Additive Manufacturing Design:
Considerations in Expanding Your Capabilities

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Additive Manufacturing Design: Considerations in Expanding Your Capabilities

In Part A of this series (AM Design: Considerations for the Full Value Stream), the discussion surrounded how to integrate the entire manufacturing process into the design thought process, from cost, powder removal, machining, material properties, and thermal processing perspectives. Now for Part B, we will step into the nitty-gritty producibility considerations that should be taken into account when creating your additive manufacturing design. In addition to that, we will discuss some of the ever-evolving opportunities afforded by linking AM to design optimization software.

No one size fits all rules

Before diving in we need to provide that caveat that each process, machine type, and material potentially creates a new set of design rules and restrictions. Unfortunately there is no one size fits all rule book yet. The differentiation factor between Additive Manufacturing vendors can be found inside their knowledge base and experience, and whether they have evaluated their own machine's capabilities. Although there are some great rules of thumb out there and insightful application engineers at the OEM's that can help with geometry considerations, there is nothing better than creating a rulebook specific to the process, machine, and material.

Learning on your own dime can save in the end.

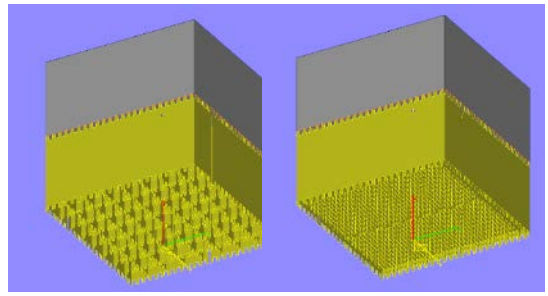
Although sometimes unavoidable, the worst place to learn about a critical design process rule is while building a deliverable component. There is the potential to lose money from scrapping a build, extend lead times by having to rework, and affect Customer relationships by not delivering to expectation.

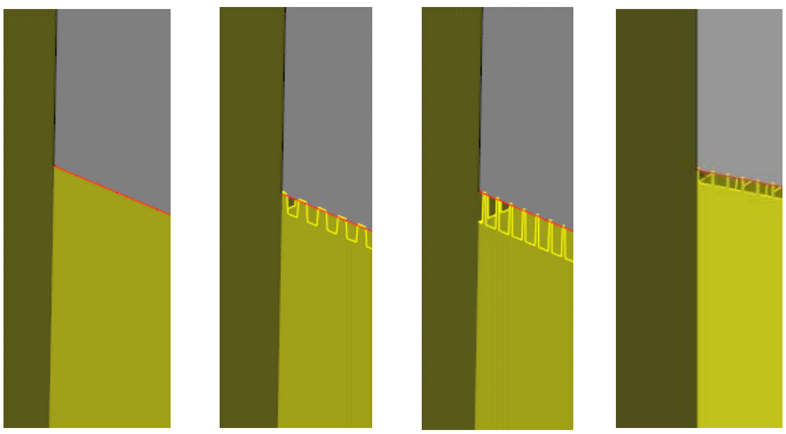
Instead of designing an additive manufacturing build and crossing fingers that it is successful, a much better approach is to spend the time up front to qualify the machine and establish the design rules that can be implemented immediately with a few internal builds and demo components. The following are some considerations to explore in your own system, and how to create those producibility guidelines necessary to tackle the majority of the geometries encountered.

Support Structure

Support structure deserves its own section since it can make or break the effectiveness of utilizing additive manufacturing over other conventional methods. Most machine OEM's provide default parameters for support structure. These parameters are set to accommodate the largest array of geometric features with the least amount of effort by the designer. Unfortunately, for most process and material combinations, there is a sweet spot for support structure depending on the geometry, but blindly using the default supports does not always produce sound and efficient results. The following are some considerations that should be made when studying and designing support structures.

