Generative Engineering and Design – A Comparison of Different Approaches to Utilize Artificial Intelligence in CAD Software Tools

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Abstract. There are new CAD software tools emerging that will likely pave the way to next generation engineering design. They are labelled Generative Engineering, Generative Design, Algorithm Based Design, Simulation Based Design or similar. Those new tools have in common that they make intensive use of Artificial Intelligence methods and extensive computing power. The focus of these algorithm-driven approaches to developing products and finding solutions is not the explicit creation of geometry but rather the definition of constraints, boundary conditions, rules and procedures that allow the computation of feasible solutions including the implicit generation of geometric models. One major idea is to initially open up wide solution spaces that are goal-oriented based on given requirements and provide engineers with all relevant information to perform trade-off studies and create new and innovative solutions instead of perpetuating existing solutions. The new tools are often associated with topology optimization and generative manufacturing, but the concepts go far beyond and lead to a complete workflow in the creation of products.

The paper systematically analyses different software tools and shows that Generative Design and Engineering is interpreted and implemented differently by various software vendors, all pursuing different goals. In addition to the potentials, the paper mainly shows the current limitations of the implemented approaches in the different CAD tools. The focus is not only on the design phase, but also on how the tools take into account different aspects such as the automation of the entire development process, cost evaluation and manufacturing processes.

Keywords: Generative design · Generative engineering · Topology optimization · Artificial intelligence

1 Introduction

Generative Design (GD), Generative Engineering, or Algorithm Based Design are terms for the next generation of engineering design which combines human capabilities with

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artificial intelligence, algorithms, and computing power[1]. Especially the technological progress in cloud computing opens completely new ways of creating and evaluate designs through the extends computing power. Furthermore, the manufacturing technique generative manufacturing also removes many constraints from the design of manufacturing and extends the design of freedom to the engineer markedly [1]. The resulting possibilities of manufacturing nature-based and lattice structures requires new ways of construction. Lattice structures are for example body centered cubic or honeycombs structures. Simultaneously, shorter development times and higher requirements lead to first best solutions, often based on existing solutions, instead of exploring the complete solution space to find the best possible solutions. To integrate all these new possibilities and to tackle the challenges a new approach for the development process is given by the approach of GD.

The definition and understanding of GD vary and is interpreted and implemented slightly differently by different CAD tool vendors. One possible cause is that GD is used in a variety of different disciplines such as architecture, art, and engineering [2]. All approaches in the field of engineering have in common that algorithms generate and evaluate various designs or alternative solutions based on user defined boundary conditions [3]. The aim of GD is not to replace engineers but to shift the ability from modeling the solution to the definition of the boundary conditions and the evaluation of the solution. Hereby, the aim is to deliberately open up the possibility that established patterns of thought are broken down and solutions do not only emerge as a gradual further development of already existing solutions. This allows a wider range of options to consider and make the solution more suitable and effective. This paper presents the state of the art in GD in distinction to topology optimization, nature-based and lattice structure. Different GD interpretations and embodiments of the approach in CAD software tools for structural components are presented as well as a comparison of implementation inside three different software tools while identifying strengths and limitations. Therefore, a schematic workflow along the product development process is presented and investigated. Although there are already GD approaches for fluid paths and temperature applications for example, this paper only refers to structural components.

2 State of the Art in Generative Design

GD is an approach to autonomously generate and evaluate designs based on algorithms, that consider user specified boundary conditions like materials, manufacturing processes, loads and supports. Instead of the traditional approach where one concept is selected and evaluate through manual iterations, GD allows to generate and evaluate multiple design at the same time automatically and compare them [4]. As a result, in addition to the traditional approach, a significantly larger solution space is explored and compared. Particularly, the explicit generation of geometry and shape of parts is not any longer the foreground of engineering work, but the definition and characterization of the design problem itself. Geometry is then created automatically and in an implicit way. The approach also takes further stages like cost evaluation into account and allows engineers to evaluate a whole concept at an early stage of development [4]. This methodology

[1] For the sake of simplicity, we will only use the abbreviation GD in the rest of the text.

is not new, there are already first attempts during the late 1970s, but for a large-scale application, further developed algorithms and primarily high computing power were necessary [5]. The technological progress in cloud-based computing performance and machine learning opens new opportunities and increases the possibilities which lead to a new generation of CAD Software tools from different vendors. But as already mentioned the definition and implementation is not set and other terms like topology optimization, nature-based design and lattices structures generation for additive manufacturing are often associated or equated with GD [6].

