香港中文大學
The Chinese University of Hong Kong

MAEG5160: Design for Additive Manufacturing

Lecture 19: Topology Optimization for Additive Manufacturing (TO4AM)

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Lecture 19: Topology Optimization for AM

This Lecture provides a synopsis of algorithmic TO methods without detailed math, including Bidirectional Evolutionary Structural Optimization (BESO), Solid-Isotropic Material with Penalization (SIMP), ground-structures, and Level-Set Methods (LSM). By summarizing these methods, practical DFAM tools are developed and their associated challenges identified; in particular, the challenges inherent in the specific TO method, and those that occur when TO methods are integrated with AM manufacturability constraints.

Two fundamental philosophies exist for TO integrated DFAM: namely, *methods that modify TO outcomes to satisfy AM manufacturability requirements*, and *methods that retain the TO structure, and add features as required*. Both philosophies are presented in detail and summarized in the context of their applicability to commercial AM design, and with reference to emerging AM technologies and methods. A brief case study is presented with a focus on commercial best practice for AM topology optimization for a high-value non-stationary aerospace component using topology and parametric optimization.

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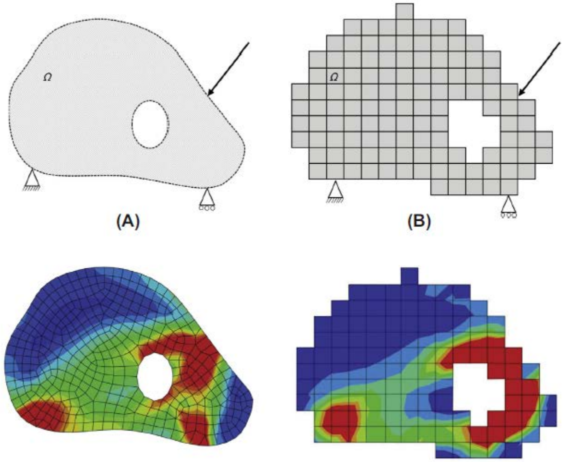
1. Topology optimization methods

1.1 Basic TO methods

In practical terms, TO refers to the identification of efficient distributions of material for a given engineering function. This function is typically structural - although it may refer to heat transfer, fluid flow, or any measurable physical outcome - and is referred to as an objective function, *O*. This objective must be satisfied subject to specific design constraints and within a specified physical domain, referred to as the design space, *Ω*. This design space defines the allowable external volume of the solid material, and includes any internal voids required for interaction with other systems, as well as fasteners and assembly hardware. The material distribution must avoid defined failure modes or undesirable states, specified as constraints. The challenge of topology optimization has been an active research problem for over a century, and numerous distinct solution strategies have been proposed. This review focusses on proposed TO methodologies that have found strong industrial application, as well as those showing promise for commercial and research DFAM activities, specifically Michell truss, ground structures, discrete (voxel) methods, and level-set methods.



Generalized representation of TO problem (A), whereby a distribution of material is sought to optimize some objective function, *O*, (typically minimizing compliance) while avoiding identified constraints (often deflection) within an allowable design space, *Ω*. The problem is typically discretized with a voxel field (B), however this discretization fundamentally alters the associated structural response.

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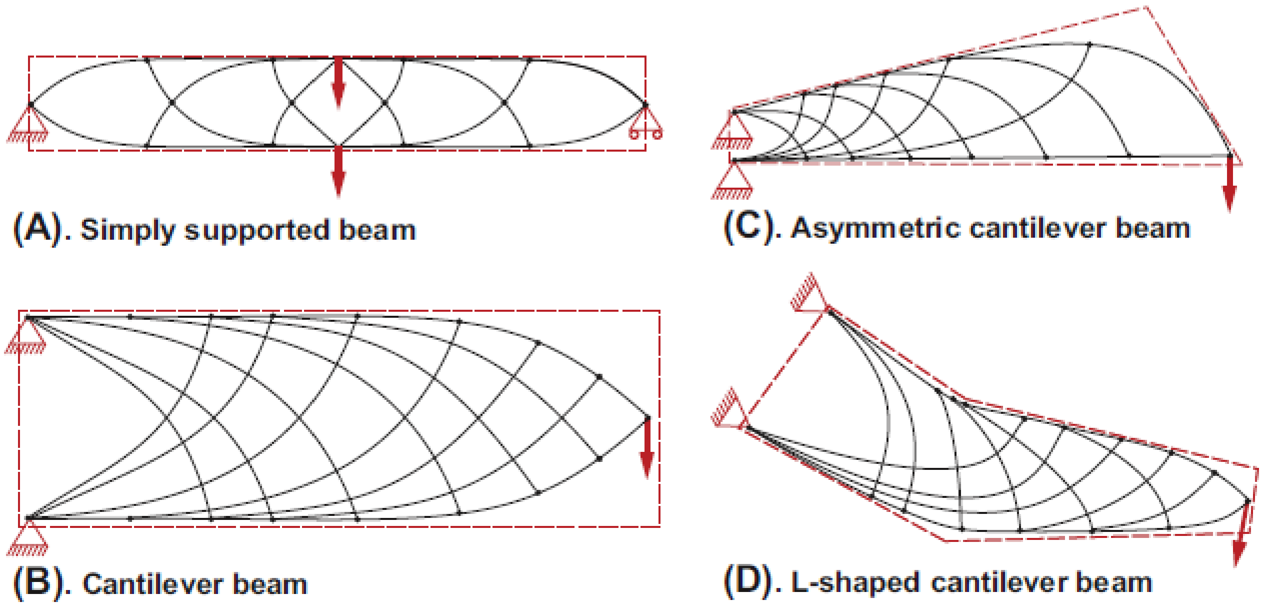
1.2 The Michell truss

The contributions of Michell in the early 1900s represent a seminal founding work in the field of TO. Michell proposed that a deflection-limited planar structure of minimal mass could be generated by aligning truss structural elements along vectors of principal strain. Michell proposed solutions to planar structures: more recently these outcomes have been extended to accommodate asymmetry and L-shape geometry. The Michell truss method has been extended to 3D structures and has been applied as a DFAM tool to accommodate AM manufacturability requirements nowadays.



Solution forms for the Michell truss TO strategy, including simply supported and cantilever beam as well as solutions with irregular design space (red dashed line).

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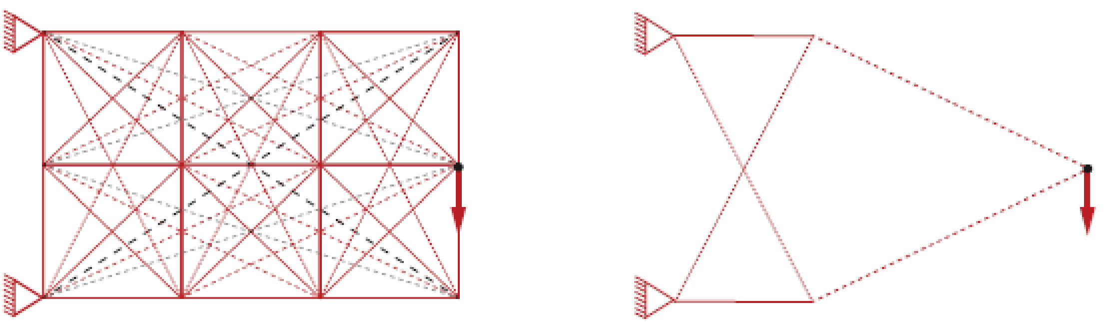
1.3 Ground structure

Ground-structure methods rely on a predetermined truss structure assembly in two-or three dimensions. This predetermined truss is often based on a self-tessellated unit-cell of connection elements, as well as permutations of node interactions. External loading is then applied, and the local strain of connection elements is assessed by numerical methods. Unit-connectors that inefficiently contribute to the associated objective function are iteratively deleted from the structure until only high efficiency elements remain. Ground structures are technically robust and have provided a reference by which to compare the convergence of other TO methods; however, the number of truss permutations associated with non-trivial design domains can result in relatively low computational efficiency.



(A). Initial ground structure (B). Optimized structure

Representative solution for two-dimensional ground structure strategy indicating (A) ground structure with multiple connective elements (identified by unique line markings) and, (B) optimized structure based on a subset of these connective elements.

