Title:
“Generative Design”: An Explorative Study

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Introduction:
Thanks to the significant increase of available computing power, generative tools, implementing artificial intelligence capabilities, have recently observed a growing interest in the design community. Generative Design (GD) has been applied to encourage creative solutions (e.g. [1,4,7]) or to pursue performance-driven design, typically by coupling plausible solutions with their FE-simulated structural behaviors in order to identify most performing shapes. In this last scenario, the most famous tool available to designers is Topology Optimization (TO), which allows to optimize parts according to compliance or minimum weight while maintaining a safety factor or a maximum deflection.

One of the companies who has arguably invested more in the development of GD tools is Autodesk. The software company has launched its Dreamcatcher project [5], 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” [9] and is hosted within Fusion 360 [3], a parametric CAD modeler. Autodesk’s GD (AGD) is a CAD suite that optimizes the shape of a component to comply with a static structural load condition. AGD is the first tool available to designers that tries to expand the capabilities beyond what is typically offered by TO. From a methodological perspective, most notable differences can be identified in 1) the core algorithm that controls the optimization step and in 2) the design framework proposed to the user. Indeed, AGD implements the level-set method [8] for the optimization, while most TO systems commonly rely on the SIMP algorithm [6]; moreover, AGD produces a series of alternative solutions that are proposed to the user who can decide, exploiting their personal know-how, which is the most convenient one.

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.

Accordingly, this article aims at a practical and effective description of the design workflow offered by AGD. The goal is to provide a hands-on guide that could help users interested in the application of this innovative technology. 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. 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. A design challenge proposed at [2] and discussed in the following section has been selected as case study.

Case Study:
The case study selected to test the functioning of the AGD is the one 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 Fig. 1; the areas to be maintained intact are marked in red in the figure. The goal is the reduction of weight of the component (fabricated using ASTM A36 steel) while maintaining a Safety Factor (SF) higher than 3 and a maximum deflection of 8mm. The load case is characterized by a static load of 20000 N applied orthogonal to the gripping surface (see Fig.1), while the part is constrained on two cylindrical surfaces that interact with the rest of the robot.

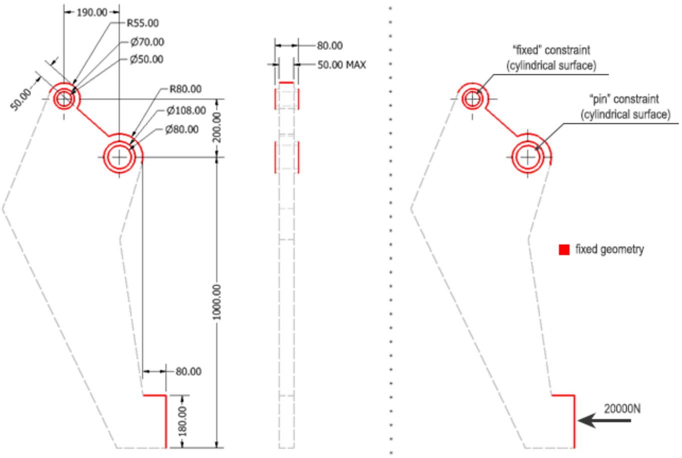

Fig. 1: Design constraints of the part to be optimized.

AGD Framework:
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:

- *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 it's optional.
- *Load cases* –AGD supports forces, pressures, gravity and bearing loads. Available constraints are identified as *fixed, pinned* and *frictionless.* Multiple load cases can be considered by the solver; dynamic conditions cannot be introduced.
- *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.
- *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. 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 identify the best possible solution. Results can be plot according to their mechanical and physical properties.
- *Selection* – the user identifies the design that best fits the desired behavior and exports it.
- *Export* – the selected design is exported. 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 in order to allow fabrication. As an example, the introduction of fillets or the modeling of new freeform surfaces that fit the ones generated by the software, can be beneficial for the production of a valid model. ergo
- *Validation* – The performances of the exported shape need to be validated by performing an additional set of FE analyses.

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.

<u>Results:</u>
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.

