Lessons Learned in Part Design from Topology Optimization through Qualification

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Honeywell Federal Manufacturing & Technologies is operated for the United States Department of Energy under Contract Number - DE-NA-0002839

Abstract*: Topology optimization is a powerful method in the field of manufacturing, but currently lacks any sort of guiding workflow. This paper introduces a first iteration workflow for using topology optimization as a design method within a digital manufacturing framework. Unlike traditionally designed and machined parts, topology optimized and additively manufactured parts lack definitive standards for processing and qualification. Through collaboration between designers, additive manufacturing process engineers, and Model Based Enterprise engineers, an effective workflow was developed for successfully designing, manufacturing, and qualifying topology optimized parts. Content will cover advantages, challenges, and best practices for using topology optimization as a design method for additive manufacturing. As additive manufacturing and topology optimization technologies mature, new design workflow processes, similar to those described in this paper, will become more standardized and accepted within engineering industries.*

Keywords*: topology optimization, additive manufacturing, Tosca, Abaqus, Abaqus CAE, stereolithography, STL*

1. Introduction

Though it is not necessarily a new technology, topology optimization (TO) is a rapidly developing and expanding capability that is revolutionizing processes for mechanical design. Using many different algorithm-based mathematical methods, TO is used to distribute material within a given mechanical envelope or design space based on specific performance criteria. Many Finite Element Analysis (FEA) software packages now offer TO options for creating lightweight, high performance designs. These designs are typically organic in nature, which can be difficult, if not impossible, to machine with subtractive manufacturing techniques. Recent additive manufacturing (AM) advancements and cost reductions have created greater opportunity for producing topology optimized parts.

Using a layer-by-layer approach, AM provides more freedom in designing and producing complex geometries. No longer limited by traditional manufacturing processes, part designers use TO technology to optimize parts for performance requirements. AM provides the ability to print features impossible to machine, allowing for the organic surfaces that TO produces to be realized. However, all AM processes have their limitations, especially processes associated with metals. For example, additively manufactured metal surface finish limitations make printing acceptable threaded surfaces challenging. Special aspects of AM methods can influence TO design and enhance the opportunities within TO, while specific TO results can in turn greatly expand the AM capabilities.

Though both AM and TO are already considered disruptive technologies, together these powerful tools offer unmatched advantages in time and material savings compared to traditional design and manufacturing processes. Currently, no standardized workflow or principles exist for designing and producing parts using TO and AM. This paper summarizes efforts made by simulation analysts, AM engineers, and Model Based Enterprise engineers to develop standardized processes for designing, manufacturing, and qualifying topology optimized parts using AM. This workflow was refined and improved throughout the creation of dozens of parts designed using Tosca, an optimization module built into finite element analysis software Abaqus/CAE. Figure 1 shows the entire standardized workflow for a TO and AM part. This paper, however, will focus on learning experiences from a design perspective and relationships that must be developed during the Design/Analyze stage in order to successfully apply TO in design for AM.

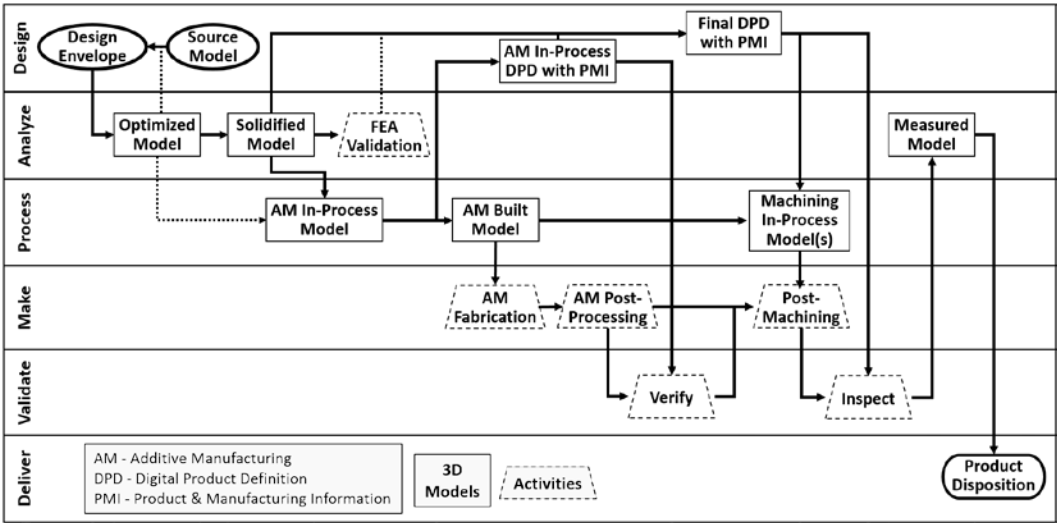

Figure 1. Novel workflow created for using topology optimization to design for additive manufacturing

2. Designing a Topology Optimized Part

2.1 Gathering Critical Design Information

The first step towards successfully designing a TO part is to identify all critical requirements. Objectives, goals, and optimization capabilities must be communicated early in the design process. This type of discussion lays the foundation for open and continued communication required throughout the design process. Typically, a traditionally-designed solid model is used as a baseline for TO processing. In an efficient workflow, this solid model as well as any associated part/assembly models and drawings will be provided. During initial set-up phase, several important questions must be addressed:

1. What is the intended function of the part during normal use?
2. What known low-likelihood conditions may the part be subjected to?
3. Are there any human factors to consider?
4. What are the optimization goals and how are they prioritized?
5. What is the allowable design envelope and what features must be maintained?