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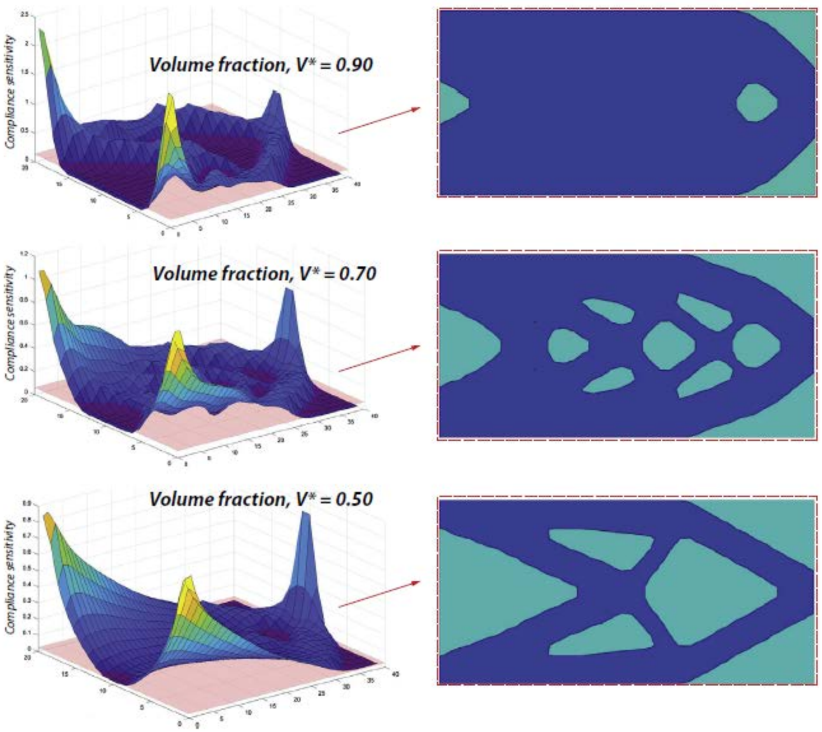
1.4 Level-set methods

Level-set methods represent the structural boundary between solid and void by some explicit mathematical expression. Various methods exist for defining this expression. One such method is to represent the sensitivity of material removal from the design domain in a closed-form function. By intersecting a plane with this sensitivity function, a level-set representation of the optimal geometry is obtained. Level-set methods enable significant advantages by allowing a mathematical definition of structure boundary and have been demonstrated for 3D geometry and for numerous physical phenomena. Despite the opportunities inherent with the level-set TO strategy, it has received relatively sparse attention from the research community and extensions of this method to AM applications represents a strategic opportunity for DFAM researchers.



Level-set TO strategy applied to 2D cantilever beam for various volume fractions, V*.

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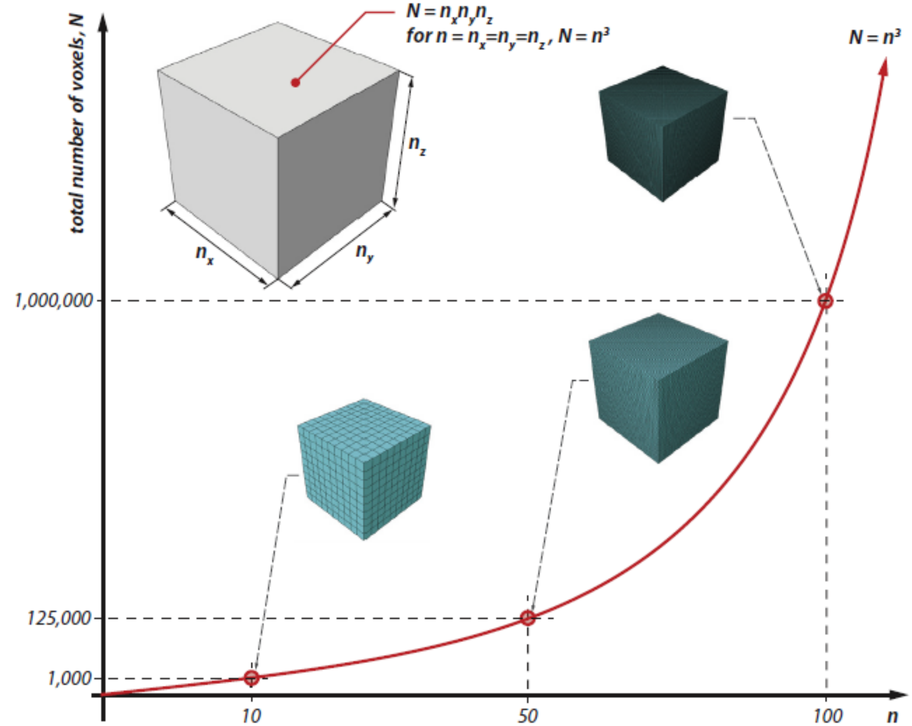
1.5 Discrete (voxel) methods

Commercially applied TO strategies are typically based on a discrete representation of a continuum of interest. Although any geometric discretization may be acceptable, discretization to square or cubic geometries is common - hence the reference to these strategies as voxel methods. The continuum design domain is typically discretized by n_x, n_y, n_z voxels in 3D space, resulting in a total of N unique voxels. Numerical methods are then applied to this voxel array to assess the state of stress and strain at individual voxels as well as to assess the associated performance measures, typically structure mass and deflection. Of the available voxel TO methods, BESO and SIMP dominate the literature.



Voxel discretization of continuum design domain. This discretization is subject to the curse of dimensionality, implying that the total number of voxels, N, increases exponentially with n.

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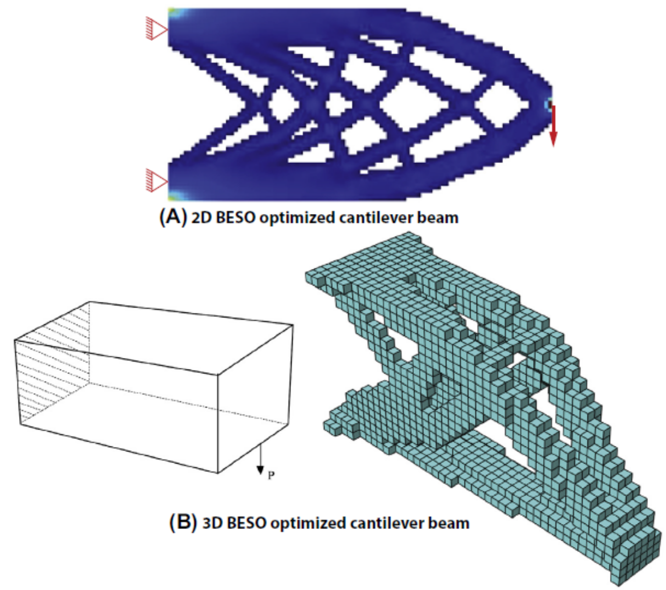
1.6 Bidirectional evolutionary structural optimization (BESO) methods

The Bidirectional Evolutionary Structural Optimization (BESO) method of topology optimization progresses by an initial application of a numerical analysis to a voxel discretization of the available design space. The results of this analysis are then evaluated by a representative characteristic, for example stress or energy density. Based on relative values of this characteristic, discrete voxels are either *added or removed* such that the strain energy is minimized for a specific volume fraction constraint, V^*. The structure iteratively evolves from the initial form to a more efficient topology until some convergence criteria is achieved. This method accommodates control factors including the allowable rate of evolution, ER, and a filter radius, rmin, to control undesirable solutions. The BESO method has been implemented in both hard and soft variants, whereby the soft variant avoids discontinuities associated with zero density voxels. The method is applicable to a range of objective functions of relevance to commercial engineering challenges including thermal and vibrational problems. BESO is well documented and numerous publications provide guidance on maximization of TO outcomes for a given computational resource. Robust, open-source code is available, making the BESO method a capable platform for the development of commercial code and for research contributions on the application of TO as a DFAM tool.



