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A GENERALIZED CONSOLIDATED TOPOLOGY OPTIMIZATION AND DfAM DESIGN APPROACH AND ITS APPLICATION FOR ASSEMBLY DESIGN

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Abstract — As additive manufacturing (AM) is widely adopted, there is a growing need for design for additive manufacturing (DfAM) tools and design methodologies. The increased design freedom allotted by AM has facilitated the adoption of topology optimization (TO) for AM. This presents an opportunity to introduce TO into DfAM best practices to improve assembly designs. A consolidated topology optimization and DfAM design approach for general assembly design is proposed. Unlike current DfAM methodologies, all critical aspects of assembly design are incorporated to ensure a fully optimized design. The efficacy of the consolidated design approach is demonstrated by its implementation for the redesign of a Bombardier business aircraft cockpit pedestal assembly. The manufacturing cost was reduced by 18%, satisfying the primary design objective. The installation cost will be greatly lowered due to a reduced assembly complexity: A major and minor part count and fastener count reduction of 17%, 89% and 56% was achieved. The current paper contributes to the applicability and efficacy of DfAM by outlining a generalized design procedure sufficiently complex and complete for industry level assembly design problems.

Keywords - Additive Manufacturing; Design for Additive Manufacturing; Topology Optimization; Part Consolidation

I. INTRODUCTION

Additive manufacturing (AM) is a term that describes a collection of manufacturing methods that produce three-dimensional objects by adding material successively. The ability to add material successively greatly reduces the manufacturing constraints, widening the scope of use of AM methods. Traditionally, design for manufacturing (DfM) is used to ensure that parts or assemblies are designed such that manufacturing cost and time are minimized. Additive manufacturing poses a new set of advantages, and disadvantages, such that traditional DfM methods are no longer suitable [1]. As updated design practices are required, design for additive manufacturing (DfAM) has been an active topic of research in recent years. DfAM broadly encompasses design methods and tools used to design a part or assembly to be produced using AM methods.

Perhaps the most promising advantage of AM is that the reduced constraints allow for a more optimization driven design process [2]. Topology optimization (TO), a numerical tool that optimizes the material distribution within a structure, is being increasingly used in industry to produce structurally efficient designs. While difficult to produce using traditional subtractive manufacturing methods, the increased design freedom allotted by AM enables engineers to exploit the designs obtained using TO. Incorporating TO into the DfAM design process properly has been demonstrated through case studies to be an effective approach for the design of high-performance structures [3]. However, integrating TO with generalized DfAM design methodologies and best practices remains a challenge for industry level design problems. As AM is more widely adopted, there is a growing need for design for additive manufacturing (DfAM) tools and design methodologies for end-user products.

Recent academic contributions to DfAM can be broadly grouped into two categories. The first category includes mathematical algorithms and methods developed to improve AM performance. Many academic contributions focus on reducing support material and improving part quality [4][5][6][7]. Recently, there has been a significant emergence of TO algorithms for AM [4][5][8][7]. Academic contributions in the first category remain limited to simple academic examples.

The second category includes DfAM methods, tools and case studies of the implementation of additive manufacturing technologies for practical use. Current academic contributions within this category are largely focused on DfAM methods for, and the application to, AM parts [3][9][10][11][12][13]. While utilizing DfAM for parts design has been shown to be beneficial, the most significant benefits can be achieved with assembly design [14]. This can partially be attributed to the opportunity for part consolidation, which often results in lower manufacturing and assembly costs [1]. The DfAM methods and tools suitable for assembly design emerging in literature vary widely in scope and applicability, and as a result each have specific limitations [14]. Even well-developed methodologies often lack at least one critical aspect of

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assembly design such as structural optimization, part consolidation, joint design, design for assembly and/or design for manufacture [15][16][17][18]. Reference 19 proposed a topology optimization and manufacturing-based part consolidation methodology for a similar application to that presented in this paper. Due to the specific focus on part consolidation, the methodology was insufficient in producing a fully optimized design. Poor integration of design for manufacture is the probable cause of an increased final weight. Additionally, current academic contributions to DfAM are tailored to a specific application, constraining the extension of the method [3][18][20].