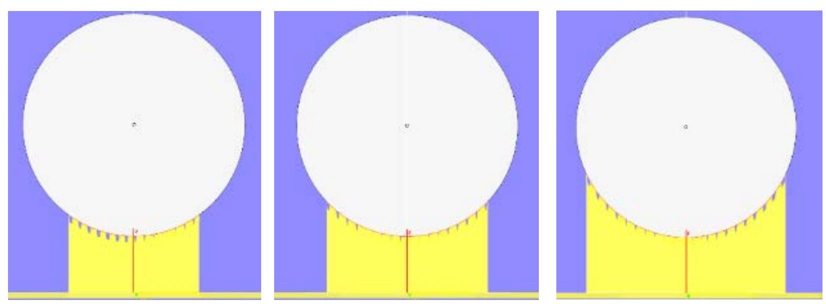
Hatch Density: For ease of powder removal, as well as support removal, a coarse support structure is favorable. In addition to aiding in the post processing efforts, reducing support structure may also slightly reduce build time since there is a decreased amount of cross section melting each layer. Although post processing efforts favor a coarse support structure, the parts themselves sometimes favor a fine support structure. Bulk melt parameters, and consequently bulk material properties, are based on material which has full connectivity and conduction to the previously melted layer. When the previously melted layer is support structure, the amount of conduction of heat away from the layer is decreased, which can cause the layer to overheat and swell. Therefore, sometimes a fine support structure can help because it behaves more closely to the optimized bulk material.

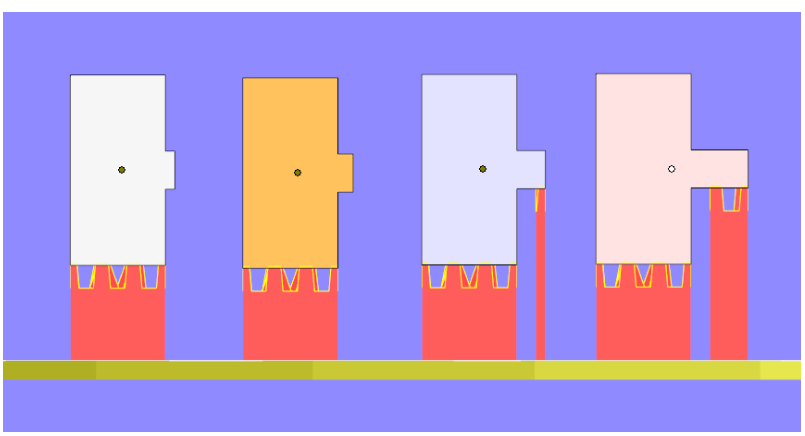




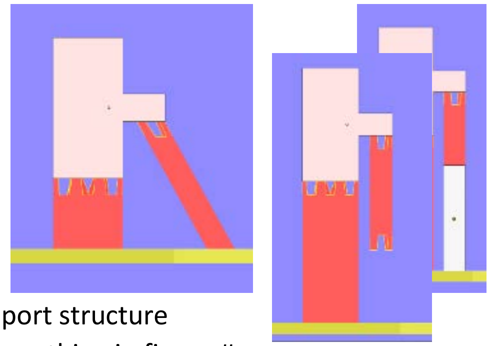
Support/Part interface geometry: Similar to the above discussion in regards to a fine support structure, it's also common to see an influence of support structure in the transitioning layers between support and bulk material. The influence can be on surface roughness, geometric accuracy, as well as microstructure and opportunities for voids or other material defects. The connection geometry between the support structure and the component can be varied to identify the optimal setting, but melt parameters of the transition layers may also need to vary in order to find the best settings.

Minimum overhang angle: A minimum overhang angle that provides consistent geometric accuracy without over-supporting curved surfaces. This is a fairly straightforward rule that is usually accurate from the machine OEM from their default parameters, but depending on the geometry the support angle may need to increase, or be allowed to decrease with the same geometric accuracy results post-build.

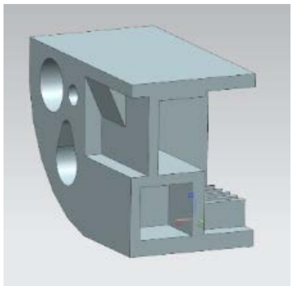




Minimum surface area: It's always a good idea to find out "how far" you can push certain geometries such as overhang sizes and hole diameters before you are required to add support structure. It wouldn't be uncommon to be overly conservative for a one-off build component, however for a component that will be produced in a high volume production setting, reducing unnecessary supports will make post processing more efficient.



