Title:
Incorporating Design for Additive Manufacturing in Multidisciplinary Design Automation – Challenges Identified

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Keywords:
Design for Additive Manufacturing, Multidisciplinary Design Automation, Lattice-based structural Topology Optimization

DOI: 10.14733/cadconfP.2019.372-376

Introduction:

Opportunities provided by Additive manufacturing (AM) span several fields of research and industries, however, AM is still in its infancy and there are several challenges to address [18]. Design methods, guidelines, tools, and models are necessary to effectively and efficiently take advantage of the opportunities presented by AM. Existing design theory and methodologies have shown to lack especially with respect to capturing AM's unique capabilities [20]. There seems to be a consensus that it is not enough to simply manufacture existing products with AM, but instead include some level of re-design as well [18], [15]. One interesting Design for Additive Manufacturing (DfAM) approach is the application of Topology Optimization (TO) and lattice-structures to take advantage of AM's particular potential and simultaneously address some of its challenges.

This paper presents the results and experiences from attempting to incorporate a DfAM module in an existing multidisciplinary design automation system within the aerospace industry. Lattice-based structural topology optimization (LSTO) was introduced to synthesis AM specific solutions using a CAD integrated automation approach. A state of art and practice is outlined with challenges in current commercial CAD tools and issues with respect to the strict requirements on aerospace components discussed.

Research Context, Focus and Approach:

This work is part of a research project, called ProAct which is short for "Platform Models for Agile Product Development – Building an Ability to Adapt" where the main goal is to address "the need for new models, methods, knowledge and tools to build an ability to rapidly develop and adapt products when needs and requirements from different stakeholders rapidly change." In one of the case-companies addressed here there is currently an interest in AM which potentially could directly reduce manufacturing costs, and TO which could help reduce weight. In the conceptual product development stages, there is a multidisciplinary design automation system which analyses designs by varying geometry and environmental requirements (e.g. temperature) which can be used to find out how robust a design is with respect to stakeholder requirements. As an initial focus the objective was to formalize and incorporate DfAM methods and models within this system. The work presented here is part of a prescriptive phase where a structured literature review and action research has been applied by frequently visiting the case-company and developing methods and models in close collaboration with the company experts.

Multidisciplinary Design Automation and DfAM:

The multidisciplinary design automation system addressed here is a distributed system where a shared model is used to communicate between geometric modelling and simulation. Fig. 1 shows a general use-case process, first the design space to explore is defined in terms of design requirements and parameters, including their limits. These are used to generate a Design of Experiment (DoE) which specifies the designs which will need to be generated and analyzed to get an understanding of their correlations in order to evaluate for instance the robustness of the concept. From the project specification a system instance is set up by choosing from different system methods and models, such as scripts for CAD-model configuration and automated meshing as well as parametric CAD-models and template load-cases. See [10] for a more comprehensive description.

The idea was to incorporate a DfAM module to a system instance utilizing programmed features which refer to geometric objects (e.g. load interfaces, constraint interfaces, optimization regions) and saves all other information (e.g. number of lattice-cells, relative density limits) within it. Then, using template pre-processor scripts and a standardized geometric representation the TO model could be created, executed, and the results retrieved in parallel to the existing procedure. During the system instance setup, the specific lattice type, size, relative density limits and configuration would be defined in regions where weight could be reduced, or additional space could be used to increase stiffness or strength. During execution the TO results would be used to calculate theoretical weight savings and to configure the lattice-structures according to the relative density maps. Finally, a meshable geometry (using either 1D, 2D, or 3D elements) would be offered to analyze all design variants (with and without lattice-structures) according to the level of fidelity required and time as well as resources available.

