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BRIEF OVERVIEW OF GENERATIVE DESIGN SUPPORT SOFTWARE

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Abstract: The new generative design process that has emerged in recent years has become available in more and more software. With the classic rapid prototyping procedures, it was not possible to test the designed products during long-term operation. However, the advent of metal powder printing and additive technology already allows for the long-term testing of designed prototypes, and even, if the deviation from the required properties of the product is negligible, the production of the final products. As a result, with the generative design process, design engineers also can create products that seemed unthinkable so far.

Keywords: *shape optimization, topology optimization, generative design*

1. INTRODUCTION

The shape of a product is primarily determined by the functions to be implemented by that, which may be slightly influenced by the manufacturing process properties of the product (e.g. machined or cast parts). During the development of a given product, it is advisable to perform various engineering tests and then improve the product by its analysis. This can happen by the reduction of the weight of the product, the of the load capacity of the product, or the change of the final geometry. This iterative design-development process can also be considered as the search for an optimal solution; however, this process is time consuming and requires a more experience. If the traditional manufacturing technology operations are considered (e.g. prismatic milling) when developing a product, solutions may have which are limited by manufacturing technology. Most *CAD/CAM* modules in computer-aided design systems, or most custom *CAD* and *CAM* software, support modelling procedures or manufacturing processes that conform to the traditional design approach. The built-in algorithms that provide shape optimization in the software have been designed to meet the limitations of the traditional design approach. However, using additive manufacturing technology, products that were previously thought to be unmanufacturable can also be produced (e.g., inaccessible surfaces, "native" elements). It should be noted that additive manufacturing is a collective term, including the long-known rapid prototyping processes, which mostly work with polymeric raw materials, however, due to the development of technology, the processes working from metallic raw materials e.g. by developing and disseminating the properties of

***S**elective **L**aser **M**elting (SLM)*, ***L**aser **M**etal **D**eposition (LMD)* and the base metal powders, the product thus produced is not a prototype but an end product [1]. If additive manufacturing technology is considered during the design process, producing the geometry of the part to be optimized with traditional modelling methods is an extremely time-consuming operation. Generative design software and modules were created in order to solve these kinds of issues.

2. SHAPE OPTIMIZATION AND TOPOLOGY OPTIMIZATION

Optimization during mechanical design means the best solution selected under the given operating conditions, which is selected from the set of solutions produced. Mathematically, optimization means the determination of the maximum or minimum of an objective function. In general, the optimization searches for the best value of an objective function in each acceptable range, where both the acceptable range and the objective function can be of different types. Often the objective function defined at the design phase is multi-objective and multivariate, so optimization can be defined as the calculation of several target values.

During shape optimization, the shape of the margin surface of the generated body model is changed so that the best possible value of the objective function is obtained by observing the optimization conditions. The *CAD* model data also includes design variables, design parameters, material properties, and boundary conditions for finite element tests. During shape optimization, the design variables are selected from the parameters describing the geometry, this parametric data set (e.g. dimensions, shape features, part history) is automatically generated in the applied parametric integrated design systems. Since a model of a part can be produced in several ways (e.g. choice of shape features, sequence of operations, dimensions of sketches), it is important to note that this can affect the optimization task, so the geometry must be carefully prepared already during modelling.

In case of topology optimization, the goal is to determine the optimal design of the part within a given volume under predefined boundary conditions and loads. During topology optimization, the elements of the initial volume are deleted from the design space, considering the design variables and the objective function. A detailed elaborate initial geometry is available for shape optimization, while it is not necessary for topological optimization. There may be names for some software that refer to shape optimization, but the result produced is the result of a topology optimization. The difference between shape and topological optimization is made clear by the applied procedure. Topological optimization procedures require computationally intensive numerical and finite element algorithms, and their proliferation has become possible in recent decades. In practice, several methods have been developed, which can be divided into two major groups:

(1) gradient type methods:

- material distribution method: *SIMP (**S**olid **I**sotropic **M**icrostructure/**M**aterial with **P**enalties)* [2],
- homogenizing methods *OMP (**O**ptimal **M**icrostructure with **P**enalization)* [3],

– discrete, global methods [4],
– topological derivative and level set method *(LSM – **L**evel **S**et **M**ethod)* [5],
– method using ***S**udden **D**eath **M**ethod*, e.g. *ESO (**E**volutionary **S**tructural **O**ptimization)* [6];

(2) non-gradient-type, heuristic methods [7].