Representative BESO solutions implemented with (A) open-source code for cantilever beam in 2D and (B) an example of a 3D implementation

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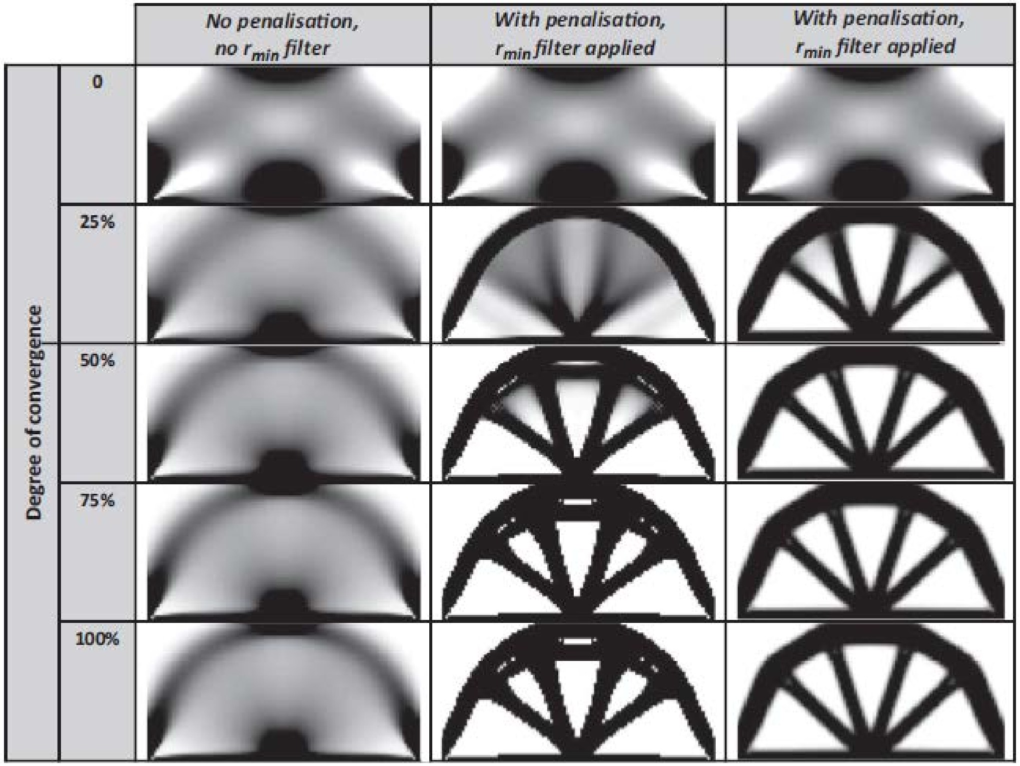
1.7 Solid isotropic material with penalization (SIMP) method



Representative SIMP solutions presented for various degrees of convergence with varying control parameters, including the effects of penalization and filter radius, r_{min}.

The dependence of the TO outcome on the associated control parameters. For example, figure on the right indicates several design solutions with common boundary conditions and loading solved with varying SIMP control parameters, resulting in varying topological solutions. This outcome demonstrates that, as for BESO, SIMP is not guaranteed to identify a global optima and the specific solution generated is a function of the associated input parameters. However, much research and practical guidance is available that provides strategies to assist in the systematic identification of high performing optima. One practical method is to iteratively solve the TO problem while parametrically varying the input parameters of interest. This approach, sometimes known as extension, is useful and readily implemented; however, it is an exhaustive search and thereby compounds the required execution time.

By their fundamental nature, discrete TO methods result in geometric discontinuities and roughness at the void/solid boundary. Various methods have been proposed to algorithmically accommodate these challenges, including local mesh refinement and local geometry smoothing. These methods potentially enhance geometric outcomes but can be computationally expensive, can fail to provide technically robust solutions and may be incompatible with commercial documentation requirements. For these reasons typical commercial best practice requires that parametric optimization strategies are applied to the TO outcomes.

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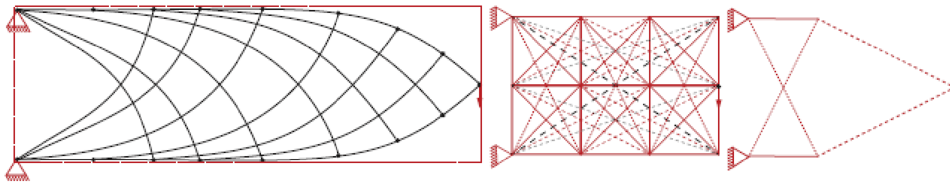
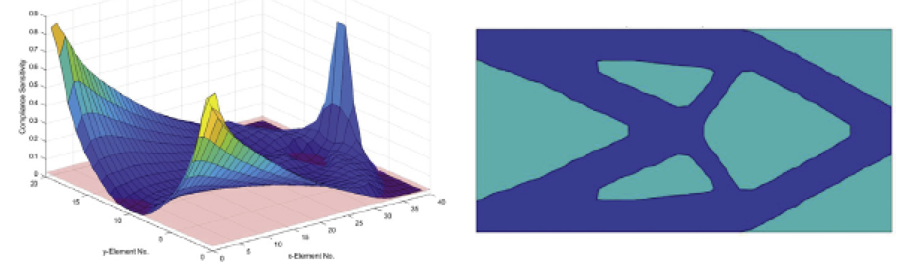
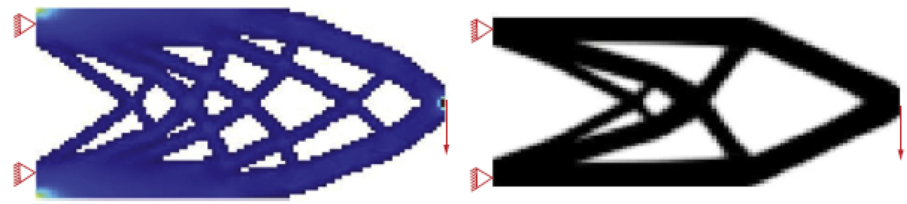
Below figure represents feasible solutions of Michell truss, ground structure, level-set and voxel methods (BESO and SIMP) for a point loaded cantilever beam. From this data it is apparent that in practical terms the generated solutions enabled by these methods are equivalent. This outcome may seem surprising given the extensive debate within the research community on the relative merit of the available TO methods. For the practicing designer with a mandate to effectively deploy TO for the identification of efficient geometries, it is sufficient that the design team select a TO method that suits their specific preferences. In addition, they must be aware of the limitations inherent in the TO methods in general, as well as specific challenges associated with the selected TO method. The following section summarizes current research and commercial best practice applications of TO in the specific domain of AM.



(A). Michell truss optimized cantilever beam (B). Ground structure optimized cantilever



(C). Level-set method optimized cantilever beam



(D). BESO optimized cantilever beam (E). SIMP optimized cantilever beam

A comparison of the solutions generated by the TO reviewed here suggests that, (despite ongoing debate within the research community) for the practicing engineer, there is little practical difference in structural insights enabled by Michell truss, ground structures, level-set, BESO or SIMP.

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2. Opportunities for TO applied to AM

Although topology optimization has been an active research area for over a century, its practical application had been reserved to a relatively small group of engineering optimization specialists. More recently, and in particular since the development of the robust and generally applicable TO methods above, topology optimization has found increasing application by generalist engineering practitioners and has become well integrated within non-specialist commercial engineering design tools.

A particular challenge associated with the commercial utilization of topology optimization is the potential incompatibility between TO outcomes and associated manufacturing constraints, especially for traditional manufacturing methods. Although, as discussed previously, the description of AM as constraint-free manufacture is incorrect and misleading, AM does enable the direct manufacture of high complexity geometry and is therefore often more compatible with the outcomes of TO methods than traditional manufacture. This synergy between TO and AM has spurred a range of commercial applications of TO for AM as well as associated DFAM research contributions and TO integrated DFAM tools, including:

- accommodation of specific AM manufacturability constraints
- allowing systematic compromise between TO outcomes and AM manufacturability
- methods to predict and mitigate the computational costs of TO simulation.

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2.1 TO integrated DFAM tools

There exist significant challenges in developing all encompassing definitions for AM manufacturability. These challenges exist because AM failure modes are often subject to complex underlying phenomena that are challenging to predict, stochastic in response, and are validated by limited experimental data. Nonetheless, AM manufacturability constraints have been defined for a range of potential failure modes. The development of TO integrated DFAM tools has progressed significantly, resulting in a useful body of research, and commercially useful methods for integrating AM manufacturability requirements within TO outcomes. However, there remains much opportunity for the development of advanced TO integrated DFAM tools, as is demonstrated by the following summary of current approaches.

Of the many applicable DFAM failure modes, *the potential limit on inclination angle* is the most commonly understood measure of AM manufacturability, and is the most commonly implemented within TO integrated DFAM tools. Several such tools have been presented within the literature that intend to modify a planar TO outcome such that allowable AM inclination angle constraints are satisfied. These DFAM tools provide useful design insight but they remain limited in the potential DFAM failure modes that are explicitly accommodated, and they are not necessarily transferrable to 3D structures.