1. What is the intended function of the part during normal use? One must have a complete understanding of the design's normal loading conditions in order to properly translate them into a finite element model. Should multiple part functions exist, each must be specified during optimization setup. An example is the optimization of a titanium lifting hanger using two straps to carry a load. While this may have been the most common loading condition, there were also occasions in which the hanger might support a load using a combination of 1–5 straps. TO software will only optimize for specific loading conditions that are simulated, so a hanger that was optimized for 2 straps may fail if it is used to lift a load using 1 strap. All possible or desired application and use scenarios must be accounted for in the finite element model, which in this case is exemplified by the number and position of the straps, as indicated on the right side of Figure 2. In this case, the hanger had to be optimized for 5 different load cases to ensure structural integrity in any potential scenario. Figure 2 shows the resulting topology using different loading conditions.

2. What known low-likelihood conditions may the part be subjected to? The hanger problem also presented unique considerations for abnormal environments. Once the optimized design was finalized, additional simulations were completed to evaluate for conditions that were not included in the optimization setup. Including low probability loading or boundary conditions in the optimization setup can be inefficient, adding hours or even days to computation time with little added value. It can also skew the design process by disproportionately weighting the significance of low likelihood conditions instead of design critical, high likelihood conditions. Later in the design process, validation simulations will be completed to ensure acceptable safety factors under other known abnormal conditions. To validate the hanger design, the part was subjected to simulated loads with directional vectors angled at 45° from the direction of gravity. Simulation analysis results ensured that an acceptable factor of safety was still maintained. Additionally, buckling analyses were completed to predict conditions of structural instability. While performance under low-likelihood conditions are important to understand, part design itself

should not be driven by these types of “what if” situations.

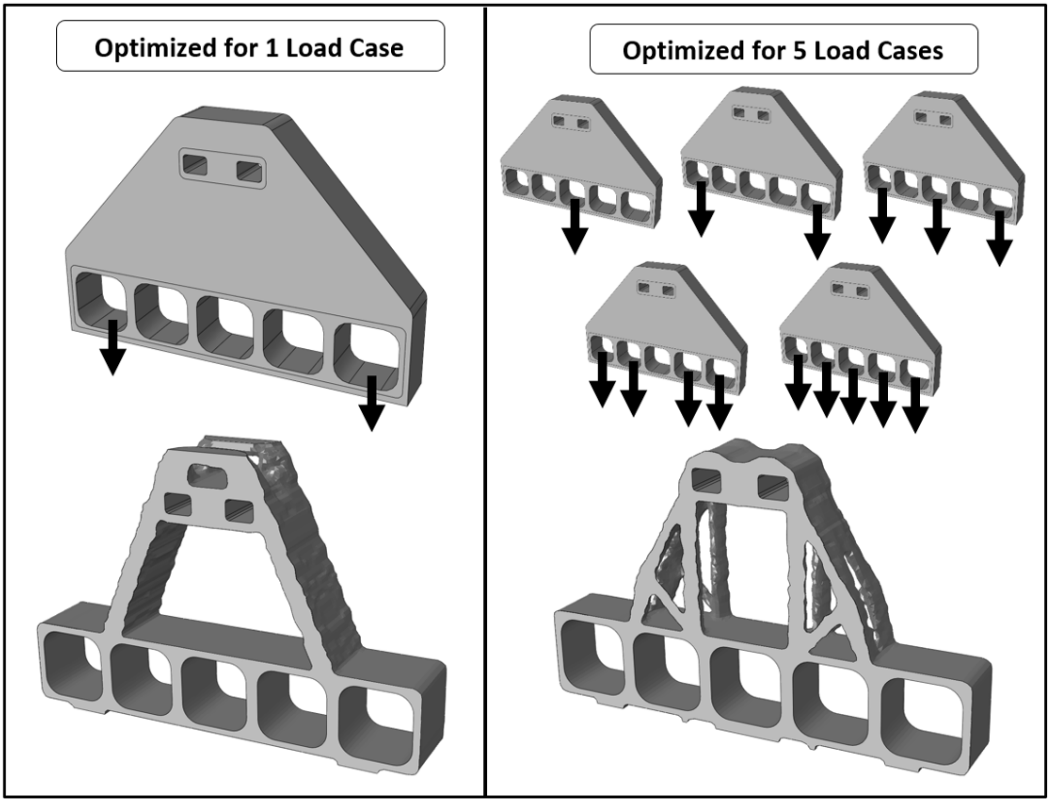

Figure 2. Results for optimizing hanger for 1 load case (left) vs optimizing hanger for 5 load cases (right)

3. Are there any human factors to consider? Another subject that is sometimes not addressed or even realized until parts have been fabricated is the importance of human factors. After the hanger design had been finalized, it was printed out of titanium. It met all critical design requirements, providing a solution that not only reduced weight, but also improved the minimum factor of safety. However, the first use of the hanger exposed the fact that the additional voids created through the TO design could mistakenly be used as crane attachment locations, jeopardizing the integrity of the system. Because this loading condition was not factored into the optimization setup, this potential human error could have resulted in catastrophic part failure. Additionally, the organic design presented a new safety concern should the user accidentally get a finger caught in one of the voids. If mistake-proofing and human factors had been communicated during the initial set-up phase, Tosca’s design constraint options could have been used to prevent these design flaws. Lattice structure could also have been used to fill areas of concern while still providing a light weight and AM friendly part.