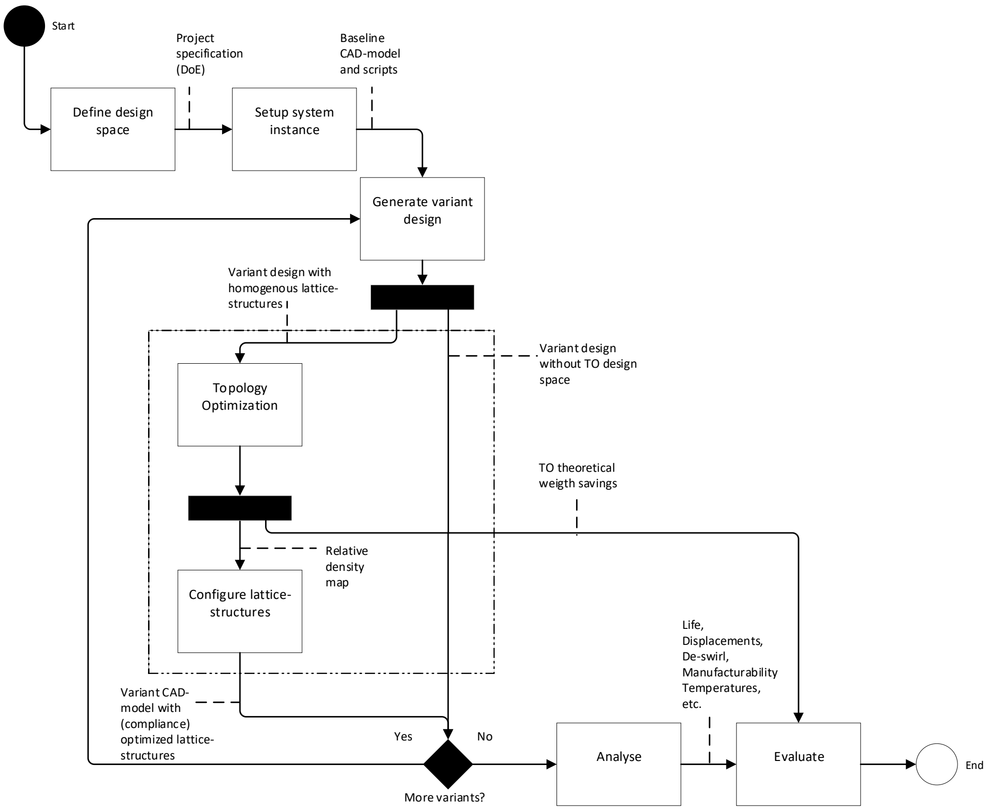

Fig. 1: Multidisciplinary design automation process overview with suggested DfAM module integration.

LSTO:
Lattice-structures usually denote three-dimensional periodic cellular structures [2] and have gained research interest the past at least two decades because of its excellent strength to weight ratio. TO is a type of computational synthesis technique focusing on the optimal distribution of material in contrast to size or shape where geometric dimensions or the position of control vertices are optimized instead [14]. Historically, TO has been criticized for its almost organic geometric propositions which have been difficult or impossible to manufacture and the optimization has focused on the distribution of completely solid or void volumetric elements. When TO is combined with AM and lattice-structures, the material distribution results (usually in terms of relative density) from TO can be used to replace intermediate (not completely solid or void) volumetric elements with lattice-structures and efficiently manufactured using AM by focusing on the manufacturability of the repeating individual lattice-cells.

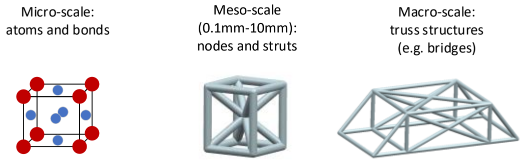

Fig. 2: Scale levels of lattice structures, adopted from [17].

Incorporating lattice-structures based on TO can be done on different levels; macro and meso (sometimes also noted as micro, but here the distinction between macro, meso, and micro follow the convention described in [17], see Fig. 2). On the macro-level, changes to the design space or boundaries where lattice-infill is allowed is optimized. This can be done using volumetric-based TO methods, removing regions deemed unnecessary. On the meso level the lattice-structure itself is optimized by looking at cell-shape and/or lattice-internal geometric dimensions. This is commonly done by using homogenization where the variations in relative density of the lattice-structure is related to some effective material property before TO since consideration of the meso level details becomes too computationally expensive [1]. The optimization problem can be simplified by only allowing changes to one of the levels. If only meso level changes are allowed the problem can be reduced to a size or shape optimization where the optimum relative densities are mapped to a pre-defined lattice pattern (as is the case presented below). Finally, some lattice structure TO methods incorporate feature positioning schemes as well. Below is a sample of different strategies and approaches found:

- general strategies: [12], [17]
- only meso level: [4], [6], [8], [9], [11]
- meso and feature positioning: [5]
- only macro level: [13]
- both meso and macro level: [7], [19]

Case-example:
The case-example involved a sector of a Turbine Rear Structure (TRS) designed to be manufactured using Selective Laser Melting (SLM), a powder-based AM technique which is well suited for lattice-structure manufacturing [3]. The TRS is a component within engines of commercial airliners and helps to de-swirl the gas-flow and works as a connection to the wing. To test the proposed method a simplified sector was filled with three different types of lattice; gyroid, square honeycomb, and center-supported cubic lattices (see Fig. 3). The center-supported cubic lattice was then configured according to the results from Solid Isotropic Material with Penalization (SIMP) TO with the following settings: objective to minimize strain-energy, volume constraint set to 50% of the original, relative volume between 0.2 and 0.8, and penalization factor P=1 using Abaqus Tosca™.