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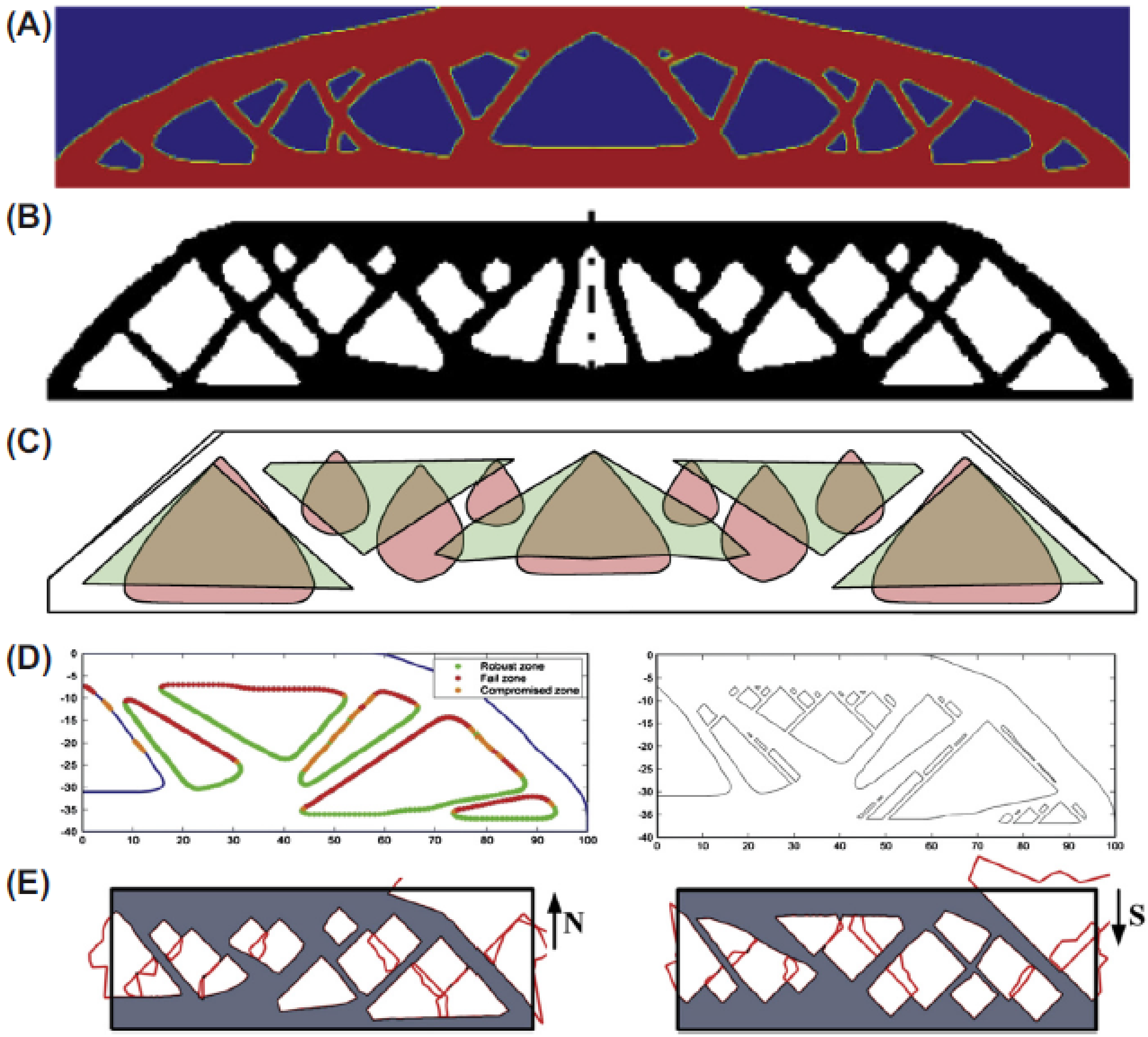

TO integrated DFAM tools that intend to modify a planar TO outcome such that allowable AM inclination angle constraints are satisfied.

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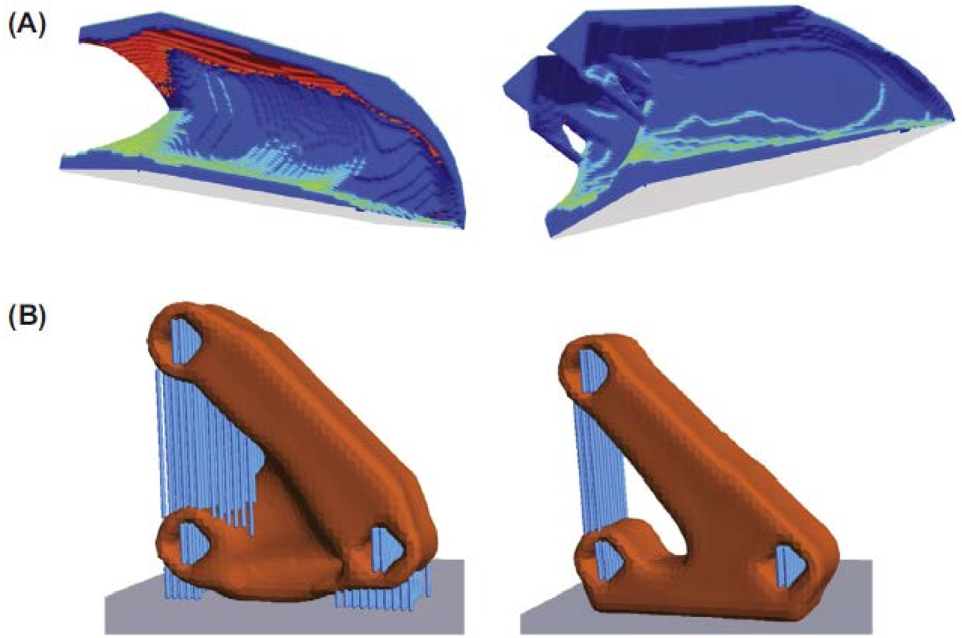
Fewer TO integrated DFAM tools that can accommodate 3D space fields exist than for the equivalent 2D scenario; however, innovative methods have been proposed in the research literature below. These methods are primarily based on the avoidance of specific inclination angles: note that some of the proposed 3D methods utilize a diagonal voxel field (equivalent to a 45 degree angle) to represent the allowable inclination angle and cannot be modified to accommodate alternate inclinations. However, more advanced methods are emerging that can accommodate integrated requirements for support structure optimization, including combined requirements for support-free inclinations, as well as methods to minimize the overall volume of support material required.



TO integrated DFAM tools that accommodate AM inclination angle constraints in a 3D space field to optimizes the standard TO outcome (left) for advanced AM manufacturability (right), including (A) restriction of allowable overhang, and (B) outcomes that minimize support volume

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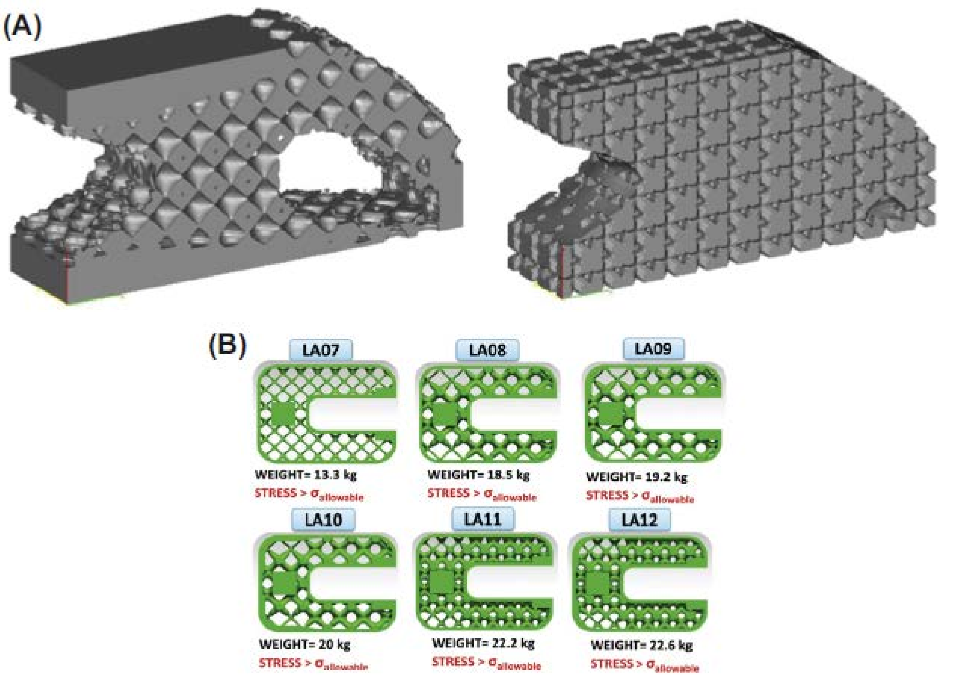
Furthermore, methods that accommodate AM manufacturability constraints by the application of self-supporting internal trusses have been proposed for 2D and 3D scenarios, as shown below. Despite their inherent commercial value, relatively few DFAM tools exist that accommodate AM manufacturability constraints. The existing tools reported here utilize only inclination angle and, to a lesser extent, minimum feature size as the measures that characterize manufacturability. It is apparent then that significant opportunities exists in the design of TO strategies that accommodate DFAM constraints. In particular, existing methods do not accommodate temperature field as a TO constraint; however, the avoidance of excessive local temperatures is critically important for high-value product manufactured with thermal AM systems.



