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Design for Manufacturing and Topology Optimization in Additive Manufacturing

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ABSTRACT

Additive Manufacturing (AM) processes are used to fabricate complex geometries using a layer by layer material deposition technique. These processes are recognized for creating complex shapes which are difficult to manufacture otherwise and for enabling designers to be more creative with their designs. However, as AM is still in its developing stages, relevant literature with respect to design guidelines for AM is not readily available. This research proposes a novel design methodology which can assist designers in creating parts with high manufacturability. The research includes formulation of design guidelines by studying the relationship between input part geometry and AM process parameters. Two approaches are considered for application of the developed design guidelines. The first approach presents a feature graph based design improvement method in which the concept of Producibility Index (PI) is used to compare the designs. This method is useful for performing manufacturing validation of pre-existing designs and modifying it for better manufacturability. The second approach presents a DFAM constrained topology optimization based design advisory which can help designers in creating entirely new lightweight designs that are additive friendly. In this approach, the developed AM design guidelines are mathematically integrated with existing structural optimization techniques. Application of both the methods is presented in the form of case studies where design improvement and evolution is observed.
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1. INTRODUCTION

Additive Manufacturing (AM) is a non-traditional manufacturing process which uses a layer by layer material deposition method for fabricating complex geometries. This layered material deposition method makes the process independent of input geometry and enables designer to be more creative with designs. Presently, a number of AM processes are being used in the industry such as Fused Deposition Modeling (FDM), Stereo lithography (SLA), Selective Laser Sintering (SLS), Direct Metal Laser Sintering (DMLS), Electron Beam Melting (EBM), etc. The main steps involved in any AM process are presented below [1]:

1. **CAD modelling:** A solid model of the part design is created using a 3D modeling software.

2. **File conversion:** Present industry standard for additive manufacturing is the STL file format. This step includes conversion of a CAD model into STL format by approximating the surfaces using triangular facets.

3. **File transfer to machine:** The file is modified for correct size, position and orientation according to machine chamber and uploaded in the machine software.

4. **Machine Setup:** The machine is prepared for part fabrication by selecting the correct process parameters including energy source, layer thickness, material constraints etc.

5. **Build:** The part is manufactured by generating slices.

6. **Part Removal:** The manufactured part is then removed from the machine chamber.

7. **Post processing:** Once removed from machine chamber, parts may require additional cleaning up before they are ready for use. Support removal is also performed at this stage.

8. **Application:** Parts may now be ready to be used.
Additive Manufacturing processes are primarily classified based on the method of adhesion between the layers [5]. Figure 2. shows a classification chart for AM technologies. Direct Metal Laser Sintering (DMLS) is one of the leading AM process which is used by industries to fabricate high strength metal parts. This process uses a laser power source for binding metal layers. This process is also particularly beneficial while working with materials which are hard to machine such as Titanium alloys. The process employs a laser power source which sinters the metal powder for every slice geometry. Laser sintering process is followed by a re-coater arm movement which lays a powder layer on top of newly sintered layer. Subsequently, the fabrication bed moves down by the amount of layer thickness so that a new layer can be sintered. Figure 3. shows the set up for the DMLS process [44].
1.1. MOTIVATION OF RESEARCH

One of the most important objectives for any manufacturing process is to achieve desired part accuracy. Previous research in the area of Additive Manufacturing suggests that there are some process induced errors which directly affect part quality and mechanical properties. Laser sintering process results in a thermal gradient which induces residual stresses. Also the necessity of support structures results in increased cost and build time. Ideally an engineer should always include these manufacturability issues while conceptualizing a design as it has direct implications on design’s feasibility. The concept of Design for Manufacturing (DFM) and Design for Assembly (DFA) were developed so that the manufacturability constraints can be taken into consideration and incorporated during early design stages. DFM implies that a designer should ensure that their designs are easy to manufacture and overall cost including assembly and logistics is minimized [1]. Although generally design guidelines are formulated specific to manufacturing process, still

![Figure 2. Classification of AM processes [5]](image-url)
producibility of a design depends on several other factors such as geometry, dimensional tolerances and raw material [2]. As Additive Manufacturing is still in its infancy, relevant literature describing design rules for AM are not readily available. This research work aims at developing DFM framework and design methodologies for AM processes.

![Set up for DMLS process](image)

**Figure 3. Set up for DMLS process [44]**

1.2. **OBJECTIVES AND IMPACT OF RESEARCH**

The objective of this research is to develop design methodologies for Additive Manufacturing which can assist designers in developing parts with high manufacturability. The research proposed here presents an integrated approach which combines AM design rules with the product development process. A knowledge base for DMLS manufacturability is developed by studying the relation between CAD model, input process parameters and end part quality. A graph based
design validation method is presented which can decompose a design into its constitutive elements and identify features which violates design rules. A producibility index based design quantification scheme is presented which can compare manufacturability of different designs. This method is suitable for modifying pre-existing designs for making them feasible for Additive Manufacturing. However, designers are often supposed to conceive novel designs based on given loading conditions. The method of topology optimization is a suitable tool for finding minimum material requirements within a design space. Unfortunately designs suggested by this method are very difficult to manufacture due to the intricate geometry generated. As AM uses a layer by layer manufacturing method, relatively difficult designs are now possible to fabricate but AM unfriendly design features result in poor part quality and mechanical properties. Thus there is a clear need to develop design rules specific to DMLS type additive process and correlate them with design features. This research focuses on developing DFAM rules, identifying violations using a graph based feature recognition approach and subsequently integrating the design guidelines within a topology optimization process to generate designs which are manufacturable using the DMLS process.

1.3. **THESIS OUTLINE**

This research is divided into five chapters. Chapter 1 focuses on introduction to Additive Manufacturing technologies and common procedures associated with it. This chapter also covers motivation, problem statement and desired objective of this research. Chapter 2 discusses relevant literature conducted in the field of Additive Manufacturing, Design for Additive Manufacturing, Design representation and topology optimization. Chapter 3 elaborates the development of design rules along with graph based validation methodology. This chapter focuses on an integrated topology optimization method which combines structural optimization with developed design
rules. Chapter 4 presents five case studies depicting the implementation of developed design methodologies. Inferences and conclusions from obtained results are presented in chapter 5. This chapter also contains scope of future research in this field.
2. LITERATURE REVIEW

This chapter discusses the current and past research conducted in the areas of design and Additive Manufacturing. The chapter has been divided into four sections. The first section is a review of part design features that are difficult to manufacture using DMLS process. As part accuracy is the most important quality governing parameter for any manufacturing process, a thorough review of available research is conducted and design rules are formulated. Second subsection describes different Design for Additive Manufacturing (DFAM) methodologies presented in recent publications. This is followed by a review of different methods for representing a design. The last subsection describes research conducted in the area of Topology Optimization.