While current DfAM methodologies do vary, incorporating TO with DfAM is becoming widely accepted as good practice for improving structural performance [3]. Reference 21 utilized TO to redesign a lightweight turbomachinery component to be produced using metal AM. Reference 22 redesigned an industrial robot link utilizing TO, for additive manufacturing. Despite some success, poor integration of both technologies often prevents full exploitation of their individual and collective benefits. Reference 24 highlighted that the multi-solution nature of TO results in final optimized designs that, although they may have the same structural performance, require different costs to produce using AM. It is common that failure to alter designs obtained with TO to improve manufacturability results in a sub optimal design [23].

Review of literature revealed that current DfAM design methodologies and application methods are not sufficiently developed for the complex assembly designs often encountered in industry. Current methods either lack at least one aspect of design for assembly, design for manufacturability or design for performance, or are limited by ineffective application of these aspects together. Additionally, poor integration of TO with DfAM often prevents the user from producing a fully optimized design.

A generalized consolidated topology optimization and DfAM design approach suitable for complex assembly design is proposed. The objective of this paper is to fully exploit the benefits of AM for assembly design by addressing the limitations of methodologies currently available in literature that restrict the user from obtaining a fully optimized design. A thorough understanding of TO and DfAM is utilized to effectively integrate both tools such that their individual and collective benefits are maximized. The method is applied to the redesign of a business aircraft cockpit pedestal assembly to demonstrate the effectiveness and the application of the method. The methodology is generalized to improve its scalability and applicability for use within industry.

II. Design Methodology

The proposed consolidated topology optimization and DfAM design methodology was intended to be applied for design utilizing polymer AM. The proposed methodology is comprised of 5 main steps, as summarized in Figure 1. A detailed description of each step is included subsequently. The methodology is utilized for a case study in Section 4 to demonstrate how it is applied.

The first step of the design approach is to produce a preliminary design. A finite element analysis (FEA) model is built, including the design and non-design regions, applied forces, inertial forces and the constraints that describe the design problem. Topology optimization is run to identify the primary load paths within the design space. The TO results are interpreted to produce a preliminary design. Interpretation is required because the results obtained using the density method are defined by the element densities, rather than by geometric features. The FEA model and the preliminary design may have limited detail such that the computational cost and the required time is not disproportional to the benefit at this stage of the design process.

The feasibility study is employed to assess if the preliminary design is a viable candidate for AM. Important considerations include an approximation of the required support material, the cost, the weight and the part and joint count. Analysis of TO results may also provide an indication of whether utilizing polymer AM will produce a design that meets the structural performance requirements. Though the design will be considerably improved throughout the entire design process, initial estimates for the preliminary design should provide a reasonable indication of feasibility.

Once determined if the assembly is a suitable candidate for AM, the detailed design phase is employed to make significant improvements to the preliminary design. Design for manufacture must be considered at this early stage of the design process in order to achieve an optimal design. To begin the detailed design phase, the CAD model is updated to include significantly more detail. If possible, the FEA model should be refined (reduced element size) to ensure that the static behavior is well captured. A TO is run with the updated FEA model. Design for manufacture, including print cost, and design for assembly, including part consolidation, should be employed as the TO results are interpreted to produce an updated design. The most significant contributor to the print cost is often the amount of support structure required. The geometry should be defined such that a compromise is obtained between following the loads paths and reducing the support structure. The most effective way to reduce the amount of support structure is usually to properly define the print direction. At this stage of the design process, the number of parts and the ideal print direction for each part should be defined. Part consolidation is employed to consider the costs and benefits of combining or separating parts. Joint design should be simultaneously considered. The design is then modified further by employing AM best practices such as minimum member size, tolerancing and geometrical considerations.

Upon completion of the detailed design, the final assembly is validated with a static analysis. The stress and displacement results are reviewed to ensure that they satisfy the defined requirements. If applicable, a modal analysis should be completed to obtain potential resonance frequencies. A final weight, part count, joint count, and cost estimate should be obtained to ensure that the assembly design satisfies any outlined design objectives.