Custom supports: As Additive Manufacturing designers become more and more familiar with a certain process, machine, and material, custom support structures can be utilized to increase build efficiency, post processing costs, and thermal stability. Angling supports, floating supports (such as in Electron Beam Melting), and adding sacrificial materials for thermal consistency are just a few ways customization is common.



A good option when trying to learn about support structure specifics is to create a demo part, similar to something in figure #, where different types of geometries can be built with various support parameters. The learning from this study should allow designers to create custom supports for components without relying solely on default methods.

To download a copy of this file, go to http://www.laico.com/additive-manufacturing

Layout & Orientation Considerations

Beyond support structure, there are many other considerations when building upon the internal knowledge database. Below are some important guidelines that should be considered and evaluated when making your internal design rulebook.

Optimal cross sectional “foot print”: This does not have to do with the size of the parts, but rather where the parts are building on the plate (spread out across the plate vs. minimized close to the center. For example, in Electron Beam Melting, special care should be taken in the first few layers to establish a large layer footprint perhaps with sacrificial material on the edges to push heat equally across the plate. On the contrary in laser systems, expansive footprints can sometimes induce distortion from large residual stress. In both types of systems, drastic cross section area changes should be avoided, but to what extent needs to be established internally dependent on machine and material.

Part spacing: A minimum part spacing requirement should be established so when creating a packed build layout, there is no opportunity for parts to melt together. It should be noted however that just because the parts don’t melt together, tightly packing components together can cause difficulty when removing powder, or parts from the plate.

Thin walls: Thin walls may be difficult to build in general, so determining minimum buildable wall thickness is important, in addition to which orientation those walls can be built. By orientation, not only should the overhang angle be considered, but also the angle with respect to the powder distribution mechanism.

Feature limitations: Generic feature limitations should be considered such as the smallest radius which can be achieved, the smallest hole which can be built in multiple orientations, the largest hole without support structure, the sharpest point or edge which can be produced, etc. These features may be dependent on the industry or component types most commonly built in the machine.

Scale factors: Most systems require scale factors to be applied so the parts are built slightly larger to compensate for the shrink that occurs once the build cools down. While default scale factors might be suitable, it's important to understand if scale factors can be influenced by build height, part thickness, or build layout. Some may find it necessary to scale parts individually based on development runs.

Build envelope: Generate data to prove that a part builds with the same quality, independent of build envelope location (whether it's close to the center and low in the build, or at the maximized height and distance away from the center). As the industry specifications continue to develop, it will not only be a requirement to establish geometric accuracy in all locations, but also consistent material properties throughout the buildable area. Consider this when evaluating material capability during machine qualification.

Part grouping & melt ordering: Establish consistent rules for grouping or melt-order. As machine OEM's continue to optimize their melt algorithms the grouping an ordering may be handled by the software, however if grouping and melt orders are continuing to affect material quality, it's best to establish rules so that all the designers tackle the grouping in the same way.

Part marking: It is becoming increasingly important to track pedigree through serialized parts and material specimens. Assuming that the rest of the electronic records (CAD models, software versions, melt parameters, etc.) are all being traced sufficiently, establishing a methodology to always mark parts in the same way is important when in development. Being able to link back to what build and what location a part or specimen was made in always adds to the knowledge base when trying to duplicate or troubleshoot an outcome.

Leveraging Optimization Methods

After the basic design rulebook is established, designers can now expand their knowledge into the other opportunities which exist when utilizing the Additive Manufacturing technology. Pairing the technology with optimization methods and software tools allows designers to take their AM components to the next level. There is much more to optimizing the geometry beyond using the straight output from a design tool. In order to effectively use the tools, designers must take a lot into consideration.

The geometric freedom of additive manufacturing allows for alternative approaches to be taken in part design. However the most efficient additive manufactured structures only come when utilizing optimization methods, and adding real-world AM expertise on top since the output of the optimization methods are not necessarily AM friendly. Mathematical optimization methods are well established and used across a variety of applications. The general optimization problem is an iterative method formulated to seek the best element, with regard to some criterion, from some set of available alternatives.