4. What are the optimization goals and how are they prioritized? Oftentimes, objectives will include weight reduction and strength maximization. In some situations, design responses such as center of gravity or moment of inertia may play a considerable role in the final part

topology. In environmental test fixtures, the main objective may be to increase the frequency of first modal response. If weight is a driving factor, one must address the importance of material density. Part material may be driven by many factors including customer preference, test requirements, or 3D printer capabilities. For example, in the case of steel versus aluminum, a part built out of aluminum will allow three times more volume than a steel part of the same weight. Giving TO triple the volume to work with can result in very different part topologies. If possible, there can be many advantages to waiting to finalize part material until optimization results can be interpreted.

5. What is the allowable design envelope and what features must be maintained? A mechanical design envelope must be created to constrain the part to a maximum allowable volume. If a traditionally-designed part exists, it can be used as a starting design envelope or additional material may be added. Careful consideration must be made when creating the mechanical design envelope. Voids must be left to allow space for tooling and testing operations. Next level assembly parts and fixturing must also be considered to ensure compatibility with final optimized part designs. If a part is going to be printed, it is important that the design envelope will fit inside the 3D printer build volume, including the consideration of the true high-quality homogeneous build volume. Material and build plate placement limitations may vary from one AM machine to another, even if machines are the same model. The part design envelope should be evaluated to ensure it is compatible with the intended machine prior to optimization.

In the mechanical envelope there exist regions where part volume should not be manipulated nor removed. Tosca has options to control these regions by assigning them a “frozen” geometric restriction. There are a number of reasons “frozen” volumes may be used with TO:

- Bolt holes or contact surfaces that may need machining
- Areas where loads or boundary conditions are applied
- Part features for handling or storage

While these features may seem insignificant, they can make part production and handling significantly easier and can be consciously incorporated into TO modeling techniques.

2.2 Setting Up the Finite Element Analysis Model

While TO tools are not limited to FEA engineering software, a working knowledge of FEA can help to successfully use TO for design. The quality put into a TO analysis directly correlates to the quality of analysis results. If the FEA software capabilities are not sufficiently understood, the TO solution will probably not represent the real boundary and loading conditions that are necessary.

The first and most important aspect when designing with TO is the capture of the necessary stress state(s). An accurate physics model builds the foundation for which topology optimizing software will make its decisions to remove material. If a bracket is being designed with TO, every potential boundary condition and loading possibility should be considered. If one combination of loads and boundary conditions is more significant than the rest, a bias may be applied to normal and abnormal conditions. Tosca is capable of considering multiple loading condition combinations or stress states by combining results from multiple steps or even physics models to make TO material density changes. Additionally, if two loading conditions equally stress the part being optimized, but are not equally occurring in use cases, Tosca can allow for a bias to be applied to the two different stress states, and optimize topology according to applied bias.

The methods in which stress states are developed must be considered for appropriate loading and boundary conditions. Some TO software can account for plasticity or damage within a material model and monitor how plastic strain or damage develops during baseline simulations. However, this may require simulating additional steps for the part being optimized.

Because TO is an iterative and repetitive process, time can be saved by simplifying models. However, model simplification must be done carefully. Oversimplification can lead to wasted computation time running simulations on models that do not fully capture system effects for which the part may be used. Careful consideration should be taken for system or assembly factors that may affect results for optimized parts. Sometimes, to properly develop stress states in a part for TO, a full assembly must be modeled even if this creates an undesirable increase in run time.

Mesh density plays an important role when significant volume reduction is required for TO analysis. A typical good rule of thumb is to apply a three element minimum for any small feature being modeled with FEA. In order to meet this rule of thumb, the mechanical design envelope for optimization must have a mesh density fine enough to obey the three element rule and a minimum member size specification. When the design envelope is a considerably larger volume than the intended final optimized volume, or when the minimum member size is considerably smaller than the mechanical envelope, many more elements will be necessary than what will eventually be used to model the solid sections of the final optimized part. Generally, the greater the number of elements used to meet feature size requirements, the longer each TO iteration will take. Preliminary optimization runs can be used to get an approximate optimized shape, with subsequent modification to reduce the mechanical envelope while still meeting element density requirements for small features. Because this process is time consuming, some TO software offerings are creating ways to automate this process to either adaptively refine the mesh, or trim the mechanical envelope and re-mesh the model during optimization. Such features will save a considerable amount of time for TO work on large volumes with potentially small features.

Once an adequate physics model for running TO has been developed, a trial run of the model should be conducted to gather data for the determination of the TO settings. Further, not all FEA tool capabilities are able to be utilized in TO software, so a quick check should be conducted to verify that element types, material models, and solver settings are in agreement with the processing capability of the TO software.

With the trial run complete, run data should be gathered to assess job run time and parallel processing efficiency. Some physics models, depending on their complexity and linearity, will scale nicely on parallel platforms, while others will suffer from diminishing returns with parallel computing. A brief check conducted using trial run data will determine resources needed to run TO software and create an estimate of how long each TO iteration will take to complete. With iterations used for TO ranging from tens to hundreds, solver changes or model simplifications can be considered to speed up TO iterations without losing model quality or inaccurately capturing stress states.