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 and including also high-performance ones (e.g. Ti6Al4V, AISI304). 4 possible alternatives were selected as 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. The unrestricted modality corresponds to an unconstrained optimization. Two separate analyses have been carried out: a first one, without any SS used to guide the optimization, and a second one that uses the shape visible in Fig.1 as starting configuration.

Each analysis brought to the generation of 28 shapes that the user can consider as plausible solutions. 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.

The solutions can be explored by means of graphs automatically generated by the software, that 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. Fig. 2 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 compare solutions that differ significantly under multiple aspects (e.g. material, manufacturing technology, macroscopic shape, etc.) dynamically; this is fundamental considering the high number of solutions generated by the AGD.

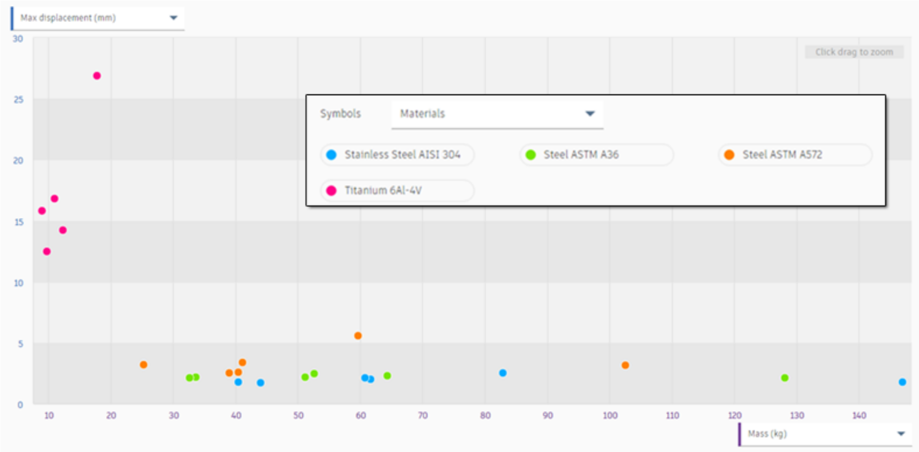

Fig. 2: Results dispersion graph produced by the AGD exploration environment, mass vs max displacement, solutions grouped according to the material.

Tab. 1 shows a subset of the shapes produced in the two AGD studies: the introduction of manufacturing constraints evidently influences the type of results produced. Solutions obtained under the same hypothesis evidently share similarities in the geometry and main elements. The introduction of a starting shape clearly influences the results, which share similarities as the tendency to occupy all the available volume (the envelope of all the shapes roughly resembles the starting shape.

Some limits in the compliance of the manufacturing constraints imposed 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 quality of the surface. A valid example, with this respect, is represented by the generation of corrugated overhang surfaces in AM parts (Fig. 3). A subsequent editing phase is required in order to refine and polish the shapes identified by the AGD analysis.

	No SS #7	*No SS #8*	*With SS #4*	*With SS #8*	*TO#1*	*TO#2*	*Challenge#1*	*Challenge#2*
								
Material	A36	A572	A36	A572	A36	A36	A36	A36
Manufacturing	M5ax	U	AM	U	-	-	-	-
Mass [kg]	33.6	25.2	24.3	19.4	44.6	63.3	38.4	33.1
Max Displacement [mm]	2.19	3.2	1.78	2.37	1.08	0.67	1.09	1.67

Tab. 1: 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).

The structural behavior of the generated shapes is valid for the selected application, as they satisfy the constraints of Tab. 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. 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, industrial know-how. In the case study considered, the results in terms of manufacturability, obtained by means of CAM analyses simulating milling and AM processes, confirmed the beneficial effects caused by the introduction of manufacturing constraints.

Fig. 3: Corrugated overhang surfaces introduced with the manufacturing constraints.

Conclusions:

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

AGD can unlock important advantages in real case scenarios, though with severe limitations (e.g. available loads and constraints cover only a subset of structural situations). The optimization performances seem to be comparable with the traditional tools which are commonly applied in design (e.g. TO). As showed by the comparison of results in Tab. 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.

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