2.1. PART DESIGN LIMITATIONS FOR DMLS

Input design geometry is one of the important factors that affect the part quality in DMLS process. This section presents a review of previous research that correlates various quality governing parameters in AM with manufactured part quality. In AM, every layer is generated as an extrusion of a planar 2D contour. Hence, stair step effect shown in fig. 4. is evident in all AM parts with curved or slanted surfaces. Choi and Samavedam [6] studied the staircase error and formulated a mathematical relation for determining cusp height. Arni and Gupta [7] connected cusp height with flatness tolerance while the relation for cylindricity tolerance was developed by Paul and Anand [8] along with a graph based method for finding optimal part build orientations. This method is particularly helpful for designs with multiple cylindrical features because different optimal build orientations are possible in this case. Clijsters et al. [9] reported that designs with sharp corners and thin sections are hard to manufacture as these features influence the thermal behavior of the laser sintering process. Peng et al. [10] studied fabrication of thin-walled metal
parts and reported that accuracy of complex thin-walled metal parts is compromised while controlling the build height. Soe [11] performed an experimental study relating part geometry with curling effect in laser sintering and showed that box type geometries are more susceptible to thermal distortion. This study also presents a list of preferred and not preferred build orientations for different geometries. Also, parameters such as powder bed temperature, position of part in machine chamber, part orientation etc. affects the final accuracy. As AM parts are built upright in the machine chamber, features such as overhang and undercut require support. Figure 5. presents a part with the typical features for support highlighted. The requirement of support structures have been analyzed by multiple authors [5, 12, 36]. Paul and Anand [13] presented a voxel based support minimization methodology. The analysis of support structures in AM is critically important as they not only contribute in material cost but also increase in build time. Moreover, surface roughness

![Figure 4. Cusp Height for AM parts [6]](image)

![Figure 5. Features requiring support](image)
of surfaces which comes in contact with support structure is found to be greater than other part surfaces.

2.2. DESIGN FOR ADDITIVE MANUFACTURING

The development of AM technology has motivated researchers towards developing new design approaches specific to AM. Vayre et al. [14] presented a design methodology for AM and illustrated their approach with redesigning a sample part. Ponche et al. [15] proposed a new numerical chain based design method which can find optimal geometries in terms of functionality while considering manufacturing process parameters. Klahn et al. [16] presented a list of criteria for redesigning a part for AM and illustrated the redesign process on various sample parts. They also presented part selection criteria for Additive Manufacturing which can help practitioners in identifying components which can be redesigned for AM. Seepersad et al. [17] fabricated plastic parts using laser sintering (LS) process and formulated a set of design guidelines for increasing manufacturability. Design guidelines presented here are formulated using a pass/fail criteria and results are presented in form of feature resolution tables. However, the author stated that the developed design guidelines could not be directly applied to metal sintering process because of difference in physical properties. Adam and Zimmer [18] developed a design rule catalog for Laser Sintering, Laser Melting and Fused Deposition Modelling (FDM) process. Kerbrat et al. [19] presented a hybrid manufacturing process that combines machining with additive manufacturing. The authors also proposed a manufacturability evaluation method for subtractive and additive manufacturing. Rosen [20] presented a DFAM procedure using cellular structures along with the concept of Manufacturable elements (MELs).
2.3. DESIGN REPRESENTATION

Multiple authors have presented algorithms for decomposing a design into its constitutive elements for manufacturability analysis. Joshi and Chang [21] presented the concept of Attribute Adjacency Graph (AAG) which is used to recognize machining features in 3D geometric models (boundary representation), as shown in fig. 6. In this research a similar graph based technique is used for design decomposition and DFAM implementation. Lockett and Guenov [22] presented a mid-surface based approach for feature recognition in molded parts. The concept of attributed mid-surface adjacency graph (AMAG) is introduced and implemented for feature recognition. Gershenson and Prasad [23] used a component tree diagram to establish the manufacturing modularity of a product. A representative case study of coffee maker design is presented and component tree diagram for its design is constructed, as shown in fig 7. Changchien and Lin [24] used a feature based method to represent rotational parts with machining features and established a relationship between them.

![Figure 6. Attribute Adjacency Graph (AAG) for a part [21]](image)

Huang et al. [25] represented design specifications of rotational parts in form of a graph for finding an optimal set up plan. Design graph presented by Brunetti and Golob [26] included material and geometrical information. Recently Liu [27] proposed a feature graph based approach
for finding relevant features in Layer based manufacturing. A case representation of a machine arm design is presented to illustrate the proposed approach.

![Component tree diagram for a coffee maker](image)

**Figure 7. Component tree diagram for a coffee maker [23]**

### 2.4. TOPOLOGY OPTIMIZATION

Topology Optimization is the computational method for finding minimum material distribution scheme for a defined loading condition within a design space. The field of topology optimization has been thoroughly investigated by researchers for more than two decades. A keynote paper in the area is presented by Bendsoe and Kakuchi [28] and complete theory for the process is presented in the work by Sigmund and Bendsoe [29]. Recently, Liu and Tovar [41] presented a MATLAB implementation of topology optimization process for solving minimum compliance, compliant mechanism and heat conduction problems. Figure 8. presents a sample result for minimum compliance problem for cantilever beam. Several attempts have been made by researchers to include manufacturability constraints within the topology optimization process. Zhou et al. [30] introduced casting and extrusion manufacturing constrain in the process and presented designs with increased manufacturability. Guest et al. [31] incorporated minimum length criteria in topology optimization process such that feasible designs can be obtained. Recently, Brackett et al. [32] combined support structure minimization with bi-directional evolutionary structural optimization (BESO) and presented the results for 2D cantilever beam. Gaynor and Guest [33]
implemented an overhang constraint within the topology optimization process using a Heaviside projection scheme. They presented results for 2D cantilever and MBB beam. In this paper a novel mathematical model has been formulated using a variable mapping technique for integrating design rules within the topology optimization framework.