Topology optimization is limited to the topology aspect and extracts a shape depending on the boundary conditions from a start shape based on a particular optimization algorithm. The goal of this approach is to reach a volume or mass reduction by complete focusing on the shape. As a conclusion of the necessary starting shape, material can only be subtracted from this shape. In contrast, GD is generating a form, can add material to the design space, evaluate different materials at the same time and create new shapes independent from an existing shape. Therefore, the options with GD are much larger than with topology optimization. Nonetheless, topology optimization algorithms can be part of a GD functionality to create a shape. The goals of GD are not limited to volume and mass-reduction and can also consider costs, materials, displacement, manufacturing processes and similar. Besides topology optimization, GD is also particularly excellent suited for biomimetic designs as well as the automated and algorithm-based generation of lattice structures for parts that are manufactured using additive manufacturing technologies. These structures are complex and time consuming to create with traditional modelling. In summary, topology optimization, bionics and lattice structures are like tools in a toolbox of GD methodology [1].

3 General Analysis of GD Approaches

3.1 Implicit Geometry Creation Workflow

The schematic workflow for a GD process for structural component contains is shown in Fig. 1.

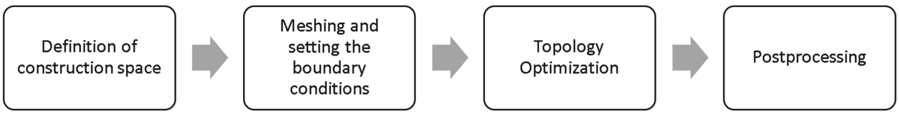

Fig. 1. Schematic workflow for GD process

Definition of the Construction Space. At the beginning of each geometry creation workflow, the definition of the construction space is necessary. This construction space contains not only a spatial area in which geometry can be created or changed (design space DS) but also the definition of spatial areas which have to be kept unchanged (non-design space NDS, retained geometries) or which are given obstacles. Initial geometry models can be imported from different CAD systems or created inside the software. For the definition of the construction space, there are two extreme options with intermediate levels possible. In the "shell-based" option the design space represents the complete construction space (like a shell). In this case the definition of obstacles is not necessary and areas outside this space would not be considered. In this, the non-design space is for geometries which are functional necessary like for instance holes with supports for screws. For the definition of the non-design space a selection through surfaces of the design space or required 3D-models are possible. The other extreme option "restraint geometries" is just the creation of retained geometries (like non-design space) and obstacles. A starting shape could also be created and is recommended if several retained geometries should be interconnected across obstacles, but it does not restrict the construction space.

Meshing and Setting the Boundary Conditions. The next step is to prepare the model for FEM analysis with meshing and defining the boundary conditions like forces, supports and material. Also, the constraints and objectives for the optimization are set. Since the objectives and constraints can be used as both, they are considered together.

For meshing, the range is between "low influence" and "customizable with parameters". In the "low influence" approach the options are limited to the resolution or similar. The "customizable with parameters" option offers many different mesh options as well as for the subsequent preparation, enhancements, and connection of multiple meshes. Mesh type (e.g., triangle or quad), mesh size and other settings can be individualized. Moreover, the option to import or integrate the mesh generation from a different tool is possible.

Potential loads are gravity, forces, moments, and pressure. Therefore, integrable load steps are linear static, buckling and modal. For the constraints or objectives are volume fraction, structural compliance, stress, and displacement as well as the consideration of one direction for extrusion and symmetry with different restrictions possible. Moreover, passive (retain) regions, buckling and modal frequency constraints or overhang constraints for additive manufacturing, can be included. To set the values for the various constraints a manual input or the automation with an import from Excel for example is possible. Another different is the support of manufacturing processes. Due to the consider of one direction for extrusion the tools are designed for additive manufacturing. Possible supported manufacturing processes are beside additive manufacturing, die casting, 2-axis cutting und milling while considering different manufacturing settings like tool properties.