Three components to consider:

Design Variables: The elements that are allowed to change during analysis iterations. Design variables are typically geometric parameters such as thickness, length, or element density. Variation of these parameters changes the geometry and/or topology of the part.

Constraints: Boundaries to the available design space. Constraints are typically established by part requirements and set the criterion for a feasible solution. Many constraints may be applied, but typical structural constraints are used to limit peak stress, deflection, or mass.

Objective Function: The goal of the analysis to be minimized (or maximized). Commonly, the objective of the optimization is to minimize mass or maximize stiffness, leading to lighter, more efficient structures.

At a basic level, the optimization problem iteratively searches the set of variables for feasible solutions within the defined constraints to best satisfy the objective function. The objective function is evaluated using a numerical method such as finite element analysis. Regions of the part that are not allowed to change are designed into the 'non-design' space. These elements/regions of the part (typically interface surfaces/mandatory component features) are not allowed to change shape or topology with the analysis iterations.

Two classes of structural optimization methods are available, those used for conceptual design and those used for design fine tuning. When used in conjunction, they provide the best results. The goal of the conceptual analyses is to determine the optimal material distribution for several sets of loads cases and constraints. This is then used as a starting point for the design, as it defines the general regions where mass needs to be included to meet the defined constraints. The shapes and topologies that result from conceptual design analyses allow designers to consider unintuitive, complex regions of the design space. These optimum material distributions are not biased by traditional 'design for manufacturability' rules.

Conceptual Design Methods

Topology Optimization: This optimization method allows for individual elements to be removed from the set of design elements. In doing so, both the shape and topology of the part is allowed to change. This method is useful to determine the optimal material distribution for structural problems where a large design space is available. The most efficient material layout is determined based on user-defined design space, design targets, and constrains of the component.

Topography Optimization: This method is typically used to determine the reinforcement beads or swages for thin-walled structures. Removal of elements is not optional with this method, rather, the thicknesses of the elements are varied to generate integrated reinforcements to achieve the objective of the analysis.

Free-Size Optimization**:** This method allows the generation of optimal thickness distribution that meet the design requirements.

After the optimal material distribution is determined, design fine tuning techniques are used to make limited changes to dimensions or model parameters to further refine the design. These methods may be applied to more accurately determine the localized features of the component.

Design Fine Tuning Methods

Shape Optimization: This method utilizes shape variables to determine optimal shape variables based on design requirements. This method is effective in reducing high stress concentrations.

Size Optimization: This method finds optimal model parameters such as cross-section dimensions and thicknesses to further optimized localized regions.

Manufacturing Optimization

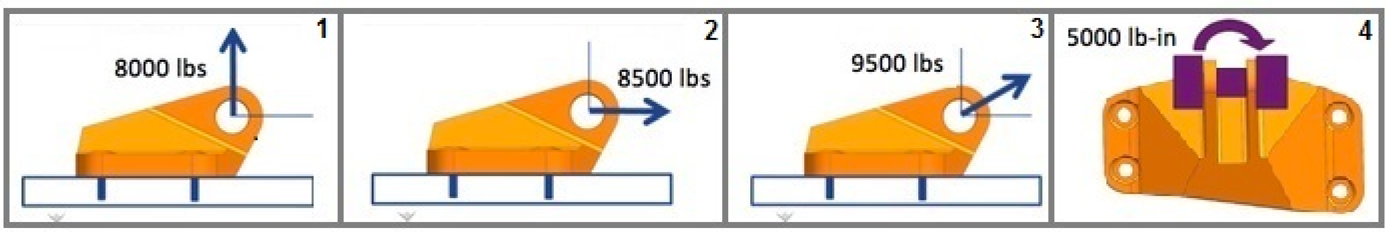
Once the detailed design is complete, the engineer must still evaluate the part within the context of the additive manufacturability rules, post processing requirements, and for ease of inspectability. By determining the constraints & limitations of the specific additive machine & process, those rules can be applied to the fine-tuned optimized design. Considerations that are available may alter orientation decisions, surface angles to reduce support structure, topology changes for post processing accessibility, as well as general stock additions for either datums or tooling to be used in the post processing steps.