Figure 8. Topology optimization result for a cantilever beam [41]
3. METHODOLOGY

In this research, a set of DMLS design guidelines are formulated based on relevant literature. As a first step, a graph based design feature extraction approach is used in conjunction with the design rules to identify and remedy AM design violations problems. In a subsequent step, a topology optimization approach is combined with the design rules to come up with light weight additive friendly designs. The last section presents a Producibility index to compare designs from AM manufacturability perspective.

3.1. DEVELOPMENT OF DESIGN GUIDELINES

The DMLS process has some inherent limitations which can be used as a basis to formulate a knowledge base of design guidelines. Design guidelines can be categorized into following three categories:

3.1.1. Geometrical Parameters

In Additive Manufacturing, parts are fabricated in the form of 2.5D layers [5] resulting in curved surface being manufactured with a staircase effect. The concept of cusp height is used to quantify this error. Equation (1) by Choi and Samavedam [6] presents a mathematical relation between cusp error, slice thickness and the angle between the build axis and the facet normal of a STL facet. The relation was further extended by Paul and Anand [8] to represent cylindricity tolerance as shown in Equation (2). In this research, similar relations for cusp height are developed for conical and spherical surfaces.

\[ Cusp \; \text{height} = \text{Slice \; Thickness} \times \cos(\phi) \]  

Where, \( \phi \) is angle between build axis and facet normal.
\[ Cusp \ height = Slice \ Thickness \times \sin(\eta) \]  
(2)

Where, \( \eta \) is the angle between axis of cylinder and build axis.

Figure 9 shows a section of a conical feature. The angle between build axis (ba) and axis of cone (bo) is \( \theta \) and semi cone angle is \( \alpha \). The relationship between cusp height (AC) and the cone geometry as shown in Eq. (3), is developed using analytical geometry.

\[ Cusp \ height(AC) = Slice \ Thickness(AB) \times \sin(\theta + \alpha) \]  
(3)

Figure 10 shows a section of a spherical feature manufactured by AM process. The relationship between radius of sphere and cusp height is presented below. AB and AC represent the cusp height and slice thickness respectively. The points A and C are given by:

\[ C(r \times \cos\beta, r \times \sin\beta) \]

\[ A(r \times \cos\beta, r \times \sin\beta + t) \]

Also, \( \sin\beta = 1 - (t/r) \)

where, \( t \) is slice thickness

\( r \) is radius of sphere

Thus maximum cusp height is given as,
\[ AB = AO - BO \]
\[ AB = \sqrt{(r^2 - t^2 + 2tr) - r} \]

In order to keep maximum cusp height less than the given cusp height threshold i.e.
\[ AB \leq c \]

The following relation is developed:
\[ r \leq \frac{t^2 + c^2}{2(t-c)} \]  \hspace{1cm} (4)

This suggests that for satisfying a cusp height threshold of \('c'\) with slice thickness \('t'\), the radius of sphere should always be less than the expression shown in Eq. (4).

Cylindrical, conical and spherical surfaces of a part are checked for cusp height threshold violation using Eq. (2), (3) and (4) respectively. Non primitive features such as extruded, revolved or freeform surfaces are approximated using triangular facets and analyzed using Eq. (1). If any surface of the part violates the cusp threshold, it is marked as critical for designer’s notification. Paul and Anand [8] proposed that cylindricity tolerance violation can be avoided by reorienting the part and presented a graph based method for finding range of optimal build orientations. However, in case of multiple features, sometimes it is not possible to avoid violations just by reorienting and thus design changes may become necessary.

The shape of laser beam and thermal nature of the sintering process can cause manufacturability issues in fabrication of certain features such as sharp corners and thin sections. Perfect knife edge is impossible to fabricate because of the shape of laser beam. Also thin openings are often fused while sintering due to the minimum feature resolution capability of laser sintering process [17]. Hence, features forming sharp corners and thin openings should be avoided at design stage.
In AM, the height of part is directly related to cost as it is proportional to build time. Although, height and volume of a part are important at design stage but no explicit recommendation can be provided as these features often defines functionality. However, these features are considered while comparing designs based on Producibility Index metric.

3.1.2. Thermal Parameters

In the laser sintering process, temperature history of part plays an important role in defining the final part quality. Mercelis and Kruth [34] have used a Thermal Gradient Mechanism (TGM) for explaining the phenomenon of residual stresses in Selective Laser Sintering (SLS). Thermal stresses are one of the most important reason for introducing curl in parts which is detrimental for quality. Box type structures are most susceptible towards curl and geometries with high curvature have less tendency to get warped [11]. Also thin sections in part’s geometry tend to warp easily [9]. Thus features forming a box type geometry and thin sections are marked as critical features.

Another parameter which is rarely considered, is the movement of the re-coater arm. The re-coater arm swipes over the part after sintering of every layer to lay the powder for the next layer to be sintered. It has been reported that if the input geometry has a long edge parallel to re-coater arm, then it can strike the re-coater arm disrupting the functioning of the machine [35]. Also features that are curled up due to residual stresses may collide with the re-coater arm causing

![Figure 11. Re-coater Arm Movement](image)
interruption in the movement. So, long edges and thin overhangs facing the re-coater arm are also marked as critical features. Figure 11 depicts the problem of a thin overhang obstructing the re-coater arm movement.

3.1.3. Support Structures

In AM, parts are built upright in the machine chamber along the build axis. Thus features such as overhangs, surfaces with negative draft and undercuts require support [5]. Also, sometimes they help in reducing thermal distortion by increasing heat dissipation [36, 37]. However, building supports structures not only increases total sintering time but also requires additional effort in removal. Generally, supports are removed using conventional processes and support removal can be detrimental to the surface finish of the areas where support comes in contact with part. Hence, minimum requirement of supports should be incorporated at design stage. Researchers have suggested partial, cellular [38] and surface inclination based [39] supports for surface. Performing topology optimization based on loading presents optimum lightweight designs but there is no assurance of minimal supports. In this study, a topology optimization based design method is presented which can create designs with low support requirement that is additive friendly.

