White paper

The 7 habits of highly effective generative design

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Executive summary

Generative Design is a new disruptive technology that delivers a paradigm shift for the design and engineering of new products. The conventional design cycle has well-defined steps that include definition, research, specification, design, development, test, revise and revise again until a suitable product is developed. Generative Design is an innovation that significantly alters this way of thinking. It leverages topology optimization, artificial intelligence, and advanced simulation which automatically creates multiple viable design alternatives by specifying simple design criteria.

Engineers are no longer limited by their imagination, experience level, or legacy designs. They are freed from routine design work as advanced algorithms take over actual geometry definition and can now use their skills to evaluate the various concepts generated. Not only are all design concepts smooth organic topologies that satisfy design criteria, but they overcome the most challenging task of being ready and optimized for Additive Manufacturing.

Generative Design bridges the engineering skills gap between theoretical knowledge and practical experience in mechanical systems and components. It boosts engineering creativity and innovation, drives efficiency, decreases weight, and reduces time-to-market for new products. Generative Design saves costs at every stage of the product's lifecycle.

This paper further elaborates, how to most effectively make use of generative design approaches, by explaining seven habits in virtual design tools:

- Design for Exploration
- Design for Usability
- Design for Productivity
- Design for Costing
- Design for Sustainability
- Design for Manufacturability
- Design for First-Time-Right

Generative Design breaks down the walls between design and manufacturing by unifying design and manufacturing specifications. Generative Design algorithms present fully optimized and manufacturing viable design alternatives early in the process to the entire team. The result is a faster, more agile product development process that increases innovation, optimizes product performance, accelerates time to market, decreases costs, reduces weight, and streamlines production.

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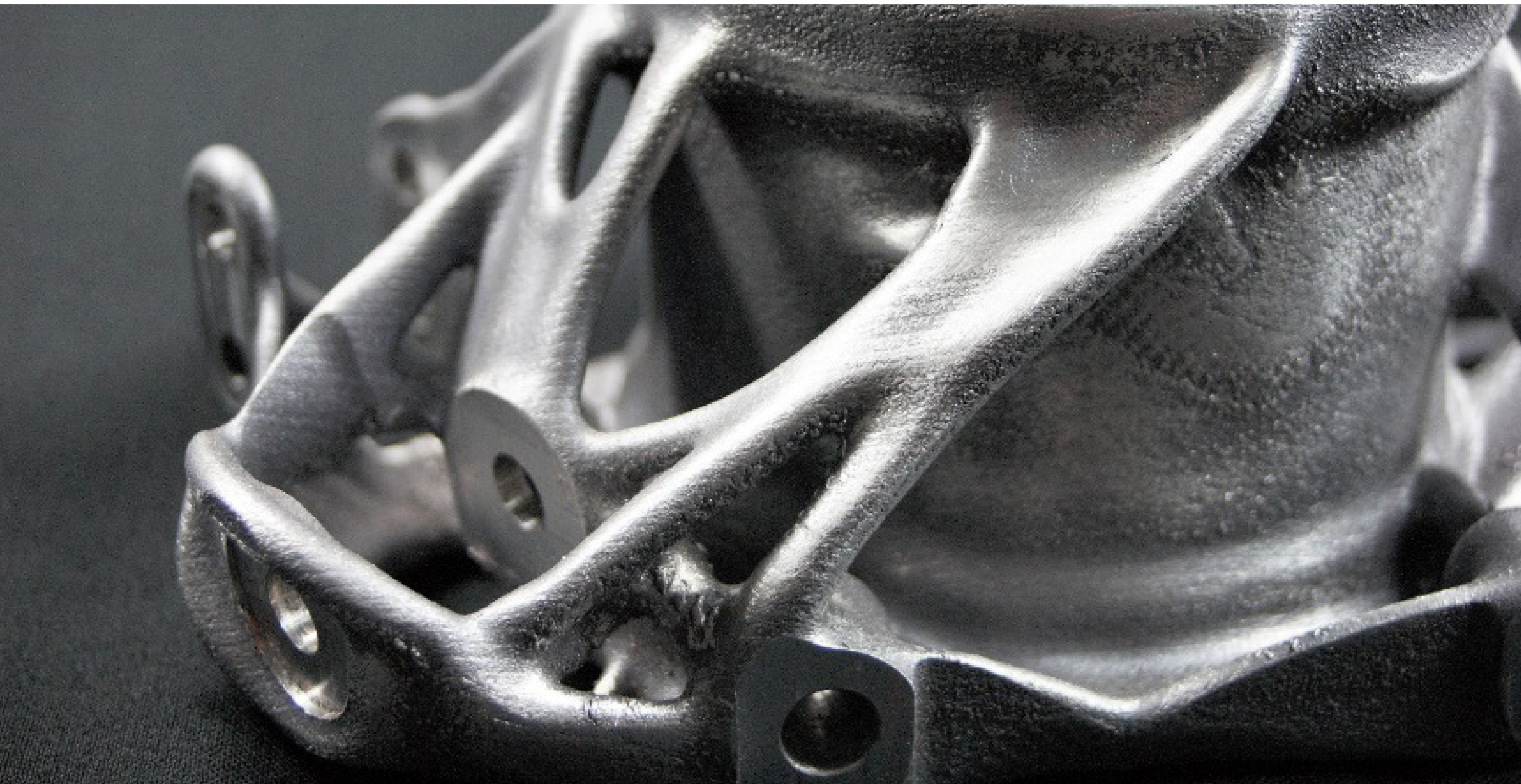


Introduction to generative design

What is generative design?