Topology Optimization. Topology optimization for exploration of alternative results includes more methods than the classical topology optimization and describes the improvement of the topology with further methods. One "basic" alternative is to implement the traditional approach of topology optimization with local computing power and provide a block which used the model, variables, objectives, constraints, and a limitation of iterations can as inputs. Also, the integration of further settings like "boundary penalty" to prefer material on the boundaries or material inside, or an option to see all iterations with a different threshold is possible. The threshold defines how much material should be removed and has a major influence on the result. Even if the constraints are fulfilled, the final result does not necessarily meet the requirements depending on the threshold. Another"advanced" alternative is to use experimental solvers or different approaches like the level-set-approach in cloud computing to explore alternative designs and solutions. With respect to the different options, the number of solutions can vary between one solution from the traditional topology optimization and multiple solution depending on the number of materials or manufacturing processes.

Besides topology optimization, another aspect in GD software tools is the generation of a field-driven design, which means for example the adaption of a shell thickness due to the stress in a special area. If the stress in a certain area higher, the shell is denser than in an area with less stress.

Postprocessing. After the topology optimization, the result needs to be prepared for manufacturing and evaluated in relation to the goal achievement. Depending on the results of the topology optimization, the results could be rough and need to be postprocessed. This can be done either automatically using individual algorithms with voxel and smoothing or manually. The next postprocessing step is the fulfilment check of load requirements. For this, different simulations like static FE, nonlinear-static FE, modal frequency, and buckling-analysis could be implemented or exported to a specialized tool. The analysis of key performance indicators (KPI) can be automatically evaluated and compared to the target values or with a manual process for given KPI. For KPI analyses, a black box or an individual approach can be implemented. In the black box approach, the data is supplied by an external tool and there is no option to customize the data. The individual approach allows input data inside a tool for customizable to company-specific data or offers mathematical operations to create own workflows for the calculation. To prepare results for manufacturing, the tools can be integrated or depend on special postprocessing software. The number of supported manufacturing processes varies in different tools.

3.2 Solution Space Exploration and Trade-off Studies

With respect to solution space exploration and the capability to perform automized and assisted trade-off studies GD approach can be divided into two main categories.

The first category **"Assisted CAD modelling"** is an adaption to the traditional CAD approach with the GD module integrated as a workspace in the same way as e.g., simulation module. The GD module user interface is designed like a traditional CAD tool with a ribbon menu for modelling, design constraints and similar as well as a viewer for representing the geometry. The approach is geometry driven and provides a user friendly and familiar environment for the engineer. The configuration options are limited, and the approach is like a black box in terms of algorithms which reduces error-proneness on the one hand side but also limits the comprehensibility on how a solution space for a given problem is created. An impact and inspection of the several steps inside the software is strongly restricted and an automation of the whole process is not possible. The exploration of the solution space and the possibility to perform trade-off studies are implicitly integrated, and the adjustment of the process is not possible.

The second category is **"Functional CAD programming environment"**. Here, the user interface is different from traditional CAD and consists of a low code programming environment. Instead of predefined workflows and CAD functions, the exploration of the solution space and the functionalities are individual arrangeable and can be automized. In this approach, the integration of further tools inside the software or through an im- and export is strongly supported. The engineer is in complete control of all steps, i.e., it is a white box approach. A user needs knowledge about the generation and application of workflows which could lead to mistakes. Nonetheless, an advantage of this approach is the customizable parametric driven generation, which allows to change settings fast and especially explore many different designs through a design of experiments study. This can be used for design automation by only changing a few boundary conditions and is powerful with respect to solution space explorations and trade-off studies.

4 GD Interpretation of Selected Software Tools

The vendors of the different CAD software tools describe GD in various ways. To understand the implementations inside the tools, in this chapter the GD approaches of three software tools are presented.