In this work, a feature graph based design improvement method is presented which can help designers in reducing supports. In this approach it has been assumed that surfaces making an angle more than 35° with the build axis needs supports [36]. Based on this criteria, features which require support or comes in contact with support are marked as critical for designer’s reconsideration. Moreover, a percentage value is given to each feature requiring support, so that features that require maximum support can be modified first. Figure 12 depicts a typical part (obtained from [45]) with support structures.
3.2. DESIGN METHODOLOGY

This section presents two approaches for optimally designing additive manufactured parts. In the first method, a feature graph based design improvement scheme is proposed that can be used for improving manufacturability of designs. The second approach integrates topology optimization with design for additive rules described in the previous section to produce lightweight designs that are manufacturable using additive processes.

3.2.1. Feature graph based design improvement method

In this section, a method of depicting a design in the form of inter related part features is presented. Features and their relations are then verified against design guidelines for DMLS. Violations are marked on the graph and this information can then be used for further design improvement.
improvement. Functional features are identified and any violation related to them are ignored because changing the functionality of a part would defeat the purpose of design. The flowchart for constructing a feature graph for manufacturability analysis is presented in Fig. 13.

All functional features are marked on the central node of the graph. A nonfunctional feature is arranged in the adjoining node based on its relation with other features. Relationship between two features is marked as an attribute on the connecting link. Guideline violations can occur either because of features (nodes) or relations (links). As shown in Fig. 14., a part is broken down into features namely F1, F2, F3, F4 and F5. F3 and F4 are identified as functional features, while the rest of the features are arranged as nodes. Relations (R1, R2 and R3) are marked as attributes on the links. Violations are recognized based on design guidelines and the corresponding element (node or link) is marked.

In order to construct the feature graph, first a feature relation table is constructed within the Siemens NX CAD environment using NX Application Programming Interface (API). All the surfaces of a 3D CAD model are analyzed and their topology information is stored in a \((N + 2) \times (N + 2)\) matrix, where \(N\) is the number of surfaces. Also adjacency relation between these surfaces is stored and marked on the feature table. The feature relation table of a sample part shown in Fig. 16. is presented in Table 1. In the table shown, the first two columns represent the CAD

![Figure 14. Features for a sample part](image)
surface ID and surface type respectively. The first two rows are transpose of first two columns. Also, ‘1’ in the table represents the adjacency status between a row and column surface similar to the AAG graph presented by Joshi and Chang [14]. Using the information presented in the feature relation table, a graph is constructed and analyzed. As complex parts may have a large number of features to be analyzed, populating the feature relation table helps in constructing the feature graph by providing information about inter feature relationships. The feature graph with design guideline violations for the sample part is shown in Fig. 17.

![Feature graph](image)

**Figure 15. Representative Feature graph**

**Table 1: Feature relation table**

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</table>
Figure 16. Sample part

Figure 17. Feature graph for sample part
3.2.2. Topology Optimization based design method

Topology optimization is a mathematical approach that optimizes material layout for given design space and loading conditions [29]. The most common application of the optimization process is for minimum compliance or maximum stiffness in which an iterative Finite Element Analysis (FEA) is conducted to find material distribution for minimum deformation. The material density ($X_{ph}$) is allowed to vary between 0 and 1 where density value of 1 represents material and 0 represents a void. Solid isotropic material with penalization (SIMP) method presented by [40] is used to penalize intermediate density values and drives the final result towards a 1/0 material configuration. This research extends the topology optimization method presented by Liu and Tovar [41] and reformulates it into a new DFAM constrained Topology Optimization based design approach by incorporating additive manufacturing constraints.

As the topology optimization process is computationally intensive, there are certain numerical difficulties such as mesh dependency, local minima and checkerboard pattern that have to be overcome. Many researchers have suggested the use of a density filter in order to reduce the effect of such computational complexities. The density filter suggested by [41] presents a relation between design variable and physical density. In this paper, a new intermediate constraint variable ($X_{\alpha}$) is introduced linking the design space and physical density to redefine the mapping.

As discussed in the section on design guidelines, fabrication and removal of support structures is one of the most important factors affecting the manufacturability of designs. Thus, an additional constraint of developing designs with minimum supports is introduced within the topology optimization algorithm. A mathematical formulation is developed which performs a support check for every element after the FEA process. The density of a properly supported element remains unchanged, however density of unsupported element is divided by a factor
proportional to number of void elements lying just below it. Due to density reduction after every FEA iteration, unsupported elements tend to diminish and subsequently a design with a lower support requirement is generated.

The process starts by dividing the entire design space into cuboidal elements (voxel). The extent of discretization specified by the number of elements in each direction (X,Y and Z) is a user defined variable. The Z direction is assumed to be the build direction for AM and constraints are applied such that elements are checked for support only along the negative Z direction. A cuboidal element can have maximum 9 elements lying just below it as shown in fig. 9(a). For boundary elements shown in fig 9(b) and 9(c) 6 or 4 elements respectively may lie below it depending on element’s location. It has been assumed that if an element has a physical density greater than 0.5 it represents material and vice versa. Also, using this assumption an element is said to be properly supported if the element lying directly below it has a physical density greater than 0.5.

![Figure 18. Support elements for (a) non boundary element (b) boundary element with six bottom elements (c) boundary element with four bottom elements](image)

The minimum compliance problem that minimizes deformation of the structure for given support and loading conditions has been modified from [41] and defined as follows:

Find, Design Variable \((X) = [X_1, X_2, X_3, \ldots, X_\phi, \ldots, X_n]^T\)

Minimize: \(C (X^{ph}) = F^T(U(X^{ph}))\)

Subject to: \(\text{Vol} (X^{ph}) = (X^{ph})^T.v - \overline{v} \leq 0\)
Where, \(v\) is vector of element volume, \(\overline{v}\) is maximum allowable volume, \(C(X_{ph})\) is compliance, \(F\) is applied load, and \(U(X_{ph})\) is nodal displacement vector.

The problem formulation and detailed solution for topology optimization is found in [41] where physical density \((X_{ph})\) is computed directly from design variable \((X)\). In this research, computation of constraint variable \((X^\alpha)\) is added in the process where physical density \((X_{ph})\) is a function of constraint variable \((X^\alpha)\) which in turn is a function of design variable \((X)\). The relation between design variable \((X)\) and constraint variable \((X^\alpha)\) is adopted from [41] and shown in Eq. (5).