2.3 Setting Up the Topology Optimization Model

Once the baseline FEA model has been established, the TO analysis can be created and the specific TO software settings selected. Ultimately, any TO software will use a combination of design variables, objective functions, and constraints to optimize part topology. This section will describe the model setup process while using Tosca and Abaqus CAE software solutions.

Tosca has two different algorithms for TO problems: sensitivity-based and condition-based. The differences in results given by these optimization algorithms can be seen in Figure 3. Note that the condition-based method resulted in more small members, which would require significant support structure if printed. While verification simulations predicted that both results would meet design requirements, the sensitivity-based result was chosen as the final design because it would require less support structure and post-process machining when printed. From a design perspective, the greatest differentiating factor between these two methods is in the design response options. A design response is a quantity derived from the FEA model simulation that will be used as an objective or constraint in the optimization process. The design goals will drive the selection of necessary TO design responses.

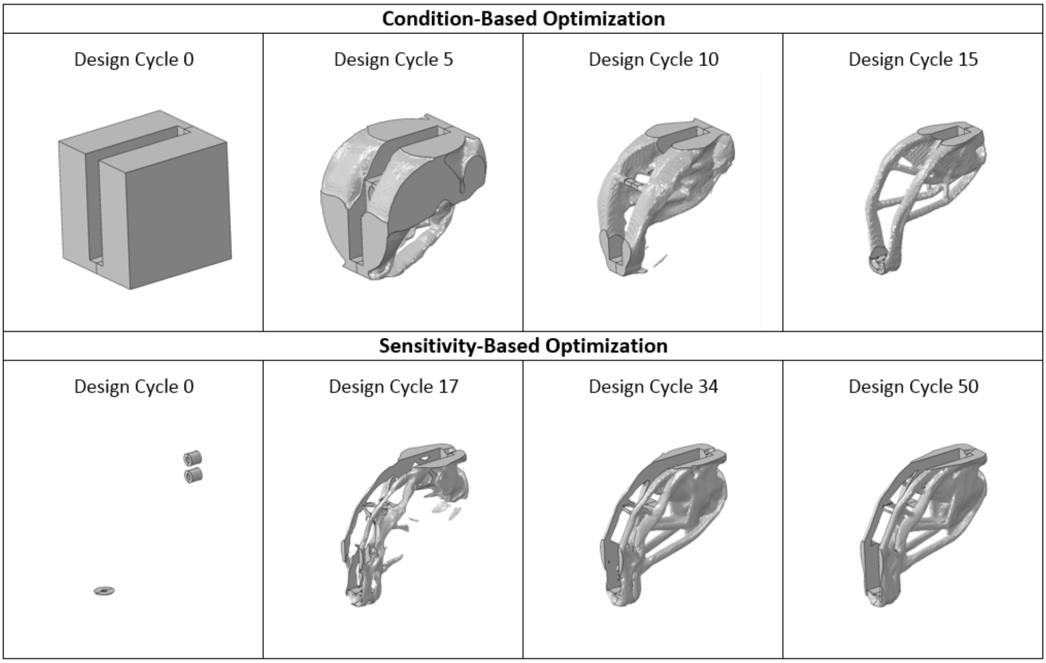

Figure 3. Design iterations for bracket using Condition-Based (top) and Sensitivity-Based (bottom) algorithms

The condition-based optimization algorithm, developed at the University of Karlsruhe, Germany (Dassault Systems, 2014, Bakhtiary, 1996), follows an iterative redesign rule, allowing only strain energy and volume as design responses. For high strength/weight reduction problems, the condition-based solver can provide solutions with a relatively quick turnaround. In these types of problems, strain energy minimization must be used as an objective function, while volume is used as a constraint to meet a specific weight requirement. Condition-based optimization tasks typically require 15-20 design cycles to reach final part topology definition. Condition-based optimization problems iteratively remove material from the design envelope until a final converged solution is met for both objective function and constraint. From a high-level, this method will appear to slowly “chew away” material until achieving final part topology. If there is flexibility in final part material, condition-based optimization allows the choice between different part topologies that will meet the same weight requirement using alternative materials. This can be advantageous in situations where small member size may present concerns for AM processing or regions of high localized stress.

With complex or multiple optimization goals, the sensitivity-based optimization algorithm (Dassault Systems, 2014, Bendsøe, 1999, Bendsøe, 2003) can be used to apply an objective function with multiple constraints. Depending on TO model complexity, sensitivity-based tasks typically require between 50-150 design cycles. Despite requiring more design cycles than condition-based optimization, this method’s greatest advantage lies in the ability to solve complex problems with multiple objectives and constraints. Sensitivity-based design response options expand to include strain energy, volume, weight, center of gravity, moment of inertia, rotation, Eigen frequency, reaction force, reaction moment, and displacement. The sensitivity-based algorithm immediately adjusts the entire model material to equal some defined initial density, potentially based on a volume constraint. It then iteratively adjusts individual element densities while trying to meet the objective function and constraints. From a high-level, this method will appear to “grow” material until reaching a final converged solution. Sensitivity-based optimization also allows for control over advanced options like density update strategy, convergence criteria, and element deletion.

The most computationally efficient method to optimize a part for strength and weight is to use strain energy and volume as design responses. Since both condition-based and sensitivity-based algorithms can support this type of optimization, it must be determined which is best to use on a case-by-case basis. Condition-based optimization may be preferable in problems requiring a design to be finalized on a short timeline. Where Sensitivity-based methods would require separate analyses to be run for each target volume, Condition-based methods remove material iteratively, allowing the use of a single TO run to consider multiple design cycles and corresponding volumes. For example, where the mechanical envelope target volume may have initially been 20%, a 25% volume may yield a design with greater structural integrity than the original target volume.