Generative Design is the automated creation of various design variants for a set of constraints and objectives. This new technology frees the designer from routine work and enables him to concentrate on concepts and creativity to drive innovation. It increases design efficiency, reduces the complexity of optimizations and enables material and energy savings with optimal designs tailored for Additive Manufacturing.

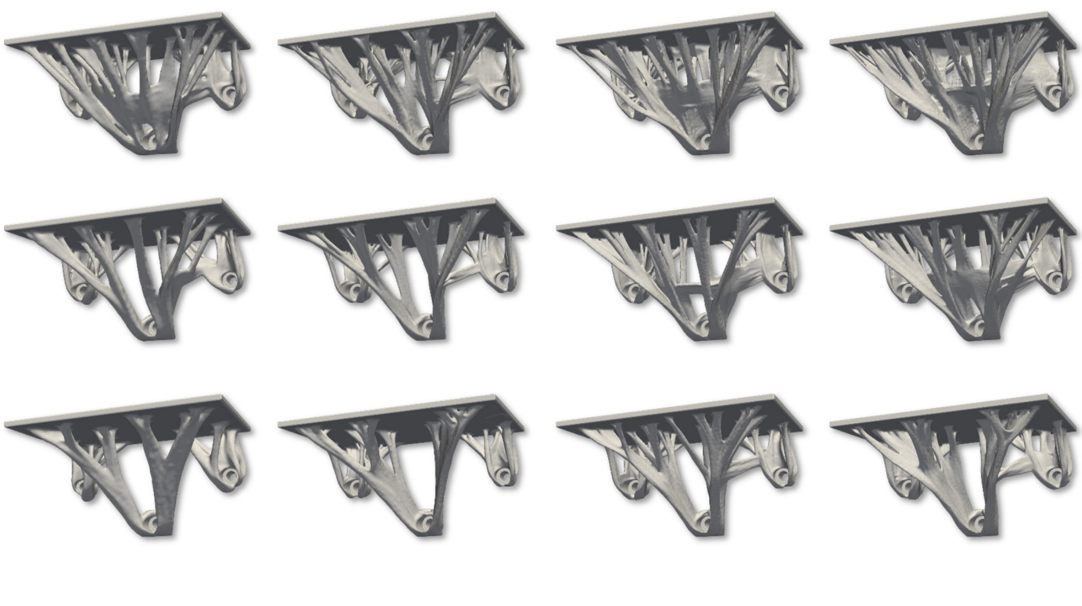
Generative Design can be accomplished in many ways depending on the criteria and constraints defined by the user. For example, a user may define a set of structural loads and boundary conditions that a component must withstand as criteria of its normal operation. The specification may call for an upper stress-limit as a constraint with the objective of minimizing mass. A method known as Topology Optimization can be used to generate several design concepts that satisfy the give criteria and conditions. Further, the technology can be used to optimize packaging for minimum space to determine the optimal fit of several designs in the specified space.

Generative Design is more than a classic topology optimization, it creates viable designs that do not require additional manual editing for additive manufacturing. The technology is highly automated, efficient, and very fast in generating results ready for 3D printing. By minimizing the time and effort for optimization, Generative Design enables the user to apply parametric variations to obtain numerous feasible geometries. The engineer can then choose the most promising design variant from those generated instead of the classic design cycle that requires him to rely on the one result that has been developed after many revisions.