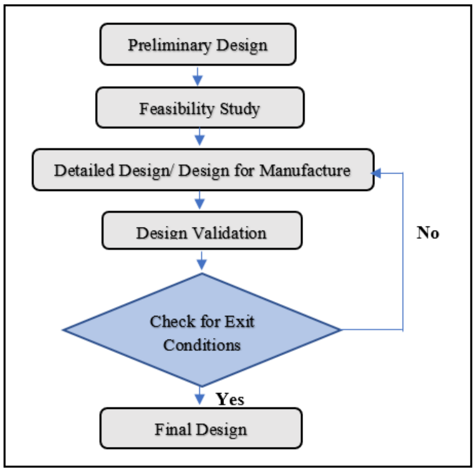

Figure 1: Design Methodology Flowchart

The first iteration of the design methodology is complete. If the static analysis results indicate insufficient structural performance, or if other design objectives are not met, the next design iteration begins. The detailed design and design validation steps should be completed again to further refine the design.

III. TOPOLOGY OPTIMIZATION

The following mathematical problem statement is used to define the topology optimization:

Minimize $C(\rho) = U^T K U$

Subject to: $K(\rho)U = F$

$$\frac{V(x)}{V_0} \leq f$$

$$\rho_{\min} \leq \rho_e \leq \rho_{\max}$$

The optimization objective is to minimize the compliance C(ρ) of the structure subject to an applied force and constrained by a maximum volume fraction *f*. If multiple applied forces are considered, C(ρ) is a weighted compliance. Compliance is equivalent to the global strain energy. As a result, minimizing compliance is mathematically equivalent to maximizing the stiffness [10]. The volume fraction is applied so that the optimizer is forced to distribute material efficiently. Otherwise, the stiffest solution would be that for which the entire design domain was filled with material. K is the global stiffness matrix, F is the force vector and U is the displacement vector. The design variables are the element densities ρ which are allowed to vary between 0 (no material) and 1 (material of density ρ). Analysis and optimization for the following case study was performed using the Altair HyperWorks suite of tools with OptiStruct as the solver.

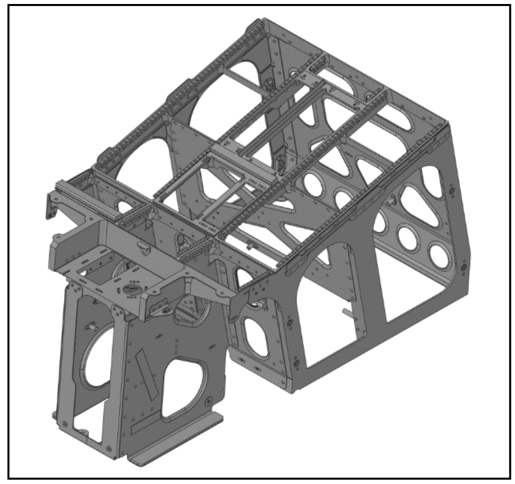

Figure 2: Original Metal Cockpit Pedestal Assembly

IV. CASE STUDY: COCKPIT PEDESTAL ASSEMBLY

The goal of the case study was to assess the feasibility of producing a Bombardier business aircraft cockpit pedestal assembly from a polymer using AM. The center pedestal console supports flight instruments located between the pilots. The current pedestal assembly is made of several metal components produced using subtractive manufacturing methods. The primary objective of the redesign was to reduce the cost. The original pedestal is shown in Figure 2.

