solutions obtained by means of TO or traditional design methods (e.g. possible solutions proposed in the challenge) (Table 5).

The element of novelty that is introduced by the AGD is the possibility of choosing among a series of solutions, equally valid from a structural point of view. Accordingly, the user can draw from their own experience in order to identify the solution that fits all the design criteria, even the ones not expressed in the AGD study. Depending on the application, different considerations might be relevant and could improve the value of the product: ergonomics, aesthetics, manufacturability and industrial know-how.

	No SS #7	*No SS #8*	*With SS #4*	*With SS #8*
				
Material	A36	A572	A36	A572
Manufacturing	M5ax	U	AM	U
Mass [kg]	33.6	25.2	24.3	19.4
Max Displacement [mm]	2.19	3.2	1.78	2.37

Table 4: Mechanical performance of a subset of AGD-generated results.

	TO#1	*TO#2*	*Challenge#1*	*Challenge#2*
				
Material	A36	A36	A36	A36
Manufacturing	-	-	-	-
Mass [kg]	44.6	63.3	38.4	33.1
Max Displacement [mm]	1.08	0.67	1.09	1.67

Table 5: Mechanical performance of a subset of AGD-generated results, compared with results obtained by means of traditional techniques (TO and shapes generated by a human user through a trial-and-error process). Challenge #1 and #2 are results proposed in the context of the design challenge.

In order to test the tools to export a result from the visualization environment, the solution marked as "no SS#7" of Table 4 (visible in Figure7) ohas been selected as best candidate and therefore exported. During this phase, a T-spline model is generated from the mesh obtained in the analysis. This introduces some local defects in the model that need to be manually amended. Finite Element analyses (see Figure 7) were carried out on the final shape of the part to confirm previously-obtained results. The same analysis has been performed also on an external FE software system to confirm the results (see Figure 8).

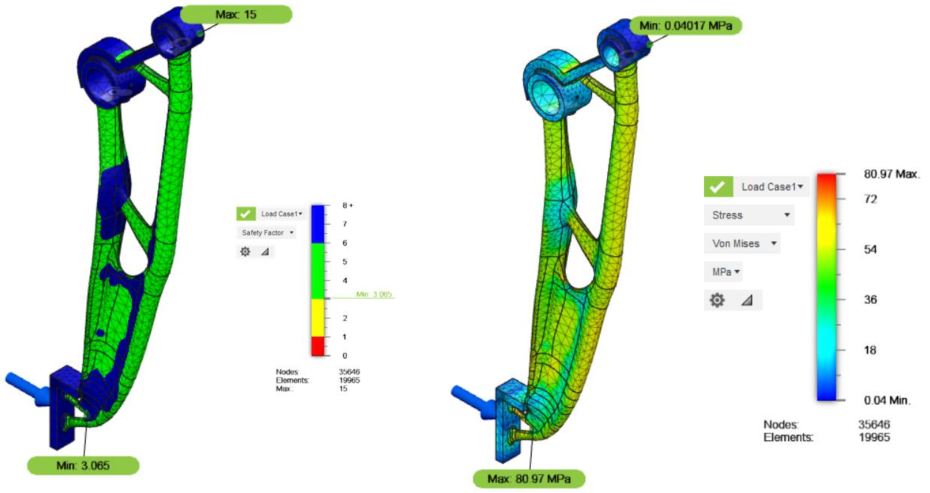

Figure 7: FE analyses performed within Fusion 360 on the final part: a) safety factor b) Von-Mises Stress values.

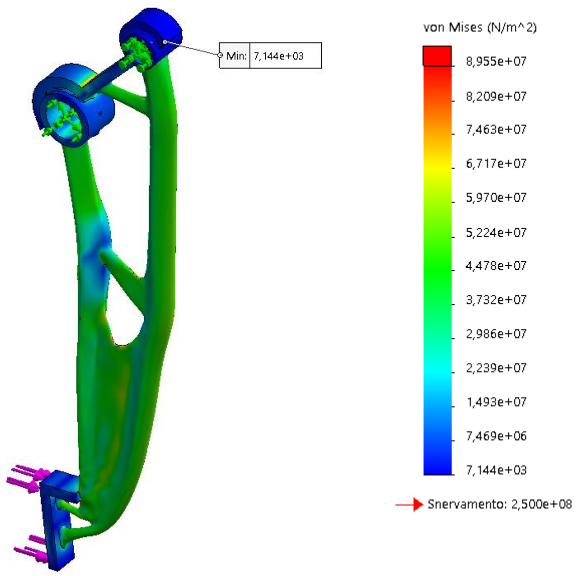

Figure 8: FE analyses performed within Solidworks Simulation on the final part: Von-Mises Stress values.