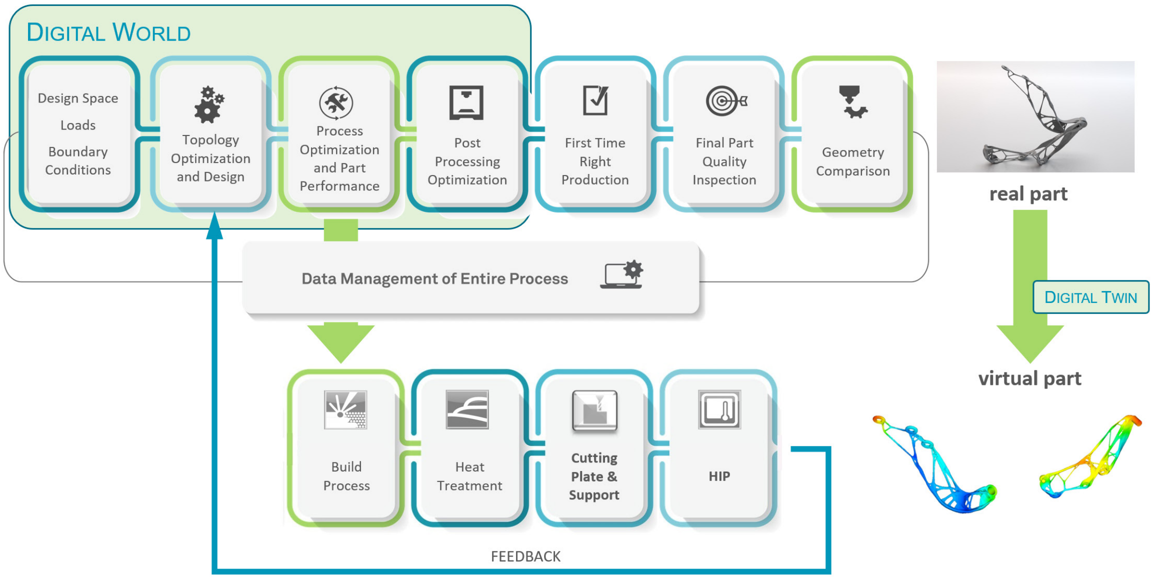
A common engineering design problem involves component consolidation. A small-batch or custom component assembly is generally a fabrication of parts that are welded, riveted, or fastened together. The optimization challenge is whether a single molded, forged, or cast component can satisfy the specifications of the entire assembly. Most engineering departments will forego such an optimization due to the time required to decompose the assembly and re-engineer (optimize) the part(s), or the increased costs to manufacture a single yet more complex part. Engineers can now use Generative Design to automatically generate several design candidates that meet the user's specifications. The tool determines how the part fits within the overall space, how it redirects loads and merges components of the assembly as its stiffness changes. Most importantly, it accounts for how the single organic component can be manufactured utilizing 3D printing. Each optimization always leads geometrical and mechanical correct design that can be used for manufacturing.

Why do we need generative design?

Generative Design assists design engineers by automatically creating organic topologies that can be manufactured utilizing 3D printing such as Laser Powder Bed Additive Manufacturing. Technologies such as Topology Optimization are being reinvigorated thanks to advancements in Additive Manufacturing. While Additive Manufacturing can manufacture prismatic designs with little or no editing, organic topologies create manufacturing problems such as shrink lines, cracking, zonal overheating, etc. This has



Various generated designs of a bookshelf to choose from, created by a parameter variation



An integrated digital thread with feedback loops from the actual production results brings together design with manufacturing for a successful product lifecycle

kept Additive Manufacturing from replacing conventional manufacturing methods. Despite the technology's design freedom, it can be challenging to manufacture designs that are not aligned for Additive Manufacturing.

There are still many integration limitations in classic topology optimization software that are not consistent across processes, materials, and machines. Another limiting factor that with Additive Manufacturing technology is the expert knowledge that engineers need to prevent failures and to fully exploit the technology's capabilities. The lack of skilled employees demands software that comprises this knowledge and incorporates it in the design. These issues were not as pervasive when 3D printing was only used for prototyping, however, they have become prevalent when using Additive Manufacturing for production parts. Modern generative design tools are much better suited to create designs for 3D printing technology.

Bridging the chasm between CAE design and manufacturing

As with any new technology, the user must also understand the cost and feasibility of using Additive Manufacturing for a design candidate. Generative Design must allow users to specify manufacturing-related constraints. For example, if the goal is to minimize the cost of 3D printing, then automatic checks should be made for each design candidate such as:

(a) amount of material required for the part,

(b) volume of support structure required for support and heat dissipation in the 3D printer,

(c) cost of removal of support structures and machining for desired surface roughness,

(d) costs related to maximizing the number of parts printed at one time on a build plate, etc.

At the end of the optimization routines, Generative Design selects the candidates that meet the specified criteria and summarizes them. Today, the cost of additive manufacturing and long print times with sometimes unforeseen issues are major constraints to the wider adoption of Additive Manufacturing for mass production. Hence there is a need to account for and optimize the total manufacturing cost and print time while designing parts for Additive Manufacturing. Tools are required that put a focus not just on optimizing part design for Additive Manufacturing but also on optimizing the overall end-to-end process.

Only after engineering software tools bridge the gap between design and manufacturing can Additive Manufacturing become a sustainable, cost-effective, and widely accepted manufacturing method. From load simulation, design generation, manufacturing simulation, and verification, it all must be integrated into one fluent workflow. Every stage is a vital part of a successful product lifecycle. Thus, it is necessary to adopt a "lean approach" where simulation reduces failures and increases performance.

The 7 habits of highly effective generative design

We have identified seven underlying technologies and philosophies that will yield both a highly effective and pragmatically useful engineering Generative Design approach to additive manufacturing.