representative survey of TO methods that utilize cellular infill geometry to accommodate AM manufacturability limits

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2.2 Compromise between TO outcomes and AM manufacturability considerations

As for all manufacturing technologies, AM presents a series of unique technical manufacturability challenges; for example, minimum feature size, self-supportable inclination angle, thermal conductivity, and material entrapment. However, TO outcomes are typically more compatible with the manufacturability limitations of AM than with traditional manufacture. In response to the synergy between AM and TO, numerous TO integrated DFAM tools have been proposed, and this field remains a highly active area of research and commercial innovation. These strategies can be classified as either strategies that modify the TO optimization outcomes such that AM manufacturability constraints are satisfied; or, strategies that retain the optimized TO geometry but provide additional material, modified processing or active support structures in order to satisfy AM manufacturability. *Strategies that modify TO outcomes to satisfy manufacturability constraints are advantageous for applications that intend to be implemented algorithmically*, as they generate output topology that can be directly manufactured without requiring additional support or geometric post processing. These strategies compromise the structural optimality of the manufactured topology in favour of direct manufacturability. For scenarios where *manufacturability is less important than overall structural efficiency of the manufactured product, and for components that are not strictly net shape* (for example structures that include some post-AM machining), *methods that include additional supporting geometry to retain the optimal topology may be preferable*.

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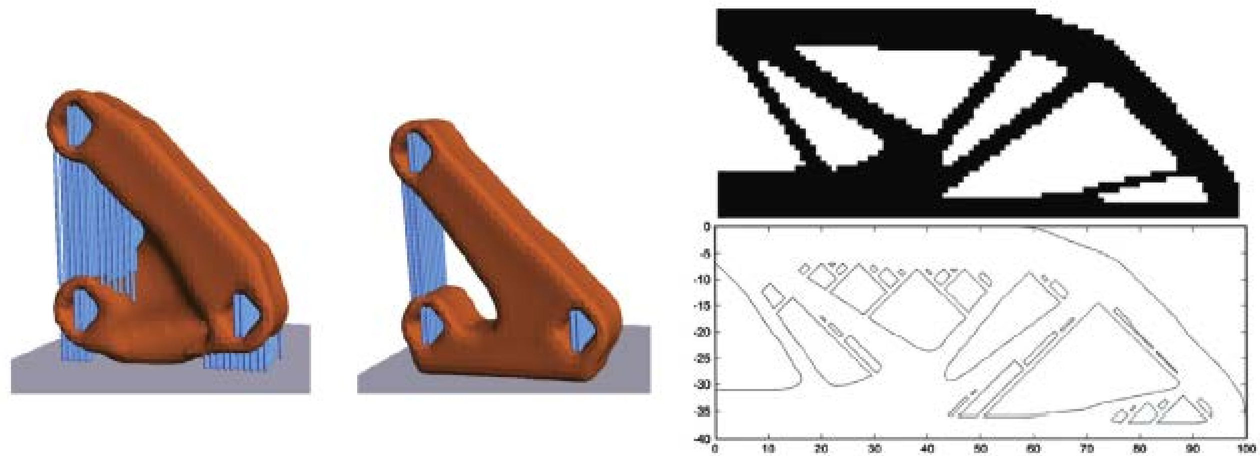

(A). TO outcomes modified to enable AM (B). TO outcomes retained

Example of TO integrated DFAM tools that: (A) modify the TO optimization outcomes to satisfy AM manufacturability constraints, and (B) retain the optimized TO geometry

The former strategy tends to be of interest to theorists who intend that manufacturability constraints be accommodated directly within the TO algorithm. The latter strategy tends to be the focus of commercially motivated designers, where it is understood that post-processing is required, and that additional material removal is typically less important than structural efficiency of the delivered component. The majority of TO integrated DFAM tools presented in the literature favour modified TO outcomes for optimal manufacturability rather than structural efficiency of the manufactured component. It is apparent that there remain significant commercial and research opportunities for the development of TO integrated DFAM tools that retain structural efficiency.

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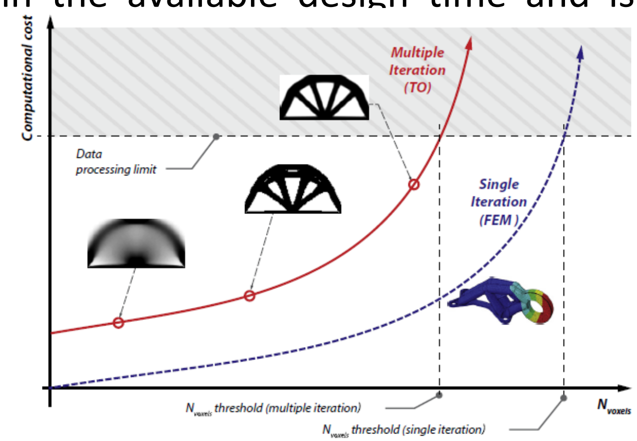
2.3 Challenges associated with computational costs of TO simulation

A fundamental technical challenge associated with the practical utilization of TO is the compounding of computational complexity as a function of associated problem size. This challenge is often referred to as the curse of dimensionality, whereby a linearly increasing problem size can rapidly become prohibitively expensive to solve. In fact, the curse of dimensionality is exacerbated for the TO methods, as these TO strategies must numerical solve a finite-element problem in an iterative manner. Specifically, TO strategies apply numerical analysis techniques to solve for the local structural field variable (for example peak displacement). Numerical methods such as the Finite Element Method (FEM) can solve this problem for generalizable geometry, boundary conditions and loading; however, FEM is dimensionally inefficient, even for single iteration solutions, and with a linearly increasing number of voxels, N, computational cost exponentially increases to values that exceed the data processing limit of the available computational hardware. For TO methods, this phenomenon is exacerbated as the numerical solution is iterated to allow convergence on a specific topological solution. Pragmatic design strategies that utilize TO methods must accommodate their inherent computational inefficiency. For example, charts such as below of computational cost versus number of voxels can be utilized to define the feasible limit on the allowable number of voxels within the solution space based on the practically allowable computational cost - this approach can reduce the risk of failing to generate solutions within the available design time and is demonstrated in the case study later on.



Simulation data indicating solution time versus number of voxels, Nvoxels. Computational cost increases non-linearly for a single iteration numerical analysis. For TO methods, computational costs are exacerbated as multiple iterations of the underlying numerical analysis are required to allow convergence on a specific TO solution. With increasing Nvoxels, computational costs rapidly exceed the technical data processing limit of the available computational hardware.

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3. Parametric optimization

The optimization methods identified above provide insight into efficient methods to generate solutions for explicit design scenarios, either by reference to closed-form solutions, design precedent, or topology optimization. These optimization methods are often highly efficient in identifying globally optimal structural topology, but due to imperfect assumptions or limitations of the solution method, may result in suboptimal refinement of the local geometry. For these scenarios, parametric optimization provides a complementary optimization method. Parametric optimization refers to techniques that optimize some objective function (typically a single value representation of desired performance) in terms of the parametrically defined control factors that represent local geometry. Parametric methods allow optimization of these local geometric variables by various methods including brute force and sequential optimization methods.