The relation between constraint variable \((X^\alpha)\) and physical density \((X_{ph})\) is presented by eq. (7), which defines the support reduction criteria. The relation uses a transformation scheme \((\psi(x))\) which basically converts material presence into a 0/1 condition. The mathematical definition of \(\psi(x)\) presented by eq. (8), is such that it returns a value of 1 for density less than 0.5 and vice versa.

Equation (7) represents the physical density \((X_{ph}^e)\) for \(e^{th}\) element where \(N_{se}\) represents the support neighborhood of \(e^{th}\) element. Support neighborhood \(N_{se}\) is defined such that it contains all the bottom neighbors of \(e^{th}\) element except the element lying directly below it. Every element is identified in 3D space according to its X,Y and Z coordinates. If \(e^{th}\) element has coordinates \((i,j,k)\), then support neighborhood \(N_{se}\) will have 8 members with coordinates as \((i-1,j,k-1)\), \((i+1,j,k-1)\), \((i,j-1,k-1)\), \((i+1,j-1,k-1)\), \((i-1,j+1,k-1)\), \((i,j+1,k-1)\) and \((i+1,j+1,k-1)\). Equation (6) presents the formulation for support coefficient \((\sigma_e)\) which serves as a division factor for unsupported elements.

\[
X_{e}^\alpha = \frac{\sum_{h \in N_e} x_{eh}^* v_h^* H_{eh}}{\sum_{h \in N_e} v_{eh}^* H_{eh}}
\]  

(5)
$$\sigma_e = \left[ C_{deg} \ast \left( \sum_{m \in N_e} \varphi(x_{m}^{ph}) + 1 \right) \right]^{\psi(x_{\text{bottom}})}$$

(6)

$$x_{e}^{ph} = \frac{x_{e}^{g}}{\sigma_e} = \frac{x_{e}^{g}}{C_{deg} \ast \left( \sum_{m \in N_e} \varphi(x_{m}^{ph}) + 1 \right) \psi(x_{\text{bottom}})}$$

(7)

Where,

X_{e}^{ph} is the physical density for e^{th} element.

N_e is neighborhood of an element X_e with volume, v_e and its definition is described in [41].

H_{eh} is the weight factor defined as H_{eh}=R-dist(e,h).

N_{e}^{s} is the support neighborhood defined such that it contains all bottom neighbors of e^{th} element except the element that lies directly below it in negative Z direction.

C_{deg} is degree of support filter.

\sigma_e is support coefficient.

X_{e}^{ph}_{bottom} represents the physical density of element that lies directly below e^{th} element in negative Z direction.

and the transformation \psi(x) is defined as-

$$\varphi(x) = \begin{cases} 
0 & x \geq 0.5 \\
1 & x < 0.5 
\end{cases}$$

(8)

The definition of support coefficient (\sigma_e) shown in eq. (6) is such that it gives a definite control to the element lying directly below e^{th} (i,j,k) element by keeping its transformed physical density as exponent of the denominator. The coordinates of such element is (i,j,k-1). Support coefficient will become 1 in case the element (i,j,k-1) has a physical density greater than 0.5 i.e. element (i,j,k)
is properly supported. This signifies that in case of proper support, element density will remain unchanged and material growth is not affected. However, if element \((i,j,k)\) is not properly supported, then support coefficient \((\sigma_e)\) becomes proportional to sum of all the void elements in neighborhood \(N^c_e\) and the resulting physical density \((\lambda_{ph})\) is reduced. The role of transformation \(\psi(x)\) is to discretize the varying physical density to \(0/1\) condition. Repeating the process iteratively reduces the probability of material growth at elements which are not properly supported. An extra ‘1’ has been added to the denominator just to avoid an indeterminate condition of \(0/0\). Another term of \(C_{deg}\) in support coefficient \((\sigma_e)\) definition basically controls the intensity of support constraint. Higher values of \(C_{deg}\) basically means that non supported elements will be more severely penalized. However, increasing \(C_{deg}\) more than a certain limit makes the process unstable and produces trivial results.

It is observed that adding the new support constraint with the topology optimization process makes it in general hard to converge. Thus, a penalty variation scheme is also introduced to increase or decrease the SIMP’s penalty depending on support availability for elements. An exponential function defined by eq. (9) is used to assign penalty for each element depending on its support coefficient.

\[
\text{Penalty} = H - \frac{H-L}{e^{S(\sigma_e-1)+1}}
\]  \hspace{1cm} (9)

Where,

\(H\) is high penalty threshold

\(L\) is low penalty threshold

\(S\) is slope constant
\( \sigma_e \) is support coefficient

The penalty function is designed to allocate a high penalty threshold, \( H \) if support coefficient \( (\sigma_e) \) is greater than 1 and a lower penalty threshold, \( L \) if support coefficient \( (\sigma_e) \) is less than 1. Figure 19. shows the plot of penalty function. Basically, the developed function signifies that if an element is not properly supported and has support coefficient greater than 1, then penalty value for that element is increased and thus the chances of material growth for that element is reduced. Also, the modified KKT conditions for optimization are given by eq. (10), (11) and (12).

\[
\frac{\partial c(X^p)}{\partial x} + \lambda \frac{\partial \text{vol}(X^p)}{\partial x} = 0
\]  
\[
\frac{\partial c(X^p)}{\partial x} = \frac{\partial c(X^p)}{\partial X^p} \frac{\partial X^p}{\partial X^a} \frac{\partial X^a}{\partial x}
\]  
\[
\frac{\partial \text{vol}(X^p)}{\partial x} = \frac{\partial \text{vol}(X^p)}{\partial X^p} \frac{\partial X^p}{\partial X^a} \frac{\partial X^a}{\partial x}
\]  

Figure 19. Plot for penalty function
3.3. PRODUCIBILITY INDEX

To assess the extent of part’s conformance to the AM design rules, a Producibility Index metric has been developed in this work. Producibility index (PI) is the measure of goodness of a design’s manufacturability in a particular build orientation. The concept is formulated to quantify and compare designs. The following eight factors are included in calculation of PI:

1. Total number of sharp corners in all the slice contours
2. Number of small holes/small openings in all slice contours
3. Number of thin regions
4. Mean Cusp Height (mm)
5. Surface Area contacting support (mm²)
6. Volume of support Structure needed (mm³)
7. Height of the part (mm)
8. Volume of the part (mm³)

Subsequent subsections describe the calculation of the first six parameters. The last two parameters are obtained directly from the NX CAD model using NX Application Programming Interface (API).