A programmed feature, called Custom Feature in Siemens NX™, was created for the center-supported lattice structure which could then be attached to the CAD-model rebuild tree and updated according to any changes to referenced model entities. It could also be used to represent the lattice in different levels of fidelity, either 1D points and lines for faster modelling or 3D solids possible to export as STL-format for printing or any standardized geometric format (e.g. STEP, Parasolid, IGES) for downstream analysis tasks.

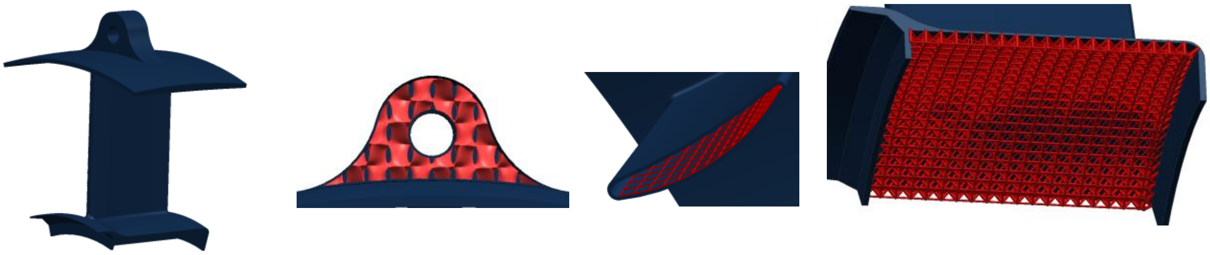

Fig. 3: Three different example lattices integrated into the simplified TRS sector, from left to right: (a) original TRS sector, (b) gyroid-lattice, (b) square honeycomb, and (c) center-supported cube.

Challenges with Current CAD-tools:

During the case-example development it was clear that the feature-based CAD-tool (Siemens NX™) used at the case-company did not have adequate feature support for lattice-structure modelling. In the latest releases (from v.11) some initial support has been added, but without the capability to export the lattice-structures in a format which can be used effectively downstream and without the capability to customize the structures further (e.g. adding additional support to the outer-most layer of cubic lattices) they are of limited use. The structures need to have light-weight representations (e.g. STL) when modelling, the capability to export in mathematically sound formats (e.g. STEP, Parasolid) when sharing with downstream disciplines, as well as the ability to further model upon. Another CAD-tool investigated during this work was ANSYS SpaceClaim™ which has a beta module with the capability to model and configure lattice-structures according to TO. Similarly, however, the model is based upon STL which makes it difficult to use for e.g. analysis. Development of these modeling techniques are rapidly evolving, however.

The approach applied in the case-example was to instead model using 1D and 2D geometric elements (points, lines, and surfaces) and only transform into 3D for either printing, visualization, or complete analysis.

Challenges with respect to Aerospace:

The case-example presented here is far from meeting the tough requirements within the aerospace industry mainly due to a lack of: AM-specific meso-level material models, life-analysis methods, and inspection methods. AM material models are highly anisotropic and depend on many product and process specific parameters such as build orientation, thickness variations, build angles, print patterns, etc. Predicting meso-level attributes does not make this any easier. Life-analysis in particular is difficult and relies on historical data and accurate behavioral models. Last, but maybe even more important is inspection. Some of the lattice-structures are difficult or even impossible to inspect in some cases using traditional approaches (look at the gyroid structure in the case-example for instance). Currently the TRS is inspected for cracks using Fluorescent Penetrant Inspection which requires tools to reach the different sections under investigation [16]. Either in-process (e.g. photographing each layer) or CT scan inspection are two interesting technologies to combat this issue.

Conclusions:

Integrating DfAM through LSTO within multidisciplinary automation systems is interesting but as identified in the work presented here it is challenging due to the increased number of detailed features requiring different representation for modelling, analysis, and manufacture, as well as the lack of historical data compared to other manufacturing technologies, and inspection techniques.

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