3.1 Brute force methods

Brute force methods, also known as exhaustive search refer to optimization methods that assess solutions for various permutations of the design space, in this case the parametrically defined control factors. Once the specified permutations of control factors are assessed, they are compared in terms of the relevant objective function to allow identification of high performing solutions. To increase their effectiveness, systematic brute force methods have been proposed, for example, full-factorial design of experiments (DOE), whereby all feasible permutations of a particular design space are assessed. To reduce the dimensionality of full-factorial DOE, partial-factorial DOE methods exist that assess some subset of the full-factorial data without losing insight into efficient parametric solutions.

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3.2 Sequential optimization methods

Sequential optimization methods differ from brute force methods in that the results of previous evaluations are used to inform the selection of future evaluations, potentially reducing the number of solution iterations required to converge to the optimal solution. Extensive research exists on these iterative optimization methods and numerous algorithms have been proposed. Of the available algorithms, gradient and Nelder-Meade simplex methods will be discussed in more detail as they provide solutions to a general category of problems, are well documented in the literature, and are readily applied to commercially relevant design problems.

Gradient methods evaluate some objective function and associated rates of change (gradient) with respect to the parametric variables of interest. Based on the local gradient, parametric variables are then selected for the next solution to be evaluated. The step size is modulated by an experientially selected learning rate. This rate may be tuned according to the observed rate of change of the objective function: too low and convergence may not occur, too high and local optima may be overshot. Gradient methods are simple to implement and are robust in enhancing performance in the region of a local optima. Acquisition of the local gradient can be computationally expensive as the effect of each control factor must be evaluated where each evaluation requires an additional numerical analysis.

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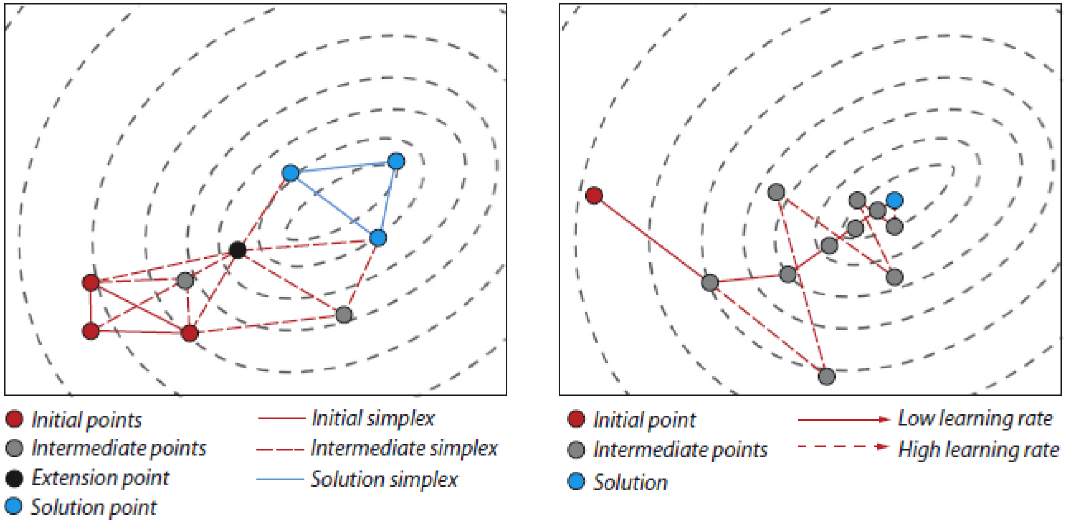
Nelder-Meade simplex methods are an industrially useful class of optimization methods that are gradient free. The method involves the initialization (usually arbitrarily) of a simplex of potential solutions. The simplex solution with lowest performance is deleted, and a replacement solution is then generated, typically by a sequence of reflection, extension and subtraction. Reflection involves moving from the deleted point to the centroid of the remaining solutions and then continuing this trajectory for the same distance again. If this solution is superior to any other existing solution, extension of this trajectory is applied. Conversely, if this solution is the least optimal of the existing solutions, the trajectory is reduced to a value half-way to the identified centroid, known as subtraction. These methods have proven to be remarkably effective in the optimization of complex industrial problems, and as the optimization method is gradient-free it has the advantage of reducing the number of numerical evaluations required per iteration.



Schematic representation of Nelder-Meade simplex methods (left) and steepest descent gradient methods (right) applied to an objective function in two dimensions. Both methods provide a mechanism to converge on local optima, but once converged are not capable of identifying neighbouring optima.

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3.3 Practical application of brute force and iterative methods

Although brute force methods often receive dismissive reviews within mathematically focused optimization literature, they do provide important advantages for the pragmatic outcomes required in commercial engineering practice. These advantages include solution parallelization, robustness to flawed analysis, and robustness to discontinuous solution space. For brute force methods, the intended simulation permutations are independent and are known *a priori*. Consequently, multiple computational simulations can be evaluated concurrently, either in parallel on a specific workstation, or by delegating simulations across multiple computational resources. This opportunity for solution parallelization is not available for sequential optimization methods as the associated solutions are not independent. Consequently, brute force methods present an important computational opportunity, especially for engineering enterprises that have access to the computational resources necessary for simulation parallelization.

A significant challenge to the automated optimization of engineering systems is associated with the robustness of parametric models. Parametric models typically include numerous control factors that interact in complex ways that can be difficult to predict, including states that are not numerically robust. Furthermore, numerical models require that these geometries are compatible with finite element meshing tools, further increasing the potential for flawed simulation outcomes.

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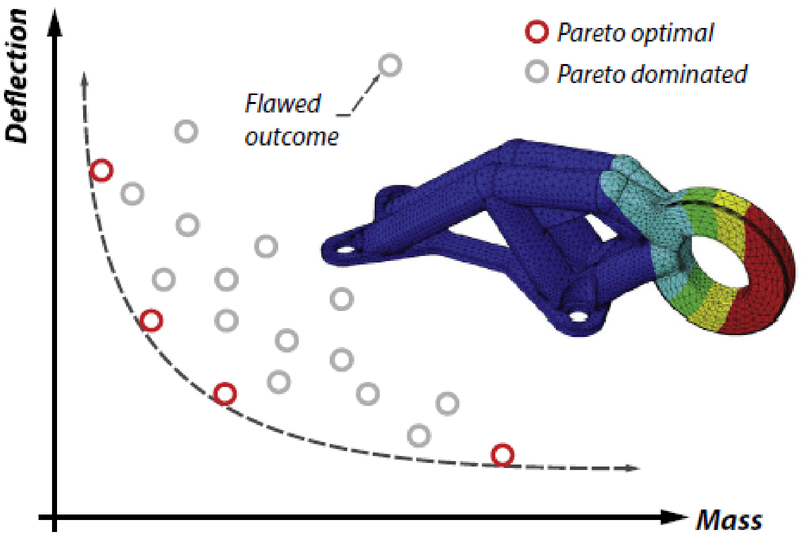
Brute force methods are robust to the flawed regeneration of the parametric model: such a flaw will simply result in a failure to generate a solution, or the generation of an incorrect solution. Neither of these results will contaminate the results for other permutations scheduled to be assessed. Conversely, sequential optimization methods are not robust to flawed parametric regeneration and will either terminate the optimization process, or will attempt to iterate with flawed data, resulting in incorrect convergence. Similarly, brute force methods are robust to discontinuities within the allowable solution space. Furthermore, where control-factors are ill-defined, the brute force DOE can be modified to omit these solutions, thereby eliminating the cost associated with a failed or invalid solution execution. From a practical point of view for commercial application of optimization methods, this is possibly the most significant imperative toward the use of brute force methods for models that have uncertainties in robust regeneration.



Parametric models ideally should generate robust geometry and finite-element mesh for any feasible parametric input. These flaws are technically the fault of the design team; however, for non-trivial design scenarios, it can be challenging to ensure that parametric models are robust for all feasible input states.