One of the most efficient and computationally simple methods is the *SIMP* method, most software developers use this method in their systems for topological optimization.

3. THE MECHANICAL GENERATIVE DESIGN PROCESS

Generative design can be applied not only in mechanical but also in other fields, like in architectural, furniture, artistic works. The design process can be generalized; however, the approach focuses on mechanical design processes. Due to the spread of additive and hybrid manufacturing technology, there has been an increasing emphasis in recent years on the emergence of generative design methods in mechanical design systems. Generative design is a new type of design process, the main features of which are artificial intelligence-based software and machine learning, which allows the shape and composition of a part to be determined by physics-based simulation and other analysis methods, taking into account expected requirements and optimizing objectives (e.g. minimum cost and/or weight). This new design process differs from traditional methods in that the generative algorithm evaluates and changes the product model for the next analysis iteration without user intervention and results in far more solution variants for a given function. The traditional design process requires additional – user-driven – iterations until we get to the manufacturing process, which increases the product implementation time.

In the generative design process, the software uses nature-based evolutionary approaches using machine learning. The user only needs to define the design variables (e.g. materials, design space, weight, manufacturing technology, production cost). Knowing this, the software produces all possible combinations by knowing the variables and parameters. Compared to traditional design processes, the number of versions produced can be orders of magnitude larger. Since each of the generated solution variants meets the prescribed manufacturability conditions, the individual that represents the final solution can be selected from the set.

Another feature of generative design is that it can be applied at an early stage of the design process without an existing conceptual design being available. As a result, the generative algorithm creates completely new solutions by considering the manufacturability aspects, thus significantly reducing the time of the part testing process. In the traditional design process, shape or topology optimization targets an already manufactured version, which removes material that is unnecessarily operational, in a way that ignores manufacturability and manufacturing costs. As a result, further modelling, conventional simulation, and testing may be required. In generative design, simulation is integrated into the design process. In the generative design process, the characteristics of the manufacturing technology can be specified as a design variable (e.g. additive manufacturing, 2.5–5D milling, and casting), so the software only produces solutions that meet the specified variables. Considering additive and hybrid elaboration, generative design can be used to combine multi-component products (function combination) into a product that was not previously possible due to traditional manufacturing technology, which can lead to further cost savings for later use, e.g. for the supply chain or for maintenance and installation.

4. Examples of software supporting generative design

Software supported generative design appeared in the first half of the 2010s. During these years, *AutoDesk* has developed optimized structures for *Airbus*, where *Jesse Coors-Blankenship* was the chief engineer in the development department. Using the experience gained here, he founded a company called *Frustum*, where he developed a kernel to support generative design called *TrueSOLID*™, a product that is available in several design software. The other big developer is *AutoDesk*, where a product to support generative design was created from a project called *Dreamcatcher* running in its research department, which is also available. Recognizing the need for generative design, products from newer software developers have become available. These are characterized by extensive optimization capabilities (e.g., size, weight, strength, material quality, cost, schedule, manufacturability) as well as cloud-based service. Computational performance in iterative processes of the generative design process is much more costly than traditional tasks, so cloud-based computing provides cost-effective access to many generated variants. *Table 1* summarizes and briefly presents the best-known products that support generative design.

Table 1
Generative design software [8]

Developer	***Product***	***Properties***
Frustum	*Generate*	A cloud-based application that combines a voxel-based design algorithm with finite element analysis. It was a stand-alone product until November 2018, after which it was acquired by *PTC*.
nTopology	*Element*	A generative, function-based application that provides instant feedback during design as it optimizes the shape of the object as well as the manufacturing process.
ParaMatters	*CogniCAD*	A cloud-based design platform that focuses primarily on additive manufacturing processes.

Procedures supporting topological optimization and generative design are also available in simulation software supporting engineering development (e.g. *FEM*, *CFD*) *(Table 2)*.

Table 2

CAE software supporting generative design [8]

Developer	*Product*	*Properties*
Altair	*OptiStruct*	It allows to run in parallel to perform large-scale optimization tasks quickly.
ANSYS	*ANSYS Mechanical*	*ANSYS* topology optimization algorithm can be started from the desktop, so it can be integrated into the simulation workflow.
Dassault Systèmes	*Tosca Structure, Tosca Fluid*	The *Tosca* structure optimization package integrates with the *CAE* environment in cooperation with the *ABAQUS*, *ANSYS* and *MSC Nastran* finite element solvers.
ESI Group	*PAM–STAMP, ProCAST, SYSTUS*	Offers built-in generative design techniques as well as special shape optimization in the *SYSTUS* simulation package
MSC Software	*MSC Nastran Optimization*	It offers a variety of processes, from shape and topology optimization to process management solutions.