1. Design for exploration

It is vital that software tools be developed to modify parts that bridge the gap between design and manufacturing. Such tools utilize Artificial Intelligence to automate the design process so that user intervention is only required to define the objectives, criteria, and constraints within the design space the user wishes to explore. For new designs, the classic product design cycle takes a lot of time and effort to generate a single geometric design. Typically, it is chosen because it is simply too time-consuming to create and test more designs iterations. MSC Apex Generative Design uses smoothed topology optimization to calculate several design variants for design challenges.

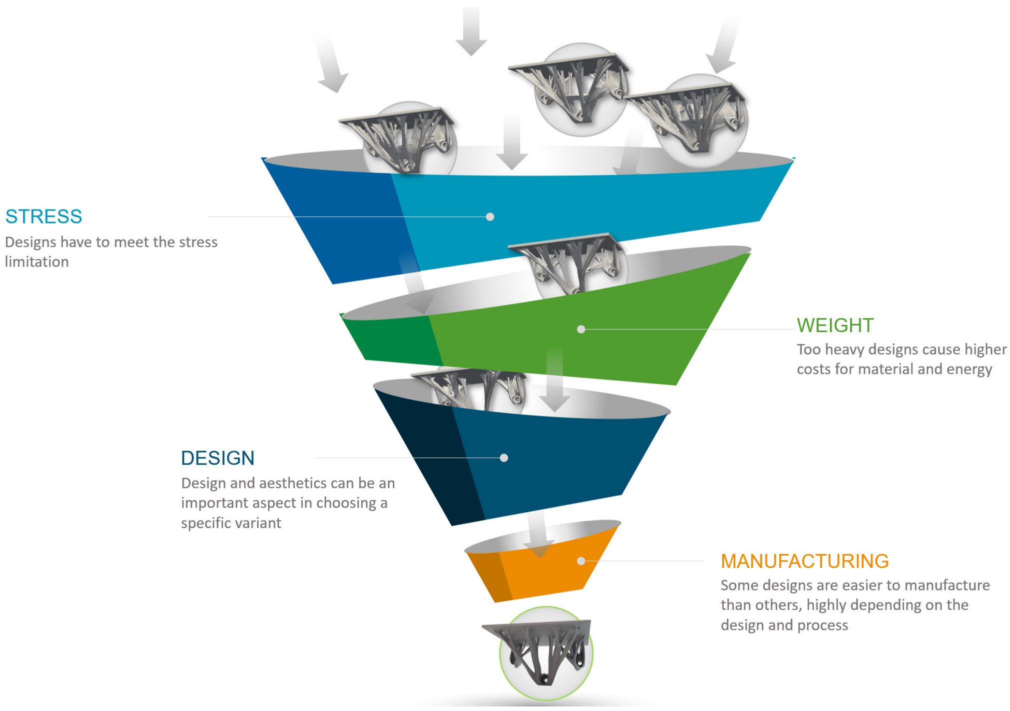
Part consolidation can be achieved by giving the topology optimization algorithm the greatest possible design freedom. Different parts of a fabricated assembly group can be joined together by MSC Apex Generative Design to form one organic single design solution. Generating a single part in place of an assembly not only reduces the weight solution, but it also reduces the number of components used and simplifies the associated assembly process. Additional savings come from reduced complexity for part handling, warehousing and elimination of tolerance stack up. Part consolidation, therefore, has a high potential to lower weight, overall complexity and costs and is a key part of the exploration process.

Designs that only "just meet" the basic requirements can be susceptible to low quality. Hidden requirements that can appear downstream during testing or after installation exposes these quality issues. MSC Apex Generative Design enables free-flowing optimization of ideas and feasible design possibilities. This is the fundamental principle to achieve truly new innovative designs. New smart designs are achieved with designs driven by intelligent algorithms rather than the standard serial design procedure based on legacy designs.

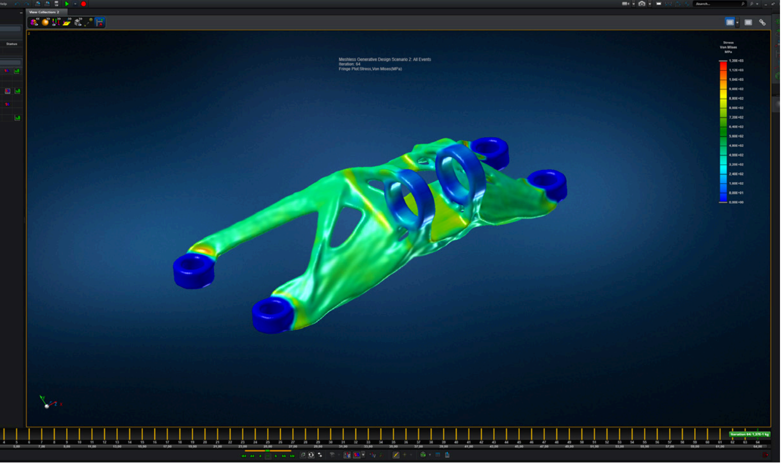
A single derived design solution pales in comparison to the exploration of several designs that experience the MSC Apex Generative Design funnel that identifies the most promising one. The ability to explore design space in a time-efficient manner ensures that the design process is not a bottleneck and thus allows our users to make decisions solely based on design criteria. Only a complete examination of the design space with a variety of results, and in a short time, leads to the best results.