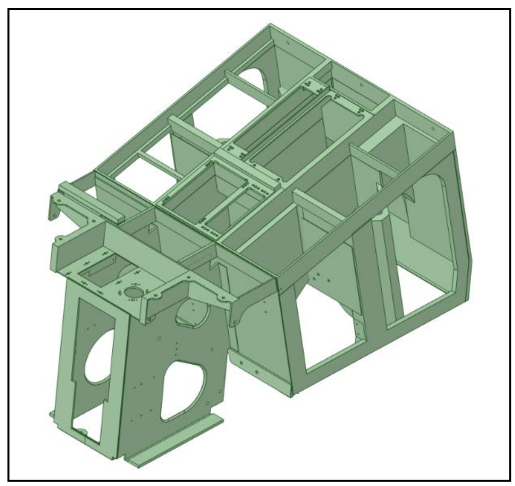

Figure 3: Preliminary Polymer Pedestal Assembly

A. Preliminary Design

The design region, non-design regions and constraints were determined by analysis of a CATIA model of the pedestal. Emergency inertial, abuse loads and pilot effort loads defined by Bombardier and flight certification regulations were incorporated. All load cases were weighted equally in the TO analysis. The initial FEA mesh was created using a voxel mesh generated with the shrink wrap feature. Precise details were not captured; however, this was deemed appropriate at this stage. To be able to understand the effect of the volume fraction constraint on the optimized design, TO results were obtained for a volume fraction of 0.2, 0.25, 0.3, 0.4 and 0.5. The results were roughly interpreted to produce the preliminary design, shown in Figure 3.

B. Feasibility Study

A feasibility study was completed to assess whether an AM polymer was a suitable replacement for the original metal. An initial approximation of the assembly weight, cost and part count of the preliminary design was obtained. A quote for manufacture was obtained by a Bombardier supplier, including a cost breakdown so that the percentage of the cost allocated to support material could be determined. By assessment of the preliminary design, and considering the opportunities that remained for design refinement, it was determined that detailed design should proceed.

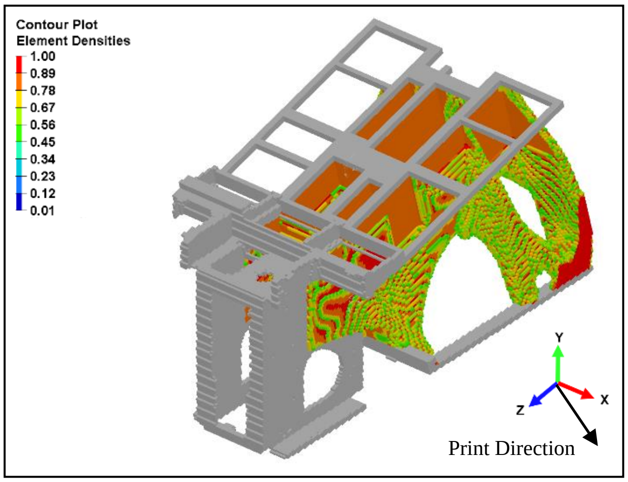

Figure 4: TO results with an overhang constraint, volume fraction = 0.25

C. Detailed Design/ Design for Manufacture

Once it was determined that the assembly was a suitable candidate for polymer AM, the detailed design phase began. The focus of the detailed design phase was to satisfy the primary objective initially outlined. First, the Cad model was updated to include significantly more detail. Material was added to ensure that the harness attachment points were unchanged. A grounding plate for the electronic equipment and the DZUS rails used to support the electronic equipment were added. Brackets and standoffs were consolidated into the main components where possible to reduce the part count. All required fasteners were incorporated.

It was noted that current methodologies that incorporate both TO and DfAM do not fully integrate both tools well, resulting in a less than optimal design. The factor that often contributes most to the cost of an additively manufactured part is the amount of support structure. To observe how constraining the support material impacted the topology optimized design, an overhang constraint was applied to the optimization. This required definition of the print direction. The print direction has a significant impact on the amount of support structure, surface quality and structural performance of a part. Obtaining the TO results without the overhang constraint first allowed for observation of what the structurally optimal design should look like. Therefore, it was easier to determine a suitable print direction. Adherence to the optimal print direction may require part consolidation or separation. Although reducing the part count typically reduces the cost of assembly, it may be beneficial to add additional parts if this facilitates cost reduction in another way. It was possible to print the pedestal in one part due to the size of the available print bed. However due to the geometry of the assembly, printing in one piece would result in a significant increase in required support material, no matter the print direction. It was decided to separate the pedestal into two components. Once the build direction was selected, the new TO results with the overhang constrained were obtained, as seen in Figure 4.