Optimization Case Study

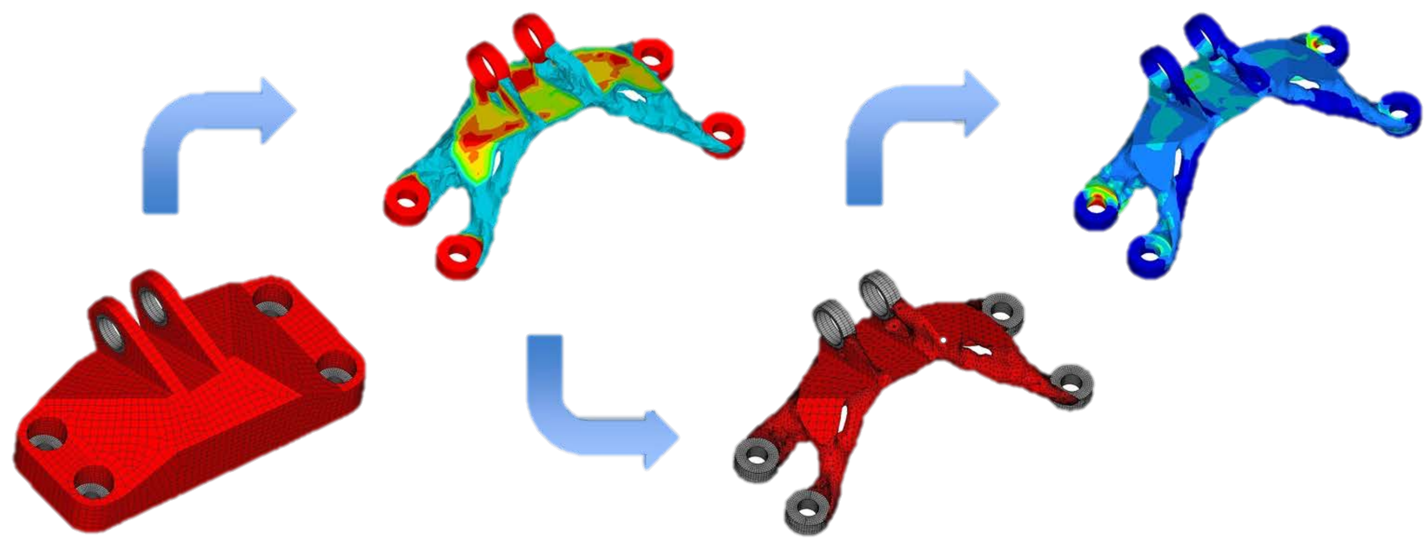
An example below is included to illustrate the new approach to design that may be achieved with additive manufacturing and structural optimization. In this case, an existing part is going to be manufacturing with additive manufacturing methods. The original part design was heavily influenced by traditional manufacturability constraints. Since additive methods have more relaxed manufacturing constraints, this part was redesigned using topology optimization.

Design Method:	***Topology Optimization***
Objective:	Minimize mass
Constraints:	von Mises Stress < 100 ksi
Design Variables:	Element density in the design space

Design Load Cases:



Topology Optimization:

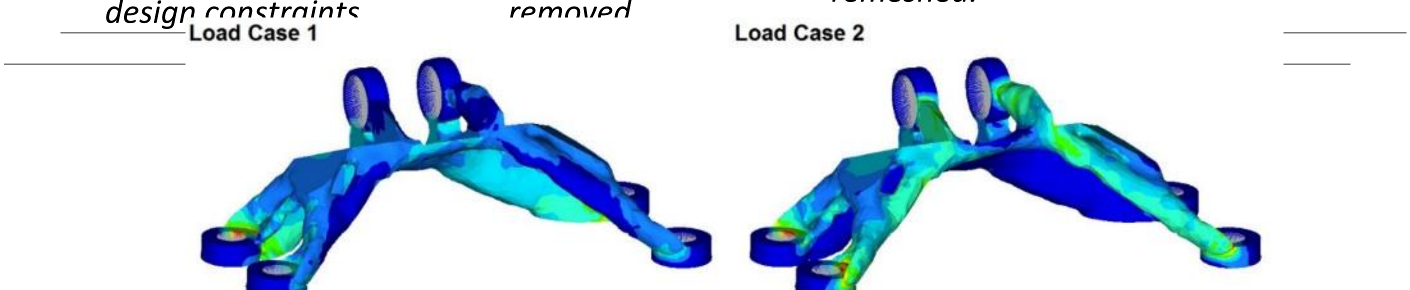


Topology optimization determines the optimal material distribution in the design space (red) for the objective, while satisfying defined design constraints