3.3.1. Slice Contour Offset Algorithm:

Sharp corners, small holes and number of thin regions are calculated using the algorithm described below. The CAD design of the part is converted into a STL format and slicing operation is performed using the algorithm described by Topcu et.al. [42]. Points obtained for every slice contour are arranged in a sequential order and connected using line segments. The internal angle (ϕ) between two consecutive line segments is computed and stored. The number of sharp corners
with interior angles less than a predefined threshold of 20° in any slice are counted and recognized as sharp corners. Next, an inward offset of the slice contour is constructed using the reverse STL facet normal and internal angle information as shown in Fig. 21(a). All offset polygons (ABCD) are examined for intersection with any other offset polygons. If the offset polygons intersect with each other a thin region is recognized in the slice (Fig 21(b)). Similarly, when the offsetting is performed in the direction of STL facet normal, the algorithm provides information about the number of small openings or holes in a slice contour (Fig 21(c)). The flowchart for contour based offset algorithm is presented in Fig 20.

Figure 20. Flowchart for contour offset algorithm
3.3.2. Triangular Facet Based Algorithm:

Next the mean cusp height, volume of support and support contact area is calculated. The part surfaces are approximated as triangular facets within NX using API functions. Cusp height for each facet is calculated and summed up using Eq. (1) [6]. Mean cusp height is thus obtained as shown in Eq. (13).

\[
Mean\ Cusp\ Height = \frac{\sum_{i=1}^{n} t \cdot \cos \theta}{n}
\]  

(13)

where, \( n \) is number of facets, \( t \) is slice thickness and \( \theta \) is angle between facet normal and build axis.

For calculation of support volume and contact area, the normal vector of each NX facet is computed and angle between the normal and build axis is calculated. If the angle is greater than 125° (90°+35°), then that facet is marked as a support facet. Supports are manually created for marked facets using the modeling tool of NX and volume of support is stored.

Further, for calculation of support contact area, a facet projection algorithm is used. First, area of every triangular support facet in NX is computed using triangle area formula. Next, the facets which are not marked for support but lie directly beneath a support facet are identified and marked

Figure 21. (a) Internal angle and offsetting (b) Thin region detection (c) detection of thin openings
as contact facets. The total contact area is given by sum of the areas of both support and contact facets. Fig 22(a) and (b) highlight the support and contact facets respectively for a part. The detailed algorithm is described in the flowchart shown in Fig 23.

Figure 22. Hollow cylinder (a) facet requiring support (b) facet touching support

Figure 23. Flowchart for triangular facet algorithm
3.3.3. **Mathematical Definition of Producibility Index (PI):**

All the eight factors considered are used to construct a part Producibility Index (PI). Since all the factors considered for PI have a different order of magnitude, they have to be normalized to the same scale for comparison. Suppose S is the set of ‘n’ designs to be compared,

\[ S(D) = \{D_1, D_2, D_3, \ldots, D_n\} \]

and C is the matrix of ‘m’ factors considered for n designs,

\[ C = \{C_1(D_1), C_1(D_2), C_1(D_3), \ldots, C_1(D_n), \]
\[ C_2(D_1), C_2(D_2), C_2(D_3), \ldots, C_2(D_n), \]
\[ \ldots \ldots \ldots \ldots \ldots \ldots \ldots \]
\[ C_m(D_1), C_m(D_2), C_m(D_3), \ldots, C_m(D_n)\} \]

Then PI for a Design \((D_j)\) is given by Eq. (14):

\[
PI(D_j) = \sum_{i=1}^{r} \frac{W_i \times C_i(D_j)}{\text{Max}\{C_iD_1, C_iD_2, \ldots, C_iD_n\}} + \sum_{k=1}^{s} \frac{W_k \times \text{Max}\{C_kD_1, C_kD_2, \ldots, C_kD_n\}}{C_k(D_j)}
\]

(14)

where,

\(W_i\) and \(W_k\) are weights for different factors

\(i = 1\) to \(r\) represents favorable criteria for design

\(k = 1\) to \(s\) represents unfavorable criteria for design

Such that,

\(r + s = m\)
where larger values of favorable criteria and smaller values of unfavorable criteria are good from a design for AM perspective. Here, $C_m (m=8)$ represents the eight factors described in the section of Producibility Index and the weights are decided based on designer’s priority for these factors such that the sum of all the weights remain unity.
4. RESULTS

This section presents the application of described design methodologies to the design evolution process. Five case studies are used to depict the improvement in the manufacturability of a design based on the design rules formulated in this work. Figure 15 depicts the proposed design improvement cycle with increasing Producibility index with every design change iteration. As the value of index increases, the designs become more amenable to manufacturing with reduced cost.

![Diagram of design evolution process](image)

**Figure 24. Process of design evolution**

The first two case studies implement the design improvement method described in 3.2.1 and increment in manufacturability is observed by comparing the Producibility Index (PI) for designs. Third case study uses a FEA based thermo-mechanical model for simulating Laser Sintering process and thermal stresses are compared. Last two case studies implement the topology optimization based design method described in section 3.2.2 and support reduction in the designs is highlighted.
4.1. CASE STUDY 1: SLICE CONTOUR ANALYSIS

In this study, the design of a heat sink is considered. The first design shown in fig. 16. presents a type of heat sink that has fins with knife edges. The feature graph of this design highlights all the knife edges as critical features because they form sharp corners in the slice contours. Also, for a heat sink design, surface area is a measure of efficiency. Thus, in the second iteration, the design is modified to eliminate features that form the sharp corners while attempting to increase the surface area for better heat transfer.