On the other hand, the sensitivity-based algorithm may be chosen for problems in which greater control over specific design criteria is necessary, such as applying a maximum member size constraint. Sensitivity-based solutions may produce smoother surfaces, and require less model post-processing time. The same analysis can be run using each algorithm if time permits, allowing for the choice of the best part design between the two algorithms’ results.

Once an appropriate optimization algorithm is selected, design responses are chosen based on optimization goals. Design responses can be a summation, maximum, or minimum value of a design region. For a problem with an objective to reduce global strain energy during a static loading condition, the design response option should be set to sum all strain energies within the design region. Care must be given to identify at which steps/loads to evaluate each design response, otherwise the design response will only be evaluated after the last step/load. Design responses can be weighted themselves, or may also be made up of combinations of other design responses and by using math operators to create combined terms.

After creating appropriate design responses, the objective function can be set up. Tosca allows for only one objective function per optimization task, but design responses can be combined or given a bias within the objective function. This is where either maximization or minimization with a design response value at the end of a specific step/load case can be designated. The optimization will stop when convergence criteria for the objective function and element density delta criterion are met.

Design responses not used within the objective function can be applied as constraints. Depending upon the optimization algorithm being utilized design responses can be constrained to a specific value or as an inequality (e.g., constraining an Eigen Frequency to a value of greater than or equal to a selected frequency). If trying to meet a weight requirement and increase the moment of inertia of a part, the volume can be constrained to be less than a percentage of the mechanical design envelope and the moment of inertia can be designated to be greater than a threshold value. Sensitivity-based optimization analyses allow for multiple constraints while Condition-based problems can only constrain volume. Multiple constraints can provide a more targeted response, but also add additional computation time. Therefore, constraints must be chosen carefully in order to capture the desired optimization goals.

Finally, geometric restrictions can be applied to limit or drive certain design characteristics. Tosca offers a geometric restriction called “frozen area,” which can be applied to declare non-design space within a mechanical design envelope. Certain design features are best achieved through machining operations after AM processing, for example threaded bolt holes. Additively manufactured metal surface finish limitations make printing acceptable threaded surfaces challenging. Typically threaded features in an AM build will be machined after the printing process, thus the finite element model is simplified by removing the actual threads of a hole. When only the face of the hole is frozen, the optimization process may remove too much material around the hole making it impossible to machine threads later. It is recommended to freeze a cylindrical cell around any bolt holes with a diameter at least 30% greater than the basic thread diameter. Figure 4 shows an example when freezing a cell is more advantageous than freezing a face. Shown on the left, when only the face is frozen, the resulting topology contains a wall that is too thin to drill the hole and machine threads. This issue can be solved by freezing a cell instead, as shown on the right. From an analysis perspective with surface contact problems, freezing cells has been proven more successful than freezing contact surfaces. For example, an optimization analysis involving non-linear contact failed to converge when only the face of a contact surface was frozen. When a thin cell layer around the contact surface was frozen the new analysis solution converged.

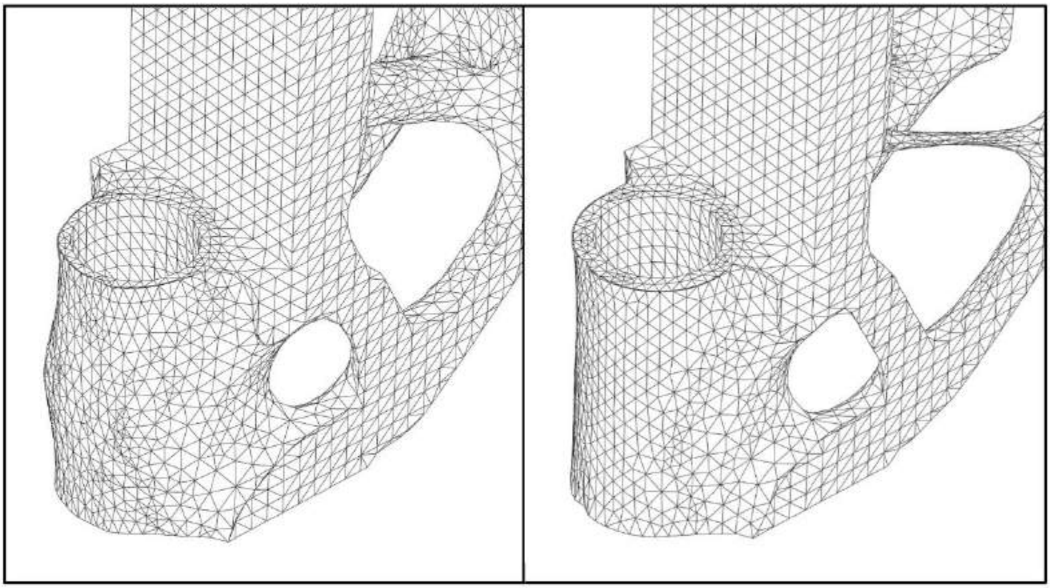

Figure 4. Freezing only hole face (left) vs. freezing a cell surrounding hole (right)

Tosca allows geometric restrictions to be applied in order to control the maximum or minimum allowable member size. Using a minimum size restriction can be extremely useful in adhering to minimum build size limitations of 3D printers. A general rule of thumb dictates at least three elements should span through the prescribed minimum size restriction. The plate shown in Figure 5 is part of a fixture used to clamp two parts together during a welding operation. When optimization was completed without a minimum size restriction, it created many small features too difficult to print, some even having disconnected regions (left panel of Figure 5). If the part was successfully built, there may still be a concern that small members would break during normal use. A minimum member size restriction can be applied in these situations to eliminate the creation of small members, as shown in the middle panel of Figure 5.