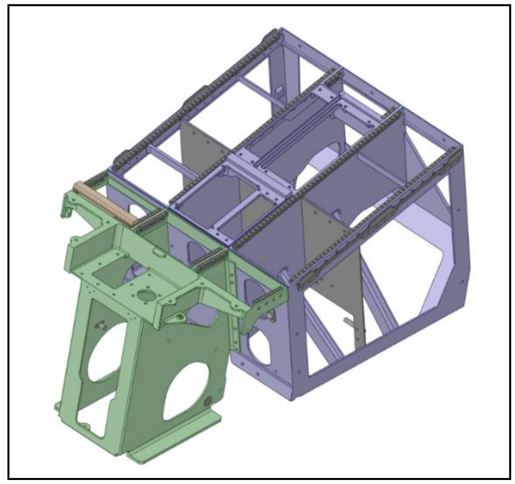

Figure 5: Polymer Pedestal Assembly V1 (C1 = Green, C2 = Purple)

The updated TO results were interpreted to produce the V1 design. Additionally, the geometry was updated to conform with AM design best practices. Filets with a suitable radius were added to sharp corners. Thin walls and members were adjusted to have a thickness that is a multiple of the filament thickness. The geometry was also modified to remove additional support material were possible. For example, the struts between the middle walls and the fuselage attachment points were angled such that they were self-supporting.

D. Design Validation

Compared to the preliminary design, design V1 shown in Figure 5 showed significant improvement in achieving the primary objectives. The major and minor part count and fastener count were reduced by 21%, 97% and 58%, respectively. The cost and weight were however increased by 12% and 2%. The Design V1 was validated by observation of the stress and displacement results for each load case. Although stress was constrained explicitly, displacement was also evaluated to ensure that there would be no interference between the assembly and the surrounding parts. The results indicated that some areas required stiffening. The results also indicated that the assembly was overdesigned in some areas, providing additional opportunity to reduce the weight and the cost. The primary objective was to reduce the cost, so it was acceptable to reduce structural performance if the stress requirements were met. Additionally, a modal analysis was performed to ensure that the assembly would not be excited by the frequencies experienced during flight. Considering the design validation and the cost, a second iteration was required.

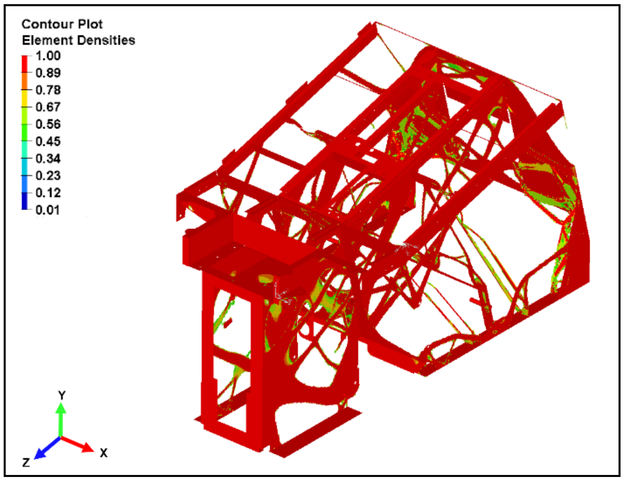

Figure 6: TO results for design refinement (V2), volume fraction = 0.25

The FEA model used to produce design V1 allowed for a large design space. The primary load paths were already determined, so design refinement was of interest at this stage. A FEA model of design V1 with a refined design space was created. The design space was significantly reduced but tailored to allow for a blank slate design space in the locations of interest. For example, large surrounding walls were filled in. Shell elements, rather than solid elements, were used to model thin walls. The final TO results, shown in Figure 6, highlight where material could be distributed more efficiently. Some features were made hollow, to be filled with honeycomb, and light weighting holes were added to large walls. The static analysis and displacement results from design V1 indicated some problem areas to be addressed. Additional stiffening features were added, and the wall thickness was increased in a few critical areas to reduce stress. Finally, the design was re-evaluated from a part consolidation perspective. It was decided to split component 1 into 2 parts to reduce the required support structure. All 3 main components have a separate print direction. As a result, the cost was significantly reduced and only 8 additional fasteners were required. Design V2 was validated with a static and modal analysis. There were no further opportunities for design improvement, so the design procedure was finished.