Figure 17. shows final iteration of the design modification process of a heat sink. It represents a modified design for a radial heat sink with twice the surface area of design 1. Also, from the point of view of conventional manufacturing methods, design 1 is easier to manufacture. But in the case of AM, design 2 shows higher PI and thus has better manufacturability where the thin regions and sharp corners have been eliminated. So, this case study is an example that showcases unique manufacturing capabilities of AM which allows a designer to incorporate complicated features for increased efficiency. Table 2 shows the computation of PI and the progression of design iterations for this case study.

Figure 25. Design 1 for heat sink

Figure 26. Design 2 for heat sink
4.2. CASE STUDY 2: SUPPORT STRUCTURE ANALYSIS

In this case study, the design of a simple bicycle pedal is considered for manufacturability validation. Figure 18(a) shows the first iteration of design with a central cylindrical feature as the main functional feature. The feature graph of this design is constructed and violations associated with every face are marked on the feature graph. It is observed that one particular face contributes to almost all of the support requirement and the same face is also responsible for problems related to re-coater movement. Thus, modification of this particular feature is the main focus in the second iteration.

In the second iteration, the design is changed by keeping the central cylindrical feature unchanged and modifying the topmost planar face to a curved feature as shown in Fig 18(b). A major reduction in support volume and support contact area is achieved in this iteration. Also,
tilted cylinders were made horizontal so that the number of sharp corners are reduced. The effect of these changes are reflected on the increased value of PI, with the PI for design 2 being 1.4 times than that of design 1. Further, using the feature graph, it is observed that there is additional scope for reduction of support volume. So, the third iteration focuses on modifying features such that support need is further minimized.

In the third design iteration shown in Fig 18(c) the side pedal members were made slightly oblique and the top curvature was adjusted such that support needs are further reduced. Owing to this change, producibility of design 3 is approximately 3.5 times more than the initial design. Table 3 presents the calculation of PI and shows the progression of the designs. Table 3. Presents the calculation of PI and shows the progression of the designs.

Figure 27. Bicycle pedal (a) design iteration1 (b) design iteration2 (c) design iteration3

<table>
<thead>
<tr>
<th>S.No</th>
<th>Factor</th>
<th>Design 1</th>
<th>Design 2</th>
<th>Design 3</th>
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</thead>
<tbody>
<tr>
<td>1.</td>
<td>Mean cusp height</td>
<td>0.024771</td>
<td>0.029488</td>
<td>0.03543</td>
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<td>2.</td>
<td>No. of sharp corners</td>
<td>24</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>3.</td>
<td>No. of thin regions</td>
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<td>0</td>
</tr>
<tr>
<td>4.</td>
<td>No. of fusible contours</td>
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<td>0</td>
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<td>Build Height (mm)</td>
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<td>127.5</td>
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<td>Volume of support (mm³)</td>
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<td>7.</td>
<td>Volume of part (mm³)</td>
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<td>81026.32</td>
<td>87925.4944</td>
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<tr>
<td>8.</td>
<td>Area touching support (mm²)</td>
<td>14556.77</td>
<td>9063.9824</td>
<td>1214.2</td>
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<tr>
<td></td>
<td><strong>Producibility Index (PI)</strong></td>
<td><strong>7.336</strong></td>
<td><strong>10.763</strong></td>
<td><strong>26.15</strong></td>
</tr>
</tbody>
</table>
4.3. **CASE STUDY 3: THERMAL ANALYSIS**

In this study, two designs are compared for the effect of curling in laser sintering. Figure 28. shows a lever with two holes 50 mm apart with 8 mm diameter. The design of the lever is such that the connecting link between two functional holes is a box type structure which is susceptible to curling. Figure 29. presents an alternate design for achieving the same functionality, by replacing the straight box with curved links. Design 2 also has the same two 8 mm holes which are 50 mm apart thus maintaining product functionality.

Both these designs are simulated using a 3D FEA model in ANSYS. The process of laser sintering is simulated using the method of birth and death of elements [43]. Figures 21 & 22 present the result for both these designs. It was found that maximum deformation in design 2 is 52% less than design 1, thus increasing the manufacturability and conformance of this part.
4.4. CASE STUDY 4: TOPOLOGY OPTIMIZATION FOR CANTILEVER BEAM

This case study presents the application of topology optimization process for generating designs with minimal support requirements. The design of a cantilever beam is considered here for application of mathematical formulation presented in section 3.2.2. Figure 32. shows the problem formulation in which loads are applied at the end of the design space and the other end is fixed and constrained for any movement. Both standard and DFAM constrained topology optimization processes are applied for finding cantilever design and results are presented. Table 4. shows the specifications used for running the topology optimization process. Figure 33(a) shows the output design of standard topology optimization process. The voxel based output of optimization process was used as a basis for developing a 3D model for the cantilever beam using NX model and is depicted in fig. 33(b). Support requirements for the designs are identified and support structures are generated using the 35° angle based criteria. Figure 33(c) shows the design with required support structures.

![Figure 32. Problem definition for cantilever beam](image)

The result for DFAM constrained topology optimization is shown in figure 34(a). NX based 3D model and support requirement for this design are shown in fig. 34(b) and 34(c) respectively. It is observed that design 1 shown in fig 33(b) has a top flat feature which is responsible for most of the support. However, for design 2 (fig. 34(b)) material distribution has
been changed to avoid such long flat feature, with a resulting total support volume reduction of 73.6% is achieved. Table 5. presents the comparison of both designs and it can be observed that a 24% reduction in total sintering volume is obtained.

Table 4. Process specifications for topology optimization

<table>
<thead>
<tr>
<th>S.No</th>
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<th>Standard topology optimization process</th>
<th>Constrained topology optimization process</th>
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<tbody>
<tr>
<td>1.</td>
<td>No. of elements in X direction, $N_x$</td>
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<td>50</td>
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<tr>
<td>2.</td>
<td>No. of elements in Y direction, $N_y$</td>
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<td>20</td>
</tr>
<tr>
<td>3.</td>
<td>No. of elements in Z direction, $N_z$</td>
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<td>10</td>
</tr>
<tr>
<td>4.</td>
<td>Initial Density</td>
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<td>0.3</td>
</tr>
<tr>
<td>5.</td>
<td>Density filter threshold</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>6.</td>
<td>Penalty</td>
<td>4</td>
<td>$6 - \frac{6 - 2}{6(\alpha - 1) + 1}$</td>
</tr>
</tbody>
</table>

Figure 33 (a) Topology optimization result (b) Design for cantilever beam (c) Design with support

Figure 34 (a) Results for constrained topology optimization process (b) 3D model for design (c) support structures
A final validation FEA for both designs is conducted in ANSYS workbench. It is found that the new design obtained by constrained topology optimization is capable of sustaining applied loads. Maximum stresses are found to be less than the yield strength of specified material i.e. 2.5e8 Pa. Table 6. presents maximum stress and deformation values for both designs and fig. 35. shows deformation results.