4.1 Autodesk Fusion 360

Autodesk describes GD as an approach for simultaneously generation of multiple solutions based on real-world goals using cloud computing. The generation is not limited to special manufacturing processes like additive manufacturing and can also take traditional processes like milling into account. For this GD approach, a human operator, artificial intelligence algorithms, cloud computing power and a strong link to manufacturing and process awareness are required. Moreover, Autodesk describes the characteristics of GD as the capacity to solve more complex problems with designs which are physics based and mimics nature as well as with generative design factors in constraints such as load, weight, and cost. The fact that Autodesk implemented GD as a module inside Fusion 360 allows the operator to easily transfer results from GD to tools such as CAD, CAM and FEM. In addition to GD for structural component, Fusion 360 also integrates a preview of GD for fluid paths [4, 7, 8].

4.2 nTopology

nTopology (nTop) is a stand-alone solution for GD and uses an approach of implicit modelling in contrast to traditional explicit modelling (e. g. B-Rep, CSG, Direct) that allows to model geometries with implicit equation in a fast and robust way, especially for lattice structures and organic shapes. For nTop, GD "is a goal-oriented and simulation-driven design methodology that uses software and computational algorithms to generate high-performance geometry based on user-defined engineering requirements". Therefore, nTop defines three key components of GD, which a GD software combines: geometry generation, design analysis & evaluation and automated iteration loops. GD enables engineers to use the full of range of possibilities from additive manufacturing. In comparison to topology optimization, this GD approach allows to consider technical and non-technical requirements like costs. The advantages of nTop approach are the development of new designs (with no inspiration from previous), high performance products and acceleration of product development. Disadvantages arise from the limitation of the constraints GD can handle and the fact that the quality of the result is limited to the quality of the workflow/simulation. nTop is also not limited to structural components and integrates also GD for thermal applications [9].

4.3 ELISE

ELISE describes the product development process as an incremental process with many manual iterations due to different departments, software tools and data types. To improve this process, engineers should be able to use computers to develop optimal products automatically. ELISE can be interpreted as a low-code enabled CAD integration platform that combines several commercial engineering tools in a stable, all-encompassing software. In ELISE the algorithm-based design is defined as a technical DNA (workflow) which automatically generates shape and geometry, based on the boundary conditions. These boundary conditions contain clear design rules, limits, and target values. The workflow integrates and evaluates all different processes and tools like CAD design, FE-Simulation, and calculations inside and is completely customizable. The advantages of this approach are that changing boundary conditions automatically lead to new parts. There is no longer an individually creation of each component necessary and the DNA can be reused partially or completely. By this approach, the new degree of design freedom provided through additive manufacturing is captured and enabled well [10].

4.4 Assessment of the Modules

Table 1 shows an assessment and a comparison of the two categories.

The **assisted CAD-modelling** approach shows how to integrate GD as a module inside the existing solution while providing the traditional CAD-user interface. The generation of the structure is like topology optimization with focusing on a design for manufacturing and include a selection of further features like cost analysis and comparison of options. The simultaneous generated results are due to the cloud computing support and different solver involvement manifold and more nature based. But the options to configure individual solutions are restricted, the workflow cannot be completely automated, and the approach is limited customizable due to only changing boundary conditions and the resolution of the mesh.

In contrast, the new vendors follow with **Functional CAD programming environment** a similar concept for GD, although the used term is different. Both software solutions rely on the individual generation of reusable workflows for the automation of the entire process and allow to change many parameters. But the visualization options for comparison the results of different parameters as a trade-off study are limited. The approaches of both are not limited to generate a shape like with topology optimization, they are more holistic and individual depending on the circumstances. The engineer has all options to variate the whole process by creating an own workflow and can track all steps to create the design from the construction space over topology optimization to evaluation. The focus of both platforms is on additive manufacturing although not