Another type of geometric restriction, demold controls, can be useful for incorporating other manufacturing considerations into the optimization process. Geometric restrictions can be applied to create a final design that can be forged or cast with a mold. In the same fixture plate example, a stamping demold control could be used to create a waterjet-cut design option (right panel of Figure 5). Another useful geometric restriction is symmetry. Tosca offers plane, rotational, point, and cyclic symmetry geometric controls. Symmetry geometric restrictions prove useful for designing parts with center of gravity requirements or specific bolt patterns.

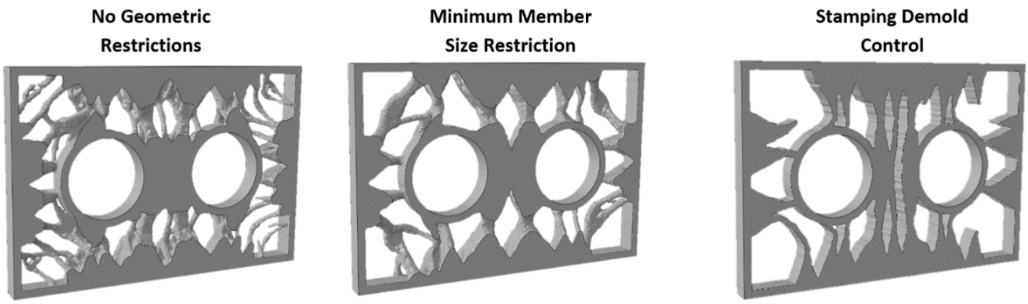

Figure 5. Optimized plate using different geometric restrictions

2.4 Design Feedback

Using TO as a design tool can result in unpredictable, organic shapes. Sometimes, the mathematically optimized solution may be very different from the customer's optimal solution. The Feedback Step is a term created to represent the potential loop that may need to be added to the design process with TO. It is necessary to assess whether the optimization process has correctly captured all of the inputs required for a successful design. It can also be helpful in ensuring accuracy in loading and boundary conditions, human factors, manufacturing concerns or limitations, support structure, and abnormal loading safety factors.

TO is a unique tool that can help verify that the loading and boundary conditions applied to a physics model are correct, or within acceptable limits. This is especially true when considering a combination of boundary conditions. The shape and solution produced by TO can reveal details that may have been missed or not modeled properly.

The Feedback Step is a good opportunity to perform a status check using images, 3D models, or even a prototype of the optimized solution. While there is still considerable work to be completed, it is a good time to determine whether the optimized solution and shape adequately satisfy the requirements. Sometimes this check can even reveal new requirements that were unknown at the initial intake meeting, such as member size requirements, overlooked features, or access locations that need material removed. Gathering this information during the Feedback Step can reduce the number of simulations required and the time and costs associated with engineering design.

Depending on the mechanical envelope's shape, the actual producibility of the final design may not be apparent. During the Feedback Step, the TO results can be assessed and used to make production decisions. Decisions like waterjet versus 3D printing, or AM build orientation and layout, can start to be made based on the optimized solution's shape. Once these manufacturing decisions are finalized, some may be incorporated into the TO process during a potential second series of runs. Tosca includes multiple geometric restriction tools associated with manufacturing methods—casting, molding, waterjet, and 3D printing. These restriction tools can be applied and used to improve the final design during a second round of TO.

Many TO software developers are working on next generation TO features and improvements. Features like support structure minimization and deformation mitigation will greatly reduce build times and material waste. Support structure strategy is typically applied after the design has been finalized. As these new AM constraints become available with TO software, they can be included during the Feedback Step.

The Feedback Step will also provide verification that final optimized topology will meet the general use requirements, revealing possible new handling or functional concerns. This information can be used to determine whether the optimization setup needs to be modified to account for these concerns. In some cases, the optimized design may be found to be unacceptable for reasons like human factors or manufacturing considerations. The hanger example provided a situation in which the organically defined voids created a human factor concern. Changes for a new analysis run may be as simple as freezing additional material or as complicated as creating a brand new mechanical design envelope and loading conditions.

2.5 Part Definition Format

The next step in the design process is verification simulations, and before those can take place, the final part definition format must be decided upon. Developed by Chuck Hull, the inventor of 3D printing, the STL file (3D Systems, 2017, 3D Systems, 1989) is the final resulting output for most current 3D topology optimization tools. To extract the surface definition from topology optimization results, some tools, including TOSCA, have advanced settings which allow the user to set surface smoothing parameters to better control the STL surface file representation. Depending on the use case for the optimized part being designed, an STL file definition may be acceptable, especially if the part will likely be sent directly to a slicing software before it is 3D printed. Despite its historical popularity, there are several inherent downsides and inadequacies to using an STL file as the surface or part definition:

- STL files define individual triangles, not surfaces, and do not explicitly define surface connectivity
- The STL file type has no known standard, the original definition as proposed by the developer had no units, all positive values, and was single precision
- STL files can be difficult to modify and complicated for creating geometric dimensioning and tolerance (GD&T) rules
- Organic STL surface files can be quite large, and cumbersome to manage within other engineering modeling software