2. Design for usability

Speed is crucial and is the key enabler for exploring different designs. To evaluate several design candidates in a time-effective manner, it is necessary to couple artificial intelligence with complete system optimization. The



From many different design variants, the most promising and best suited design has to be chosen based on different criteria, depending on the respective application



Topology optimization of an aerospace engine bracket inside MSC Apex Generative Design

underlying finite element solver and an optimization engine that can take advantage of the latest computing technologies for extremely fast performance. As such, it needs to be written to optimization and analysis engine to scale on multiple GPUs and CPUs.

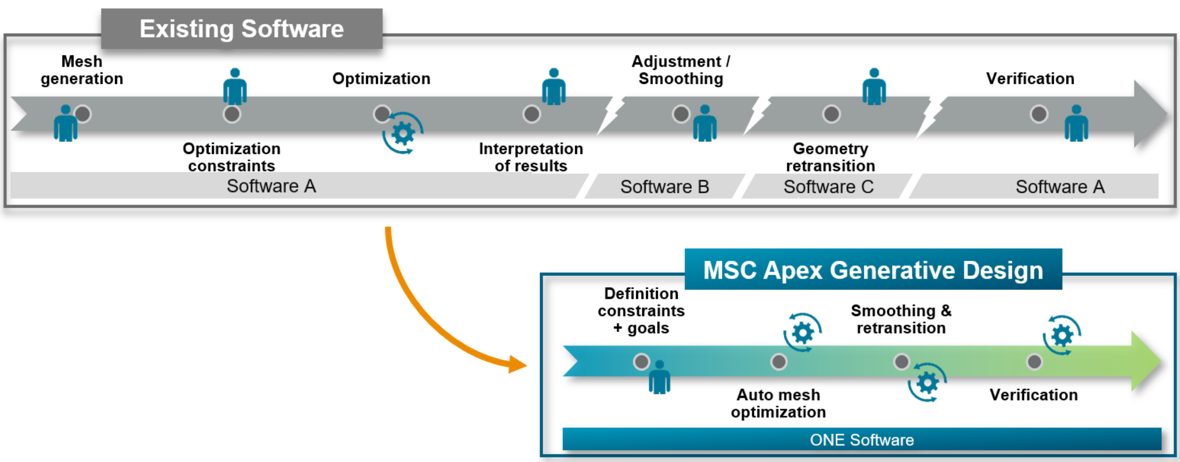
MSC Apex Generative Design is designed from the user's point of view utilizing a simple yet supportive model setup with full automation of the optimization and analysis process. Although Finite Element based, the time-consuming process step of meshing must be automated, self-healing, error-free, and performed within seconds. Similarly, interpretation of the optimization results should also be conducted by the software. Reducing the complexity of this sophisticated optimization to a "non-expert" level is one of the crucial points for generative design. The user does not have to deal with complex FE calculations. MSC Apex Generative Design, therefore, leverages the practical MSC Apex modeler functionalities which are already known to many users. The familiar working environment facilitates a fast and productive start without an extensive training period.

The same CAE-specific direct modeling enables a continuous application of the same user interface for different simulation products. The solution features sophisticated and interactive tools that are easy to learn and easy to use. With MSC Apex Modeler, CAD data at any complexity can be used as input for preparing the optimization, or the user can start right from scratch. CAD manipulation for defining design and non-design spaces is lean and smooth, the data can easily be adapted to the requirements. Different variations can be conducted and compared in a single, integrated software. This is where usability drives innovative design.

3. Design for productivity

Business demands are relentless. While product complexity is ever increasing, time-to-market is ever decreasing. Additionally, manufacturing is pressured to reduce costs yet create products of high quality. These antagonisms require much higher productivity and engineers are tasked to deliver more and higher quality and performance part designs in even less time. For this, the traditional product design cycle is broken. Disruptive technology is an innovation that significantly alters the way that we operate. For engineers, MSC Apex Generate Design a disruptive technology that sweeps away the traditional design cycle and replaces it with recognizably superior attributes. First-time-right 3D printing is essential to significantly save cost and time. Significantly reducing the time to conceive, create, and develop a viable engineering solution is the first step to achieving this breakthrough. For this, solver speed is vital. One of the biggest benefits of MSC Apex Generative Design is that it will shorten the design candidate list quickly and enhance those remaining designs. To solve such complex problems promptly the underlying finite element solver and optimization engine must take advantage of the latest computing technologies for extremely fast performance.