Table 1. Assessment of different approaches to features

	Assisted CAD-modelling (e. g., Fusion 360)	Functional CAD programming environment (e. g., nTop/ELISE)
Geometry Definition		
Definition of construction space	Restraint geometries	Shell-based
Mesh generation for topology optimization	Low influence	Customizable with parameters
Considerable loads	Gravity, forces, moments, pressure	
Considerable load steps	Linear, in preview: modal, buckling	Linear
Constraints/objective for optimization	Volume fraction, structural compliance, stress, passive regions, extrusion direction	
	In preview: displacement, modal, symmetry	Displacement, symmetry
Manufacturing processes	Additive, die casting, 2-axis cutting, milling	Focused on design for additive manufacturing
Topology Optimization	Advanced (cloud computing)	Basic, field-driven (local)
Postprocessing	Manual	Automatic
Topology reconstruction	Not necessary	Voxel, smooth
Evaluation for fulfilment of the requirements	Static FE, modal frequency, buckling-analysis	
	Nonlinear-static FE	Im- and export for external tools
KPIs evaluation	Black box, automatically for technical, manual for non-technical	Individual, automatically through mathematical operators
Preparing for the manufacturing processes	Not inside GD	For additive
Further Aspects		
Design automation	No	Individual
Lattice structures	No	Yes
Design of experiments	No	Yes

limited to it. Differences are in the provided load steps and constraints. ELISE allows modal and buckling load steps and therefore constraints, while nTop allows moreover an overhang constraint with focus on additive manufacturing. For the evaluation of the KPI, ELISE has besides the mathematical operator's unique blocks for some KPI to evaluate them automatically.

An advantage of the implicit modeling platform nTop against the open platform ELISE is that nearly all features are integrated inside the platform and no other license or software is necessary. The only exception is the design of experiments in nTop. Against this, ELISE provides many features, but it also relies on partners for integration of different tools like lattice structures. Moreover, notable is the necessary license for the basic function of topology optimization. But besides the typical workflow, the new vendors provide further features like field-driven design, lattice structures.

Figure 2 shows the differences in the definition of the construction space for the three presented software tools and the generated results after the development process. All results show a reduction of the used material while take over the preserved areas and meet the stress requirements. Especially the experimental result from Fusion 360 shows a design that is clearly different from the traditional approach compared to the other.

Further advantages of GD are shown in the example of a seat bracket from General Motors and Autodesk where the GD solution is 40% lighter but also 20% stronger and eight parts are consolidate into one [11].

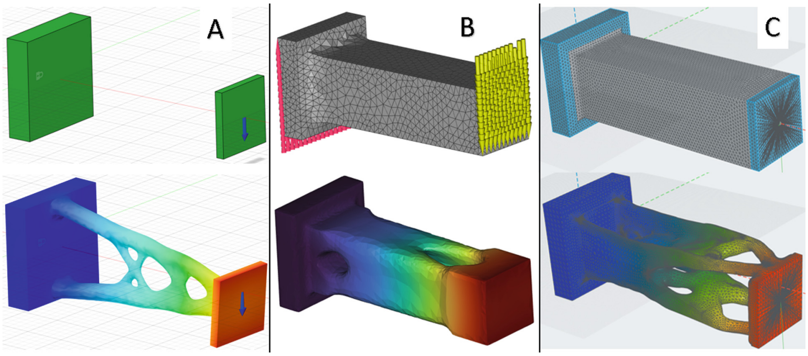

Fig. 2. Example of construction space and results in Fusion 360 (A), nTop (B) and ELISE (C)

5 Conclusion and Outlook

This paper shows a systematic overview and a comparison of different approaches to implement GD inside CAD software tools. For all mentioned features along the product development process, the possibilities for integration are manifold and differs in most cases between an individual and a black box approach as well as a manual against an automatic process. The implementation of the features inside three selected software tools were analyzed. The results show that the implementation can be divided into an “Assisted CAD-modelling” and “Functional CAD programming environment” approach while the embodiment was always slightly different and not completely equal. Each software tools have its strength and limitations in different aspects. In this paper, the focus was on the features for the generation of a single part, but no consideration was given to the generation of assemblies. Also, the reproduction and variation of results by similar boundary conditions as trade-off study was not analyzed. Moreover, the results need to be validated regarding building options and fulfillment of the requirements. Also, it needs to be considered that all software tools are still under development. Therefore, it is necessary to evaluation the functions of these tools in future and compare them if new functions are available.

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