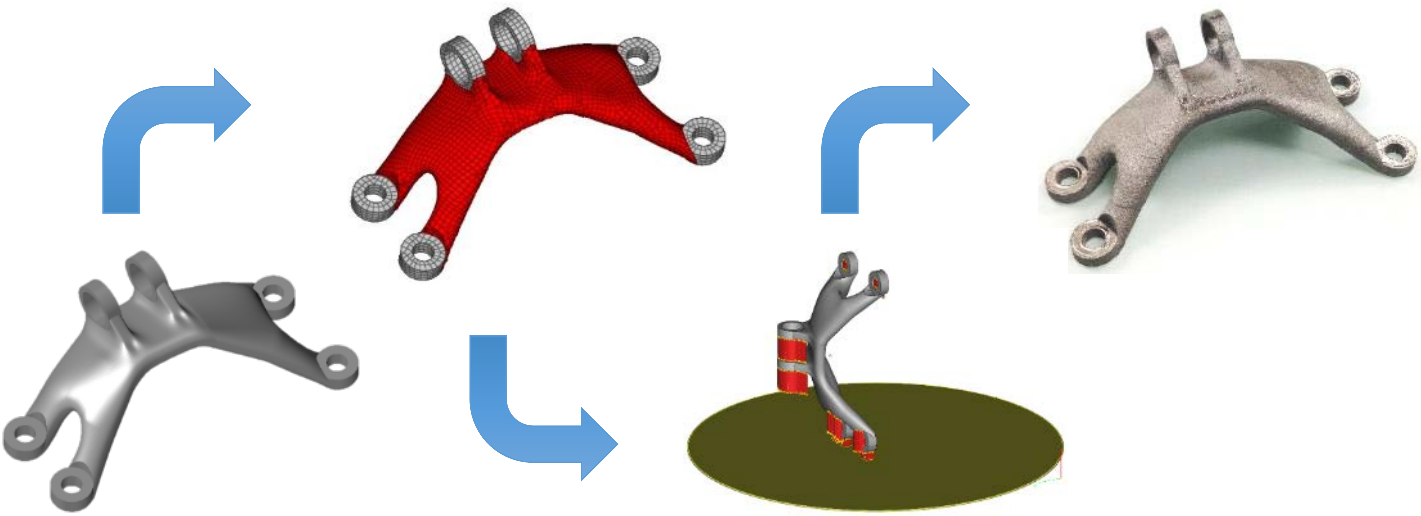
The optimization yields a distribution of variable density. A threshold density is selected to determine which elements will be removed

Elements below the threshold are removed. Elements above the threshold are considered fully dense and are remeshed.

Finite element analysis is applied to the remeshed model to verify the design constraints have been met.



Manufacturing Optimization



The raw optimized model is smoothed with NURBS based CAD tool. This removes stress concentrations while increasing manufacturability and inspectability.

The smoothed geometry is remeshed & reanalyzed to ensure the cleanup of the geometry did not affect performance.

A build feasibility analysis is performed to determine manufacturability, identify post-processing difficulties, and to estimate scale factors.

A first article is built, inspected, and compared to the build feasibility analysis. Scale factors are adjusted if the part is out of tolerance dimensionally.

The end result

Tying it all together

Whether the AM machine is making simple blocks or fully functional and topology optimized components, the AM Designer has a lot to take into consideration when constructing an AM design and build layout. The creativity and opportunities that exist with the technology can be overwhelming for a beginner, so it's important to create guidelines and to initiate best practices for the teams to follow. In addition, building demo or example parts can go a long way when growing the internal knowledge base. Once basic guidelines and limitations are understood, designers can step into a whole new world of opportunities when they consider pairing AM with design optimization methods. It is there where designs can exploit the true benefits of Additive Manufacturing, and create a component which is efficient in cost, quality, and function.

To learn more, please feel free to contact us!

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