Finite Element (FE) solvers and the optimization engine need to scale on multiple GPUs and CPUs. With the further implementation of generative design technology into everyday design work, high-performance computing devices are a necessity to fully exploit the technology. To make the best use of all available computing power, the full bandwidth of cloud services, on-premise



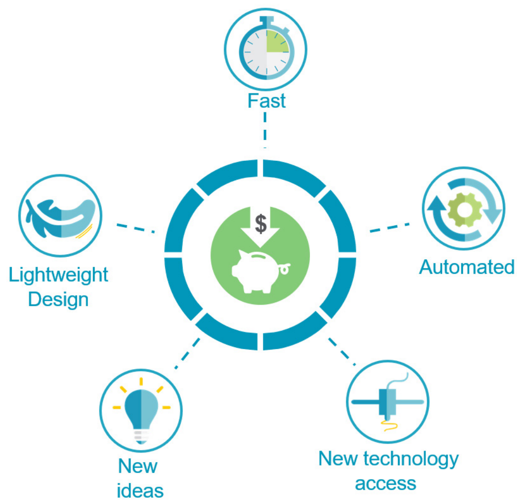
With generative design the process of optimization is automized and significantly shortened workstations, as well as remote servers must be accessible and utilizable by the software. This enables users to explore the design space in a time-efficient manner so that the design process is not a bottleneck and it becomes feasible to make decisions solely based on design criteria. This is where the engineer and the software grow together to one team where each applies the best of its knowledge to a specific design challenge where the hard and time-consuming work is automized.

4. Design for costing

Every design optimization carried out shall lead to a geometrically and mechanically correct design that can be used for manufacturing. Beyond geometry a part designer needs to understand the cost and feasibility of using AM for each design candidate he considers. If the design goal, for instance, is to minimize the cost of 3D printing, then a design tool should automatically check each design candidate with regards to the

- Amount of material required for the part,
- Volume of support structure required for support and heat dissipation in the 3D printer,
- Costs related to the orientation of a part and corresponding production costs
- Maximizing the number of parts printed at one time on a build plate.

These checks should be performed in the background using specific algorithms for build time estimation, and cost estimation for both metal and polymer parts. At the end of an optimization routine, the software should propose the candidates that meet the specified intent criteria.



Several aspects of generative design can reduce costs on a process, product and production level

For complex assemblies, virtual manufacturing can be applied to achieve real-time management of product quality data and they can be an efficient means to support cost optimized product development. This approach will reduce the number of loops in the cycle of design, engineering, and prototyping dramatically and will connect the different development steps better with easier feedback loops. By eliminating prototypes in the early design phase, it will save costs while delivering ROIs of a multiple. It is a crucial building block for manufacturers to meet the requirements of a seamless workflow and data management environment that connects to the users' PLM or ERP environment to drive down cost.

5. Design for sustainability

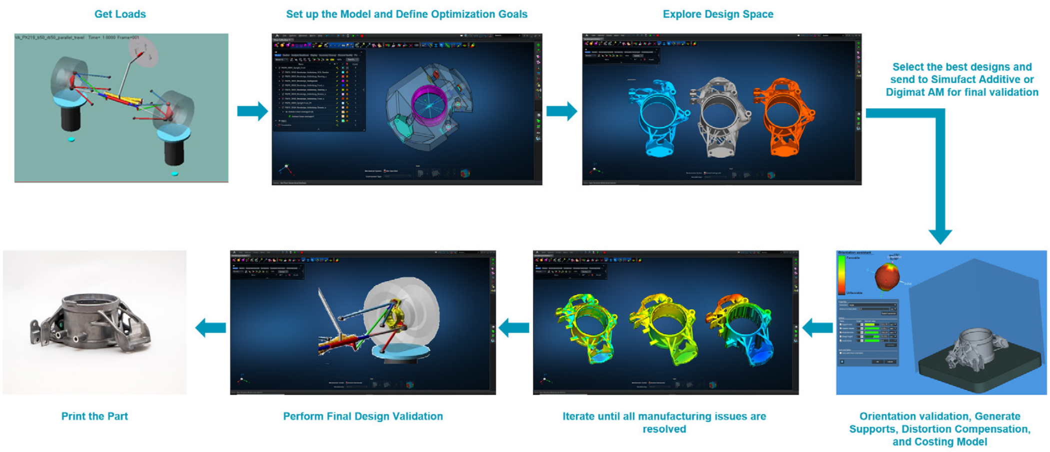
As our world's material resources become scarce, recyclability needs to be factored in from the conception of parts, the combination of additive manufacturing. MSC Apex Generative Design offers unique opportunities for fewer production runs, custom solutions, and ultimately reduced waste with potentially no scrappage whatsoever. Modern smart sustainable design solutions for manufacturing in the emerging 'circular economy' of the 21st century need to improve recyclability and should make good business as well as sustainable environmental sense. Such digital simulation tools for design, engineering, production, and manufacturing should lead to a Lightweight part design is therefore beneficial to meet the increasing demand for sustainability.