The number of challenges associated with using an STL file, both for design and manufacturing, may require the creation of a solid part definition of the optimized part using a reverse engineering software tool like Evolve or Space Claim. This process occurs within the Analyze/Process stage of the standardized workflow shown in Figure 1. There are several advantages to creating a solid part definition:

- GD&T definitions are easier to create on solid geometry
- Part modifications for post-print machining operations are easier to create
- The file is easily transferable to an assembly model
- The organic surfaces can be represented with defining equations (non-uniform rational basis spline or NURBS) instead of multiple disconnected triangles

- Solid files are easier to create by using finite element meshes—useful for part validation simulations

The downstream design benefits of using a solid file, as opposed the STL file definition, will greatly outweigh the added design cost and validate the decision. Even as the STL file quality and surface extraction capabilities continue to improve for TO tools, inherent inadequacies of the STL file type will still exist, challenging the engineers responsible for the GD&T and design modifications necessary for successful manufacture of a part.

2.6 Verification Simulations

The solid definition of a part will differ from the true TO solution because of changes made during the STL smoothing and model solidification processes. New stress risers, STL surface errors, and volume changes may exist and must be calculated before the design is finalized. Once the final geometric definition has been established it is important to run verification simulations to account for these potential unseen changes, and to catch any potential problems. This FEA validation activity can be seen in the Analyze stage of the workflow diagram shown in Figure 1.

The main purpose of the validation simulation step is to confirm that the design criteria have been adequately met. This step in the design process is also a convenient step for any final simulation work that might model scenarios outside of the boundary and loading conditions for which the design was originally optimized. Some of these scenarios can include low probability loading conditions or thermal extremes. If it was not included in the original optimization, this step is also an appropriate time for an eigenvalue analysis to detect if problematic natural frequencies or mode shapes exist.

Lastly, once the final geometry has been defined, some simulation tools exist to provide part distortion predictions for additively manufactured parts. Depending on the specific AM process, design features and the build direction can cause excessive distortions due to thermal strains. Simulation tools can help approximate these distortions and inform the support structure strategy in order to minimize them. Simulation tools exist to help predict stresses developed during other non-AM machining or casting processes. In general, manufacturing simulations completed at this time can help predict potential problems downstream in product manufacturing.

3. ADDITIVE MANUFACTURING

While there are many types of AM, this section focuses specifically on challenges faced in printing metallic TO parts using powder bed fusion. Two terms will be used to distinguish between different conditions of an additively manufactured part. When a part has been printed but not undergone any additional processing steps, it is considered to be in the “as-AM” condition. After support structures have been removed and additional machining operations are completed, it is then in the “Processed” condition. Each of these conditions requires different drawings and inspection processes. This section will explain lessons learned in preparing a part for AM via powder bed fusion, post-processing, and material quality considerations.

Several pre-processing steps must be taken before an optimized part can be built using AM. These processes span between the Design, Analyze, and Process stages shown in Figure 1. STL smoothing and extracting capabilities can often leave surface finish irregularities that make the "as-AM" condition unacceptable as the final part design. Additionally, "as-AM" parts lack adequate precision for holes and counterbores in order to meet tolerance requirements. If a solid part definition was not created, manual modifications must be made to the STL file. This can be a time consuming process even when advanced STL editing tools, like Magics, are used. For this reason, solid model definitions should be created whenever possible to allow for modifications to be more easily made. There are several reasons that the final model must be modified before it can be printed:

- Extracted STL files can leave dangerously sharp edges if printed directly
- Raw printed metal parts make for poor contact surfaces in assemblies
- Rough printed surfaces usually do not meet machining tolerances required for post-processing
- Porous and partially sintered printed contact surfaces can be cause for contamination concerns

For these instances, milling and machining post-processing can help metal AM parts meet tolerance requirements. AM fabrication and post-processing occurs during the Make stage of the workflow diagram shown in Figure 1. Before problematic AM surfaces or features can be machined during post processing, they must first be identified prior to printing. Any machined or milled feature will require that additional volume be added to the AM part definition prior to printing. Drawings specific to this "as-AM" condition must be created before machining processes can be completed. When all machining operations are finished, the part is in the "Processed" condition and can move onto final inspection steps.

There can also be a strategic approach to build plate layout, machining operations, and support structure. If multiple parts will be printed at once, layout and location of the parts can be critical. Material quality can vary between different locations on the build plate or in build height. If these differences cannot be avoided, they must be included and evaluated in a finite element model to understand their effects on part performance. Organic topology optimized parts may also be difficult to fixture for machining operations. In these cases, it may be advantageous to orient the part such that certain features can be machined while it is still connected to the build plate. Significant strategy can also be applied to support structure, a necessity to support overhangs in an AM TO part. Custom support structure can be designed to improve ease of removal, surface finish quality, minimize thermal distortions, and reduce material waste. After a part has been built, it is removed from the build plate and cleaned using media blasting.

All AM parts will inherit residual stresses due to thermal effects associated with AM. As each subsequent layer is built, additional thermal energy is added to the top of the system, while the bottom of the system is still cool. There are still many unknowns when it comes to understanding exactly how these processes affect material quality and part performance. Test specimens should be built with every AM build and undergo material testing to help qualify the build and collect material data. Accurate AM metal material models can be built from this data. If the build orientation for a part has been identified, additional simulations can evaluate the part using physical test data to predict how anisotropic properties due to AM processing affect part performance. Additionally, extreme thermal distortion may cause the part to fall outside of dimensional tolerances. Simulation toolsets that can accurately predict and compensate for AM process thermal effects are under development, and should eventually be integrated into the standard workflow for AM TO part design.