Modules supporting generative design are also available in parametric design systems *(Table 3)*. These are basically the products of the developers described above, which are available in an integrated way in the systems.

Table 3

Integrated system including generative design module [8]

Developer	*Products*	*Properties*
Autodesk	*Fusion 360, Inventor*	Provides access to optimization settings and calculations, as well as cloud computing resources for premium subscriptions.
Dassault Systèmes	*TOSCA suite*	Provides access to the *TOSCA* optimization package for *CATIA* and *SOLIDWORKS CAD* software.
Robert McNeel & Associates	*Rhino*	Grasshopper relies on a visual programming language and environment to automate design. Users logically connect parts by pulling operations as planned.
PTC	*Creo Simulate*	*Vanderplaats* uses *R&D GENESIS* for optimization. It converts the results to free-form *(B-rep)* objects, thus avoiding polygon models used elsewhere. From *Creo 7.0*, it uses *Frustum* technology.
Siemens	*NX, Solid Edge*	Integrates the *Frustum Generate* kernel for generative design. Users can modify the generated results with convergent modelling.
Altair	*solidThinking Inspire*	Topological optimization is integrated into the *CAD* modelling process.

The advantage of modules available in integrated systems is that models generated by generative design can be used directly in the given system, so there is no need to exchange product data between different software, which can cause conversion errors.

5. CASE STUDY OF GENERATIVE DESIGN

On the 12th of June in 2013, *General Electric* published a call for tenders on the *grabcad* community interface, which required the optimization of an aircraft engine mount, assuming additive manufacturing technology [9]. Considering the requirements in the tender and using the generative design method based on the available model, we produce a couple of possible solutions with *AutoDesk Fusion 360* and *Solid Edge 2020* software, the results of which are described in this chapter.

The material of the component to be tested is *Ti–6Al–4V*, the assumed yield strength $Re = 131\ ksi$, the operating temperature $T_o = 75\ F$, the minimum wall thickness $t = 0.05\ in$ (the values given in the tender were used when specifying the units). The component analysis is examined for four load cases:

(1) a load of *8000 lbs* on the pin surface in the opposite direction to the *y* axis,
(2) a load of *8500 lbs* on the pin surface in a direction parallel to the *z* axis,
(3) a load of *9500 lbs* in the *yz* plane, enclosing an angle of *42°* in case of the load F_1,
(4) a torque of *5000 lb-in* through a midpoint of the axis of symmetry of the pin surface and arousing about an axis parallel to the z axis *(Figure 1)*.

In case of topological optimization, the objective function (minimum weight) was performed with a given safety factor (n_s = 2), the original weight of the part was $m = 2.038\ kg$.

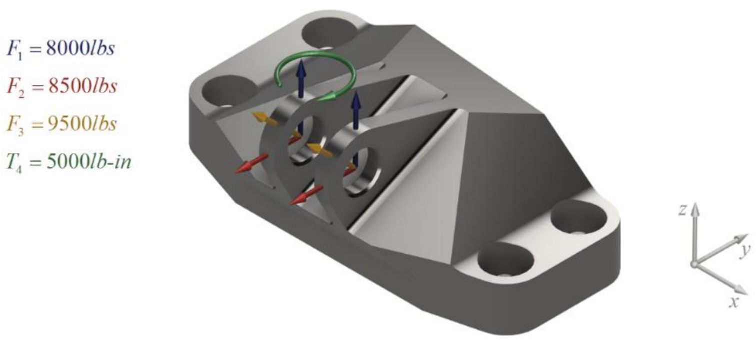
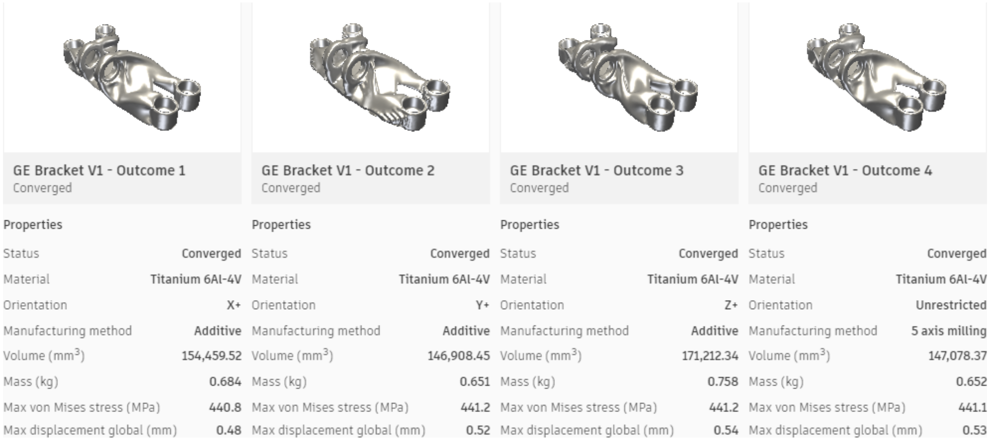