Less weight equals less energy and often, in the end, a lower consumption of fossil resources. Starting with the production process, a reduced weight requires less material to be processed, saving production time, material and energy. During the part's lifecycle, it can further save energy through lower fuel consumption in aerospace or automotive or also smaller laid-out engines for moving robotics in the automation sector. There is a huge potential ready to tap given the classic part designs for traditional manufacturing technologies. With Generative Design this can be done with manageable effort.

6. Design for manufacturability

Depending on the material, process, and part design, Additive Manufacturing can be quite costly. This becomes even more important, when a 'build job' crashes because manufacturability has not been fully ensured. This starts with the design of a part for which thoroughly embedded manufacturing know-how should be integrated as a design constraint. It also relies on proper working design algorithms and error-free data export to receive high-quality data as an input for manufacturing.

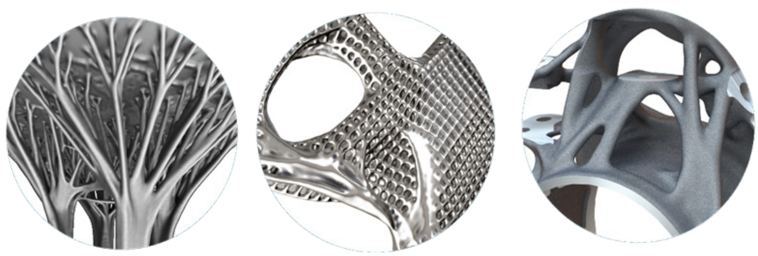
To ensure a 'build job' is perfectly prepared for manufacturing, a design engineer can perform further checks on manufacturability via a simulation of the production process like Simufact Additive and/or Digimat Additive Manufacturing. Ultimately, it should be possible to perform many of these optimizations with embedded generative design so that designs are optimized to multiple criteria concurrently and automatically. With the combination of generative design and process simulation, the design and the manufacturing parameters can be optimally adapted to the chosen production process. Simple and continuous data exchange between these software tools without any significant manual data manipulation facilitates high productivity. The benefit of each solution can thus be integrated into the part development for a high-manufacturability. This is what MSC Apex Generative Design and the further MSC products aim for: One integrated process chain where a user can start with the simulation of accruing load cases as an input for generative design. The created part designs are verified and further tweaked for an optimal production where all manufacturing issues are resolved. The final validation calculates that all requirements are fully met. The printing of the part should then work without any incidents.



Design for additive manufacturing workflow using MSC Apex Generative Design

7. Design for first-time-right

Not only in manufacturing but also in simulation a first-time-right approach is much more efficient and lean than a repetitive trial-and-error. While classic topology optimization is characterized by a highly repetitive manner where mesh, result interpretation, and CAD retransition is extensively repetitive, some generative design solutions offer the opportunity to shorten this sequence tremendously. When the algorithm creates a distinct, feasible result in every iteration, the user can inspect the created geometry in order to identify a need for change. Perhaps the user might have forgotten to add a load case to an area of the design space so that it is removed completely by the algorithm, this can usually only be noticed when the complete calculation run is finished. With modern generative design, this error in model set-up can be directly realized and corrected. With the newly applied force, the algorithm adds material again to the area. This enables a highly fluent process where the user can always intervene, adapt and influence the optimization to achieve a successful, direct and feasible end result. In one smoothly fluent process step - first-time-right within simulation! In addition, the optimization algorithm creates a design that is tailored for 3D printing. This fosters a first-time-right also in production. Usually, smooth transitions between solid and fine structures are created, reducing the risk for hot spots and warpage as well as an error of the coating device. Self-supporting structures reduce the need for support structures and make manufacturing easier. In combination with the manufacturing simulation solutions such as Simufact Additive und Digimat Additive Manufacturing the success of the production is on a very high level and design for first-time-right is at hand.



Bionic shaped complex structures are typical for achieving a lightweight design and are usually better suited for additive manufacturing as solid geometries

The simulated and produced race car of Paderborn FormulaStudent team where optimized wheel carriers reduced the overall weight

Real world generative design example: Formula Student car wheel carrier

We have demonstrated the potential of MSC Apex Generative Design by allowing a formula student team at Paderborn University to design a wheel carrier for their car - the part of the wheel suspension which supports the wheel bearing. This is a good test case due to its very complex load cases and strong demand for a lightweight design. There are also plenty of benchmarks for part optimization because the race series requires the participants to develop a new race car every year, scrutinizing every part in the pursuit of a competitive edge. MSC tools such as Adams and MSC Nastran have also been used for part optimization in the past.

The development process starts by retrieving the loads from a multi-body dynamics simulation based on Adams Car (see also the figure within the section 'Design for Manufacturability'). The Adams model simulates the overall suspension engineering including all coordinates for the connection points and the acting forces. This information was used to set up the optimization model and define its goals. This provides a "design space" that is as big as possible (shown as translucent material) in MSC Apex Generative Design.

In this Formula Student project, the space within the wheel rim minus the installation space for wishbones, and braking system was selected. Running the optimization algorithm, the material in the design space was reduced as much as possible while keeping account of the boundary conditions, constraints and optimization goal.