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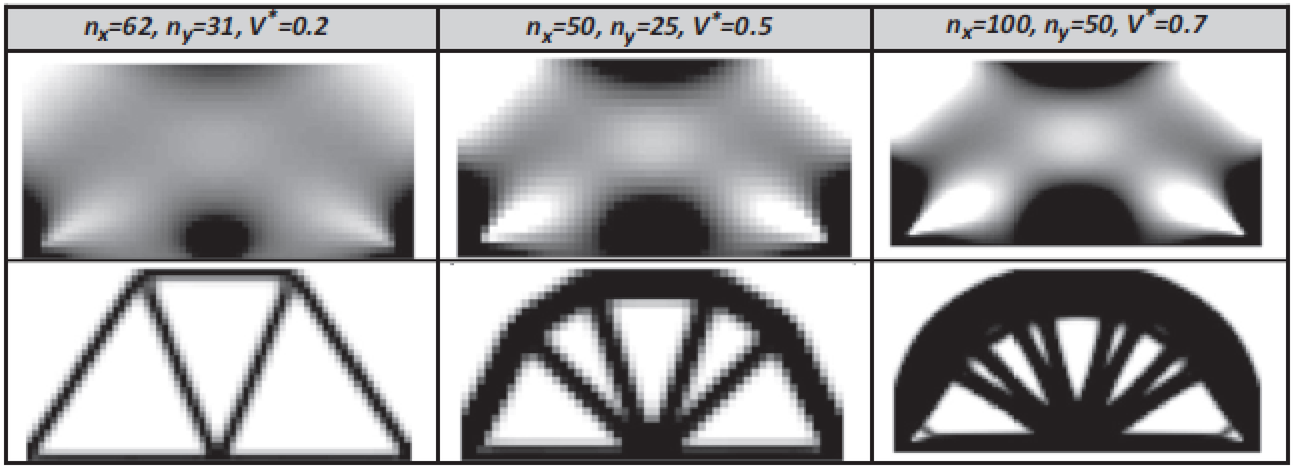
4. Topology optimization and generative design (BC2AM)

Topological optimization provides a profound opportunity for the generative design of engineering systems that are subject to sophisticated design requirements. For example, the outcomes of figure below indicate a range of potential solutions for a compliance limited structural design subject to specific loading conditions. These topological variants are generated by manipulating the control variables associated with the number of voxels within the design domain, n_x and n_y, and the intended volume fraction, V*.



For a common boundary condition, a range of candidate topologies are generated for varying number of voxels, n, and volume fraction, V*. Results are reported for intermediate (upper) and final convergence (lower). These topologies can provide the basis for generatively designed structures.

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Despite the significant commercial opportunities for TO in enabling generative design, there exist significant barriers to its implementation as a commercial DFAM tool. Commercial best practice in this space involves the use of TO for the generation of optimal topologies, which are then manually parametrized prior to production. This outcome allows the benefits of TO and parametric optimization to be integrated within the design process, as well as allowing the designer to add value from their experience and intuition by manually determining elements of the design; however, this manual intervention is not compatible with the autonomous implementation required for generative design. Specific research opportunities exist for methods that can autonomously extract a parametric representation directly from the TO outcome, as well as methods that can smooth the TO outcome such that is can be directly fabricated without the geometric discontinuities inherent to the voxel representation. The motivation of these methods is to enable robust AM outcomes to be achieved algorithmically from a specification of the functional boundary conditions (BC), therefore the acronym BC2AM may be useful in describing this emerging field of DFAM research.

4.1 Automated extraction of parametric data from TO outcomes

Commercial imperatives require that production geometry be parametrically defined. As illustrated by the examples presented in this chapter, TO outcomes include geometric features that are not directly feasible for manufacture and require subsequent refinement. Consequently, a strong commercial motivation exists towards the automated extraction of robust parametric data directly from the TO results. Despite this opportunity, there exists few robust research outcomes in this space.

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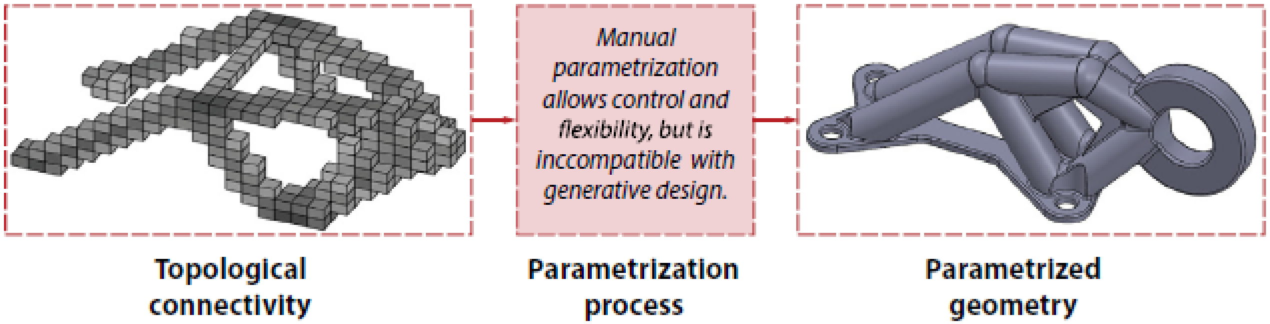
Figure below conceptually demonstrates a commercial challenge to BC2AM implementation. The TO outcomes provide robust insight into efficient geometry, but to be assessed with gradient optimization methods and for production documentation, a parametric representation is required. Commercial best practice is to manually parametrize these structural elements by inspection; however, algorithmic tools that can assist in this parametrization process are much required for commercial practice.



Conceptual representation of parametrization techniques that are typically implemented manually, thereby providing an opportunity for the development of algorithmic DFAM tools.

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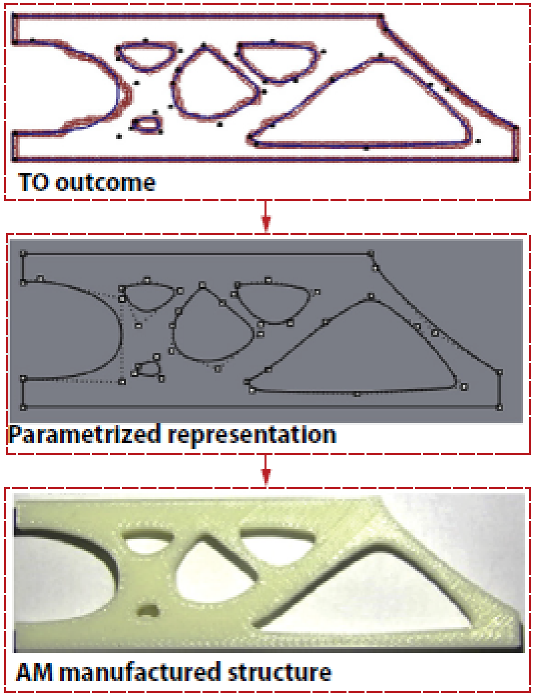
An alternate method observed in the literature involves the extraction of representative splines from a smoothed representation of the discretized solid boundary (Figure below). This method is not directly compatible with 3D structures but does indicate the potential for such DFAM implementations to enable automation of practical AM design workflows, especially as is associated with generative methods. These methods appear to have received little research attention in the DFAM relevant literature: an omission that is potentially due to the multidisciplinary nature of the underlying research required to execute this significant DFAM opportunity.



A method for extracting parametric data directly from the TO outcome.

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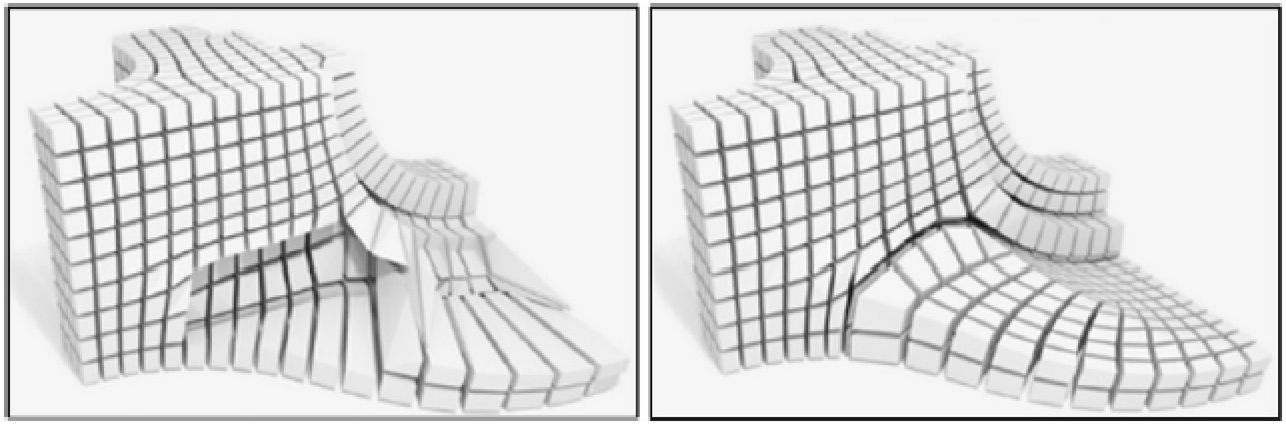
4.2 Smoothed TO outcomes

Topology optimization typically results in discontinuous data that is not directly compatible with AM manufacturability requirements. In order to achieve AM compatible outcomes algorithmically, it is required to modify this non-smooth data. Various methods have been proposed to achieve this BC2AM outcome. These methods include smoothing of the discretized TO outcome, dynamic re-meshing of the TO design domain such that resolution is enhanced locally as required, and methods that overcome singularities such that the discretized representation is geometrically conformal.