Figure 1
Load cases to be tested for the clamping element.

In addition to additive manufacturing technology, *Autodesk Fusion 360* software also supports the ability to set criteria for manufacturing products made with milling *(2.5D–5D)* machining, 2-axis machining, and casting technology. This means additional solutions in the number of versions generated. In the case study, *5D* milling and additive manufacturing were considered for machining technologies, and the tabular results generated in the software are illustrated in *Figure 2*.



Properties	GE Bracket V1 - Outcome 1 (Converged)	GE Bracket V1 - Outcome 2 (Converged)	GE Bracket V1 - Outcome 3 (Converged)	GE Bracket V1 - Outcome 4 (Converged)
Status	Converged	Converged	Converged	Converged
Material	Titanium 6Al-4V	Titanium 6Al-4V	Titanium 6Al-4V	Titanium 6Al-4V
Orientation	X+	Y+	Z+	Unrestricted
Manufacturing method	Additive	Additive	Additive	5 axis milling
Volume (mm^3)	154,459.52	146,908.45	171,212.34	147,078.37
Mass (kg)	0.684	0.651	0.758	0.652
Max von Mises stress (MPa)	440.8	441.2	441.2	441.1
Max displacement global (mm)	0.48	0.52	0.54	0.53

Figure 2
Results of generative design using AutoDesk Fusion 360 software

The generated solution variants can be compared to each other, users can analyse the selected results, which basically allows the load distribution on the part *(Figure 3)*.

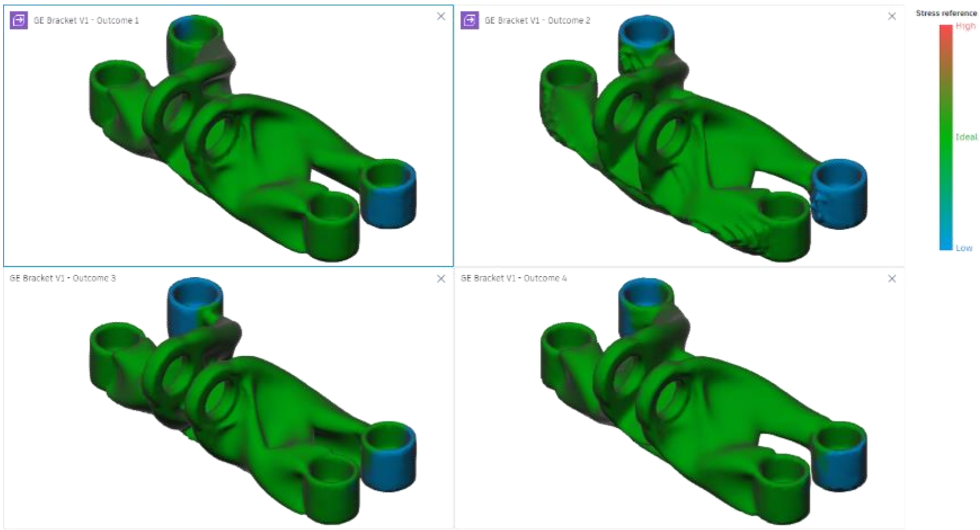
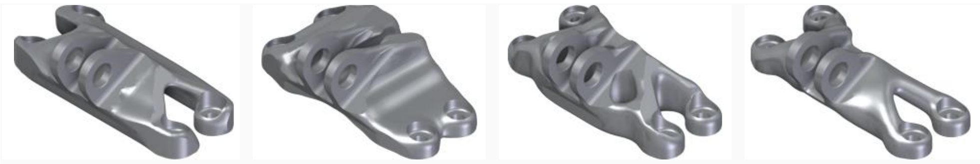


Figure 3
Results of load distribution of generated versions
in AutoDesk Fusion 360 software

The load distributions observed in the figure above are in the ideal range, the magnitude of arising stresses in some of the fixing holes is low, in practice the display of the load distribution in this case provides only useful information, numerical values can be determined by finite element analysis. The Premium version of *Solid Edge 2020* provides the ability to perform generative design processes, however, services are more limited, and operations require more user intervention, which results in more time. For manufacturing processes, additive as well as conventional (e.g. casting, turning) machining can be selected; however, it is not possible to specify more than one machining mode in one test.