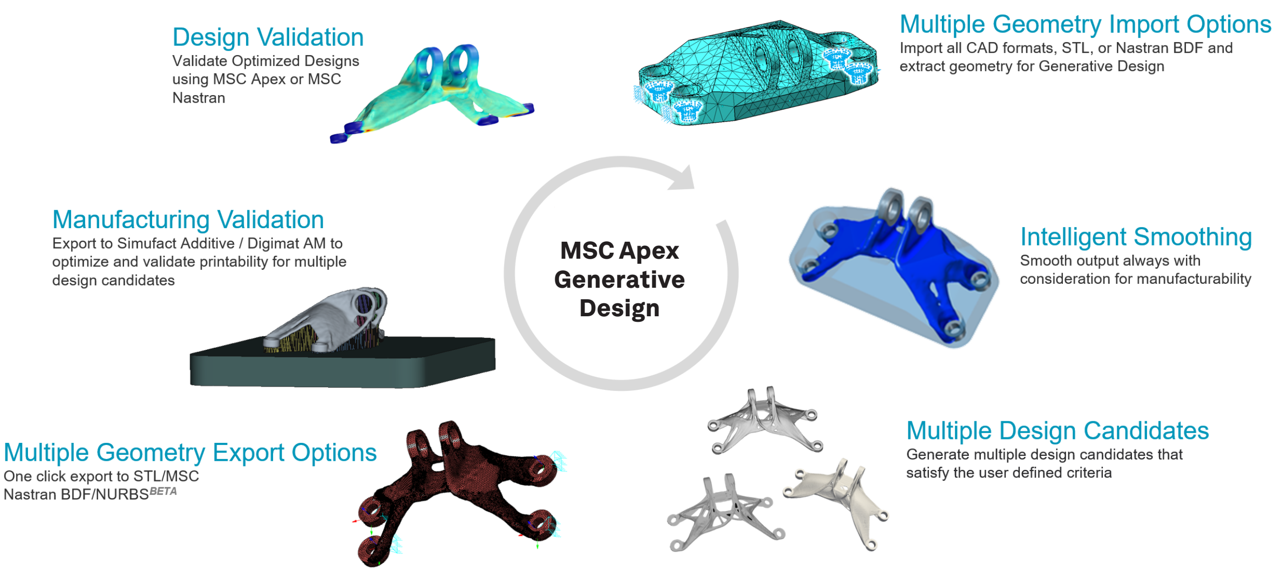
Thus, several design candidates were produced and verified in the background using Simufact Additive for this

Optimized wheel carrier produced by 3D printing. Assembly process with suspension and brake system metal part and Digimat AM for a plastic part, in this case, the accelerator pedal of the race car. While selecting the right candidate and iterating the manufacturing simulation, the students' optimal design in terms of manufacturability, weight, and cost was selected. As a last step in the virtual world, this design was finally validated by qualifying the finite element model in MSC Nastran and integrating the part into the Adams model to ensure the part provided the correct stiffness and behavior within the overall assembly. Thus, an optimal design was identified, printed successfully and used in last year's formula student season.

Summary and conclusions

Additive Manufacturing has come a long way since its inception and has changed the manufacturing landscape over the last decade. In order to realize the full potential and benefits of AM, the gap between design and manufacturing needs to be closed in order to get to design specifically validated for Additive Manufacturing. We have identified seven technology and philosophy habits that are bridging this gap to the validation of manufacturability using generative design, that is constrained by an accurate 'digital twin' of additive manufacturing from material to print process. We think this approach is compelling because it will only produce geometry candidates that have been validated for metals, advanced composite materials, and polymer processes.

Furthermore, final part quality inspection based on state-of-the-art scanning technology can verify the accuracy of the engineering simulations and compare the "as-built" part to the "as-designed" part to help users further increase confidence in Additive Manufacturing part quality and the consistency the virtual design validation provides. Time and costs are two of the major constraints to large scale Additive Manufacturing production today. MSC Apex Generative Design is helping engineers cut the time and costs of Additive Manufacturing simulations, make better decisions about costs earlier in the design process and – most importantly – get closer to "first-time-right" 3D printed parts with smarter and more sustainable additive manufacturing.



Functionalities within the workflow of MSC Apex Generative Design

Hexagon is a global leader in sensor, software and autonomous solutions. We are putting data to work to boost efficiency, productivity, and quality across industrial, manufacturing, infrastructure, safety, and mobility applications.

Our technologies are shaping urban and production ecosystems to become increasingly connected and autonomous – ensuring a scalable, sustainable future.

MSC Software, part of Hexagon's Manufacturing Intelligence division, is one of the ten original software companies and a global leader in helping product manufacturers to advance their engineering methods with simulation software and services. Learn more at mscsoftware.com. Hexagon's Manufacturing Intelligence division provides solutions that utilise data from design and engineering, production and metrology to make manufacturing smarter.

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