Finally, this study investigated the manufacturability of the produced shape. As previously discussed, AGD allows the introduction of manufacturing constraints that are taken into consideration in the analyses. However, while their general effect is visible comparing the class of shapes produced in each category of Figure 4, no additional data on the effects introduced by activating such constraints is provided by the software. Accordingly, the manufacturability of the exported shape has been verified using the CAM software included in Fusion 360 (see Figure 9) to compute possible machining paths (the component was optimized hypothesizing a milling operation). After that the manufacturability of the part was verified, the fabrication time obtained in the simulation[1] has been compared with the one required to manufacture a topologically optimized part (TO#2 in Table 5). This was done to identify if the introduction of manufacturing constraints allows the identification of shapes that are optimized even considering the manufacturability.

A total fabrication time of 2:24:58, corresponding to a total machining path length of 175.199 m, was computed for the AGD part, while a time of 2:41:34 and a 204.96m path were obtained for the TO part. It's important to highlight that this represents only a partial confirmation of the advantages achievable with AGD manufacturing constraints as a much larger pool of possible solutions should be considered to integrate the present study on this aspect. Moreover, different test case should be considered. In fact, the one that was selected in this study is essentially prone to generate planar shapes with a variable presence of reticular structures. More complex load conditions or different solution spaces might be able to better highlight the differences between AGD results and the ones obtained with traditional methods, especially considering the manufacturability of the parts.

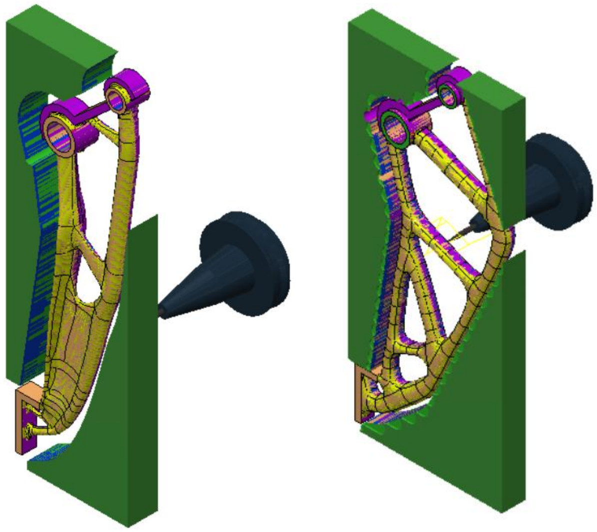

Figure 9: CAM simulations carried out on the a) AGD part and b) TO part to evaluate their fabricability.

5 CONCLUSIONS

In spite of the continuous development of structural optimization software tools, designers' experience will always remain an essential element of the design process. Indeed, the ability to analyze design problems and to identify driving factors that play a major role towards the

1 This was computed on a scaled-down part in order to ease the computation of machining paths and work with a part with global dimensions suitable for a milling operation.

achievement of a high-quality result remains a human strength that cannot be easily mimicked by AI tools. AGD proposes a promising approach to the design problem, exploiting advanced computation tools where their application is most favorable, i.e. to tackle problems that can be easily expressed mathematically, and leaving to the user the task of identifying the best solution among a set of equally valid candidates.

The results of this study indicate that the performances offered by AGD allow the application of the considered tool in real case scenarios. The optimization performances seem to be comparable with the traditional tools which are nowadays commonly applied in design (e.g. TO [6][10]). As showed by the comparison of results in Table 1, the application of AGD has not imposed severe limitations in the identification of the global optimum. Moreover, a direct comparison of the shapes produced by the tool highlights the effects caused by the introduction of manufacturing constraints in the analysis: this innovative feature could raise the interest towards AGD, as this is one of the most important factors considered at the moment in AM applications [10]. Although it's possible to identify some similarities between the behaviour of traditional TO methods and the application of AGD if a SS is provided to start the optimization, the two approaches remain fundamentally separate. TO always proceed by removing material from the design volume, while AGD maintains the possibility of adding material and, generally, to deviate from the initial SS provided. Accordingly, the indication of a SS serves as guideline for the optimization, rather that as a proper design space.

However, strong limitations are perceived considering, for instance, the available tools for modelling of structural conditions. Currently available loads and constraints limit the application of the AGD to a subset of the typical mechanical situations (i.e. static pure-structural optimizations). With this respect, the advisable introduction of dynamic and thermic loads would be the first step to promote a wider application of the tool. It's also important to highlight that, while Fusion 360 is advertised as a low-cost solution (and completely free for non-professional use), the AGD tools requires the payment of a fixed fee to launch each analysis or to export a single result in order to obtain a CAD model for downstream applications.

Sadly, a more in-depth technical discussion on the functioning of the AGD tool is not achievable, at the moment, due to the limitness of available information provided by the developers. This will be a key area to focus on during future work: indeed, a higher comprension of the mechanisms responsible for the design choices in engineering task is advisable in order to provide the user with all the desiredable tools to make informed choice. The present paper is only a first step towards this goal. Considering its overall performances, AGD could be considered as a solid starting point for a design activity whenever: i) the skillset of the designer is not sufficient to identify right from the start a valid shape for a critical component; ii) performance design needs to be integrated with other constraints.

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