E. Material Considations

Polymer AM using fused deposition modelling (FDM) were selected for the case study. Due to the layer-by-layer deposition of the material in the FDM process, the resulting material is inherently anisotropic. The material is weaker along the build direction as it is limited by the strength of the bonding between the layers. To facilitate rapid modelling, the material was modelled as isotropic for the TO and the static analysis. To ensure a conservative design, the material properties in the weakest direction were used. This may leave open an opportunity for further design refinement. Due to strict material requirements for parts within aircraft, it was required that a specific thermoplastic polymer be used for the case study. The material properties of the polymer printed with a thickness of 0.010” were obtained by a Bombardier supplier.

V. DISCUSSION

The proposed method allowed for the redesign of the Bombardier business aircraft cockpit pedestal assembly for polymer AM. The final pedestal assembly design, shown in Figure 7, satisfied the primary objective. The printing cost was reduced by 18%, while maintaining the same weight. More importantly, the case study demonstrated that topology optimization, design for performance, design for assembly and design for manufacture were effectively incorporated for a complex assembly design. Design for performance is most significantly impacted by the integration of TO. By including TO in the iterative design procedure, stress constraints were satisfied while maintaining the same structure weight, even though the polymer is weaker than the original metal. The iterative process also allowed for the material distribution to be influenced in response to the amount of support structure required, in addition to the TO results, such that the manufacturing costs were reduced. Effective design for assembly resulted in the most significant benefit of the redesign, which was the reduced assembly cost. The major and minor part count and the fastener count was reduced by 17%, 89% and 56%, respectively, significantly reducing the time required for assembly. While the proposed methodology proved effective for the case study, additional case studies are required for the proposed methodology to be fully evaluated.

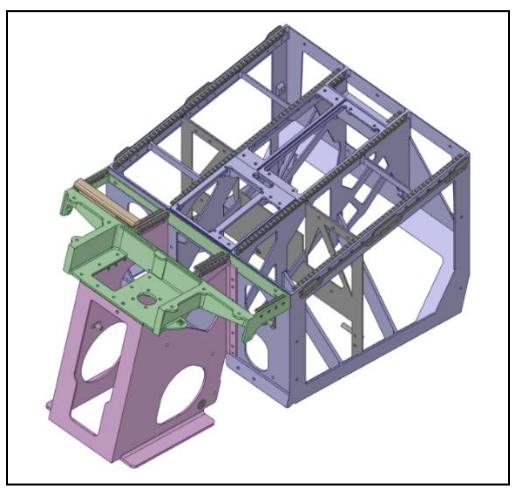

Figure 7: Pedestal Assembly Design V2 (C1 = Green, C2 = Purple, C3 = Pink)

It was mentioned that design for manufacture is included directly during the interpretation of the TO results to attempt to achieve the best compromise between structural efficiency and cost. This process is done manually, so it is not guaranteed that the result is globally optimal. However, consideration of design for manufacture early in the design process allows for a better understanding of the impacts of making design decisions on both objectives. Observing the cost and static analysis results at each iteration allows for the effects of design decisions to be observed directly and immediately.

It is recognized that the required software, the computational cost to assess detailed FEA models, and expertise of topology optimization are all barriers for the methods' widespread use. The proposed method was intended for use in industry, and therefore users are assumed to have greater access to the required resources. Additionally, such resources are required for the level of complex assembly level design encountered in industry.

VI. Conclusion

The biggest barrier to the use of AM is the understanding and the application of DfAM methods and tools [1]. Available methodologies in literature are often tailored for specific application to part design, rather than generalized methodologies for assembly design. These methods lack the complexity and completeness for assembly level design in industry. Additionally, while combining TO with DfAM is a popular trend in literature, poor understanding of these tools results in their ineffective integration and limited associated benefits. The current paper contributes to the applicability and efficacy of DfAM by introducing the required procedure for incorporating TO with DfAM for general assembly level design. The proposed method addresses the limitations of current DfAM methods and tools to be able to produce a fully optimized design. The design approach is also outlined such that engineers can apply it directly to a general assembly design. Application to the Bombardier business aircraft cockpit pedestal assembly demonstrated the effectiveness of the proposed method. Effective DfAM methodologies and best practices will allow engineers to produce the next generation of lightweight, strong and cost-efficient assembly designs.

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