Extraction	**x**	Extraction	**y**	Extraction	**z**	Extraction	**No**
Manufacturing	**Additive**	Manufacturing	**Additive**	Manufacturing	**Additive**	Manufacturing	**Additive**
Volume (mm³)	**241,533**	Volume (mm³)	**304,937**	Volume (mm³)	**198,612**	Volume (mm³)	**126,785**
Weight (kg)	**1,088**	Weight (kg)	**1,374**	Weight (kg)	**0,894**	Weight (kg)	**0,571**

Figure 4
Results of generative design using Solid Edge 2020 Premium software

If test of multiple manufacturing methods is required, the user must create additional generative tests *(Figure 4)*. If the generated versions are available, it will also be possible to compare them. The results of the load distribution in case of the different variants are illustrated in *Figure 5*.

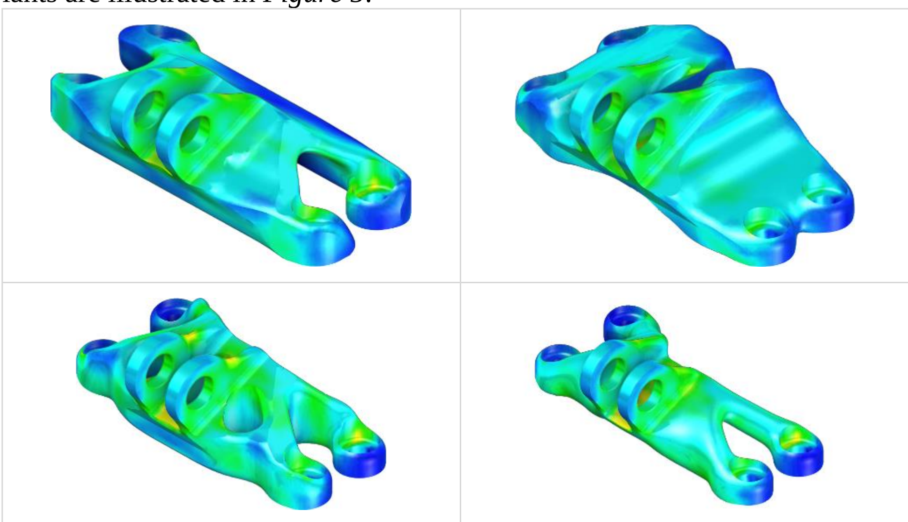


Figure 5
Results of load distribution of generated versions using Solid Edge 2020 Premium software

It is not possible to examine the numerical values of the load distribution, like *Auto-Desk Fusion 360* software. The results obtained are only for information, which allows the identification of load-critical regions; however, the load distribution is not ideal, as previously illustrated in *Figure 5*. The disadvantage is that the software does not allow the tabular display of the results and the simultaneous visual comparison of the generated versions, and the user does not even have information on the numerical values of the characteristic geometric data (e.g. volume), maximum of *von Mises* stress and global displacement is not available for the user. Comparing the results of the two softwares, it is seen that we get different solutions even with similar configuration parameters.

6. SUMMARY

In this paper, we have briefly reviewed the various software applications that support the generative design process. The solutions of two large companies *(AutoDesk, Frustum)* developing a generative module, which is widespread in mechanical design systems, were examined through a case study. Comparing the two generative design modules, the cloud-based technology used in *AutoDesk Fusion 360* software shortens the time of the generative design process and the number of generable solutions can be significantly increased by adjustable machining parameters within a given test (one test – many solutions). The main feature of the Frustum Generate generative module integrated into *Solid Edge 2020 Premium* software is that it can be run on a given machine, so the computing capacity required for the generated models is limited by the user's computer. Another characteristic disadvantage is that only one manufacturing mode can be specified at a time in the tests, which reduces the number of solutions that can be generated within a test. If you want to create multiple solution variants, you need to run multiple studies (many solutions – many studies), which increases the time of the design process.

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