These methods provide useful DFAM outcomes, but, as for the automated extraction of parametric data, little published data is available for formal application of these methods to achieve BC2AM outcomes. Again, this limitation is potentially due to the multidisciplinary research inputs required and provides a significant commercial and research opportunity for those capable of integrating mesh smoothing methods from the computer science domain to the practical requirements of commercial DFAM tools.



Methods of increasing the conformance of traditional hexahedral mesh (left) with a less distorted meshed solution (right)

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5. Case study: optimization of high-value nonstationary aerospace component

Aerospace structures are non-stationary, meaning that propulsion energy must be consumed during flight in proportion to the associated mass. For such structures, mass reduction enables commercial value in terms of increased flight capabilities, increased load carrying capability or as reduced fuel consumption. AM provides a technically and economically strategic opportunity for the commercialization of such high-value applications. As an aside, aerospace structures are often safety-critical, and are therefore subject to rigorous certification requirements. As an example of how topology optimization can be strategically applied to increase the value of non-stationary applications, a high-value aerospace application is presented below, and is structurally optimized subject to AM manufacturability requirements using the topology and parametric optimization methods presented here.

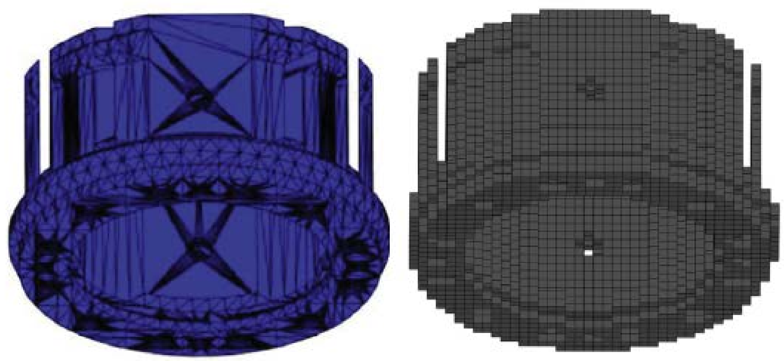
Incumbent structure design summary:

Material of manufacture:
Aluminium 6061-T6

Method of manufacture:
Machined billet

Design objectives:
Minimize mass subject to design constraints

Design constraints:
Strength-limited (multiple loads)
Allowable system cost
Vibratory modes
Allowable deflection



Incumbent structure ***Voxel representation***

Redesign of incumbent design according to defined statement of requirements

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Based on the opportunities and limitations inherent in topology optimization methods, a systematic strategy needed to be applied for the pragmatic optimization of AM for the mass-critical aerospace application specified above. This strategy includes the following phases:

- Define initial conditions: such that there is no ambiguity associated with the intended technical function and constraints of the proposed system.
- Identify spatial requirements and available design volume (including access for assembly and fasteners): such that the design domain can be systematically scheduled for topology optimization compatible with the available computational budget.
- Apply TO methods: to acquire insight into efficient material distributions.
- Accommodate AM manufacturability: this may include reference to integrated DFAM tools, but, given the current state-of-the art, commercial best practice typically requires manual input to accommodate the diverse potential failure modes associated with AM technologies.
- Generate parametric representation of the preferred topology: emerging BC2AM tools can be useful in enabling generative design at this stage. Once parametric models are specified, parametric optimization methods can be applied to optimize local geometry and document the intended design.

This allowed the rapid deployment of a functional prototype that was robustly fabricated using Selective Laser Melting with a mass reduction of over 50% when compared with the incumbent structure.

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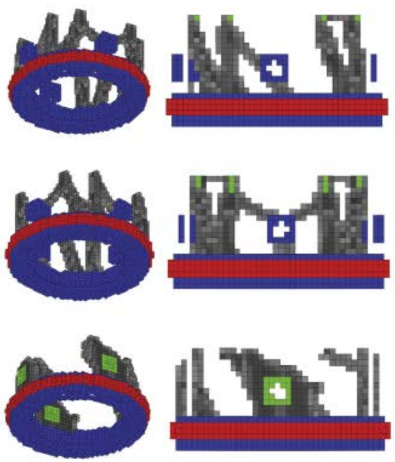
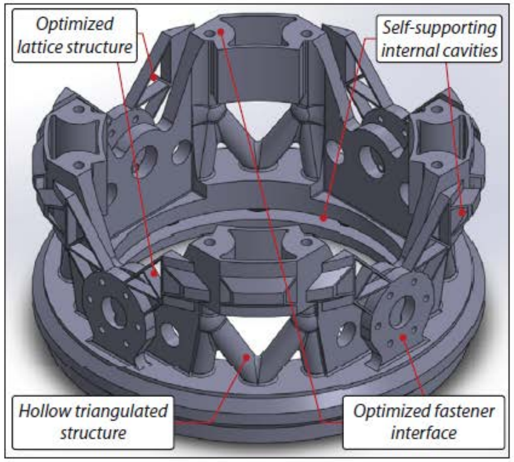
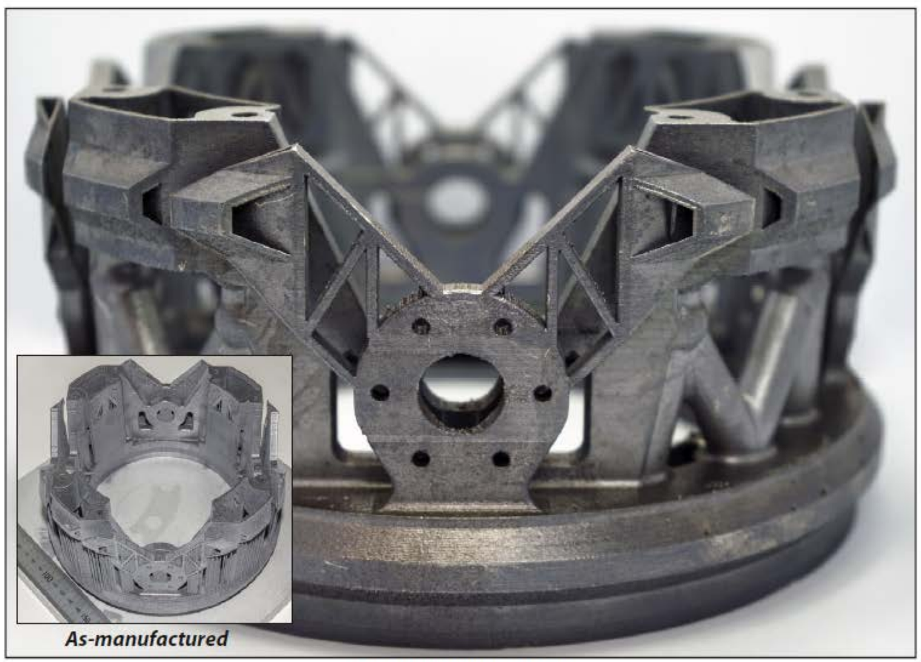


Topological outcomes for standard load cases



Paremetrized detail based on TO outcomes

Systematic strategy for the efficient application of TO and parametric optimization methods in the design of a high-value lightweight aerospace structure manufactured



Final protoype structure

- Triangulated structure to ground load-paths. These structural elements are hollow to increase structural efficiency in bending, and to allow powder removal, and are inclined to be structurally self-supporting to avoid entrapped internal support material.
- Self-supporting internal cavities were defined to increase the efficiency of the central ring feature which ensuring AM manufacturability. Powder removal was accommodated by physical conduits within low stress regions.
- Surrounding material included to allow accommodate external fasteners, but adjacent material removed in self-supportable manner.
- Lattice structure applied to enable connection of the locating ring.

Thank you for your attention