4. PART VALIDATION

Topology optimized parts are often organic in nature, lacking clearly defined datums for dimensional inspection and validation. Two potential methods for inspection are light-scanning and CT-scanning. These processes will occur during the Validate stage shown in Figure 1. Light-scanning technologies can capture high resolution and precise measurements of AM parts in less than 5 minutes. This data can be overlaid on the original part model that was used to print the AM part in order to determine whether the part meets tolerance requirements. Figure 6 shows an example of this comparison using light-scanning data captured by the GOM ATOS III Triple Scan. In this figure, red areas show where the printed part is out of tolerance with the virtual part model. This method offers many benefits in speed and accuracy, but is limited by line of sight and performs poorly with shiny surfaces. CT-scanning is an effective method for inspecting internal features in a part. Unlike light-scanning, this method can identify material quality defects and voids, but can also be time consuming and expensive. In the future, part validation and inspection processes will continue to be refined and improved.

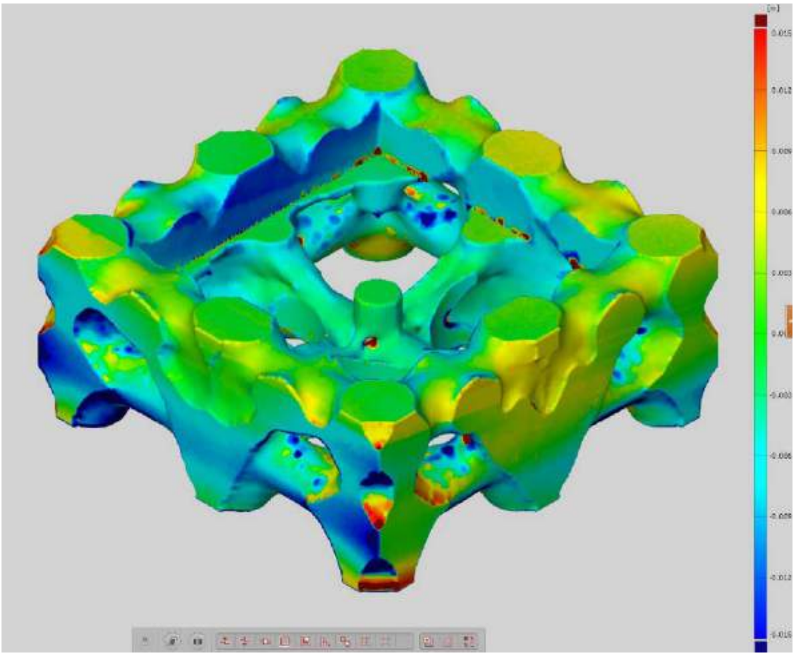

Figure 6. GOM ATOS III Triple Scan results for AM part overlaid on original part file showing tolerance discrepancies

5. CONCLUSIONS

Many challenges still face TO before it can be accepted as an efficient design method within digital manufacturing. These challenges reside not only in the optimization software, but in the unknowns with AM, and limitations of standard STL output formats. One of the greatest obstacles in designing with TO is the challenge of applying GD&T principles to the final part. The STL file format output by present day optimization software packages makes geometric manipulation and GD&T very difficult. Easy conversion of TO output into a solid model definition will be a key factor for TO technology to become an effective alternative to traditional design processes. The organic features TO produces require AM as means for production, but until AM processes can be fully controlled and material properties completely characterized, TO will be limited to small quantities and low consequence parts. The discovery of each of these challenges was met with constructive learning experiences and in turn, design workflow process improvements.

Despite the technical challenges associated with using TO for design for AM, it can still offer many advantages—development time reductions, parts mathematically optimized for specific physical performance criteria, and novel methods for creating parts with safety-conscious human factors. Traditional design methods require designers to iteratively design and test prototypes to enhance part performance. TO allows this process to be iteratively automated and reduce costs associated with engineering labor hours. A test fixture was recently designed, built, and tested in just 25 days using TO and AM. Furthermore, TO is not only being used to design high performance parts, but also for making low consequence fixtures and tools easier and safer for operators to handle. As AM technologies in polymers and metals continue to mature and become more available, and parts considered too difficult to produce become producible, TO will become a more commonly used tool for improving part design.

Future work for AM parts designed with TO will focus on refining the standardized workflow shown in Figure 1 and improving Digital Product Definitions. New documentation, similar to ASME Y14.5M, will identify standards and best practices for product definition of AM designs. Engineers must apply these new standards to the design process, and continue to expand AM material property databases and AM process modeling. Work must also be made to identify efficient and effective software tools capable of creating solid definitions of optimized parts from STL outputs. Some tools like SolidThinking Evolve, ANSYS SpaceClaim, and Dassault Systemes **3D**EXPERIENCE can assist with solid part definition but are still time consuming and inefficient. To satisfy the design demands of Aerospace and Automotive industry, TO software will also need to expand to capture dynamic, high-frequency, and multi-physics environments.

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7. Acknowledgment

Honeywell Federal Manufacturing & Technologies (Honeywell FM&T)

U.S. Department of Energy