![Deformation results](image)

**Figure 35. Deformation results for (a) standard top. opt. (b) constrained top. opt.**

<table>
<thead>
<tr>
<th>Table 5. Design comparison table for case study 4</th>
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<tbody>
<tr>
<td><strong>Build Time: Height of Part (mm)</strong></td>
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<tr>
<td>Area requiring Support (mm²)</td>
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<td>Volume (mm³)</td>
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<tr>
<td>Support Volume (mm³)</td>
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<tr>
<td>Total Sintering Volume (mm³)</td>
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</table>

<table>
<thead>
<tr>
<th>Table 6. Validation FEA results</th>
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<tr>
<td><strong>Results</strong></td>
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<tr>
<td>Standard Top. Opt.</td>
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<tr>
<td>Constrained Top. Opt.</td>
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</table>
4.5. **CASE STUDY 5: TOPOLOGY OPTIMIZATION FOR SUPPORT STRUCTURES**

Generally in AM, build orientation is decided by the manufacturing department after receiving the final design. Sometimes the presence of certain critical features plays a very important role in deciding build orientation. For e.g. it is advised to fabricate cylindrical features with high tolerances such that it is manufactured with the build axis along the cylindrical feature axis. The process of DFAM constrained topology optimization becomes more relevant in such conditions because in this process build orientation is defined before beginning the optimization. This case study applies the DFAM constrained topology optimization process for a design space which has a predefined cylindrical hole. In this situation, the axis of hole is defined as the best build orientation. Figure 36. presents the problem formulation where a square design space is loaded with uniform vertical force distribution applied along its edges. The dimensions for design space are defined as 50 units X 50 units X 10 units with a 5 units radius hole in the center. All other parameters are same as shown in table 4. Due to symmetrical design space geometry, only a quarter of design space is considered for optimization process and obtained results are extrapolated. Figure 37(a) shows the result for standard topology optimization process. The NX 3D model is created using the voxelized output of MATLAB code and supports are generated in NX using the angle based criteria. Figure 37(b) and (c) presents the NX model and support structures respectively.

![Figure 36. Design space and loading conditions for case study 5](image-url)
The DFAM constrained topology optimization process is applied on same design problem and the generated output is shown in fig. 38(a). The 3D model based on the output is constructed using NX which is shown in figure 38(b). Support structures are created by identifying regions requiring supports and support volume for both designs are compared. It is found that the need for support reduces by 45% in the case of DFAM constrained topology optimization process. Also, total sintering volume reduces by 13.6%. Figure 38(c) presents the design with required supports and table. 7. shows the reduction in support volume and contact area. Figure. 39. Shows the deformation results for both the designs and table. 8. presents the FEA validation results.

Table 7. Design comparison table for case study 5

<table>
<thead>
<tr>
<th></th>
<th>Standard Top Opt</th>
<th>Constrained Top Opt</th>
</tr>
</thead>
<tbody>
<tr>
<td>Build Time: Height of Part (mm)</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Area requiring Support (mm²)</td>
<td>232.36</td>
<td>190.1</td>
</tr>
<tr>
<td>Volume (mm³)</td>
<td>9784.74</td>
<td>8998.10</td>
</tr>
<tr>
<td>Support Volume (mm³)</td>
<td>1730.5</td>
<td>948.21</td>
</tr>
<tr>
<td>Total Sintering Volume (mm³)</td>
<td>11515.24</td>
<td>9946.31</td>
</tr>
</tbody>
</table>
A final FEA of both designs become necessary as it is observed that compliance value of DFAM constrained topology optimization is higher than that of normal topology optimization. The support criteria integrated in the DFAM topology optimization is responsible for making the process more difficult to converge and thus increasing the compliance value. In case of topology optimization process compliance is calculated assuming variable nodal densities. However, actual design is created using the described density threshold of 0.5. Thus, compliance value reported by topology optimization process is not completely accurate and the final FEA validation results verify that both the designs are suitable for sustaining the specified loads.

Table 8. Validation FEA results

<table>
<thead>
<tr>
<th>Results</th>
<th>Max. Deformation (mm)</th>
<th>Max. Stress (Von-Mises) Pa</th>
<th>Compliance (1/Pa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top. Opt.</td>
<td>6.408e-4</td>
<td>2.837e6</td>
<td>1.866e8</td>
</tr>
<tr>
<td>DFAM constrained Top. Opt.</td>
<td>7.31e-4</td>
<td>4.005e6</td>
<td>2.346e8</td>
</tr>
</tbody>
</table>

Figure 39. Deformation results for (a) standard top. opt. (b) constrained top. opt.
5. CONCLUSIONS AND FUTURE SCOPE

In this paper, the process of DMLS is analyzed and sources of error in part fabrication are identified. Using this analysis, design guidelines are formulated and two design approaches are presented which focuses on increasing part manufacturability. In the first method, a feature graph based design improvement technique which applies developed design guidelines for creating more feasible designs is presented. The concept of feature graph is presented which can assist a designer to identify features that may hinder manufacturability. In the second method, a DFAM constrained topology optimization based design which integrates DFAM design rules with topology optimization process is presented. The design methods presented in this paper are not only useful for a novice designer who may not be aware of the nuances of the DMLS process, but also beneficial for experienced designers who may find it difficult to integrate all the constraints into a unified design process. Moreover, there are features which may require tradeoffs and decisions from a designer based on functionality of the product. The proposed method can be applied to determine these features and increase manufacturability while reducing costs. Also, a scoring scheme is presented which can quantify a design and its improvement from the viewpoint of manufacturability. The methodology is demonstrated using case studies where improvement in manufacturability is observed.

Future work in this area includes further investigation of laser sintering process and development of more design guidelines. Here, feature graph based design improvement method considers only manufacturability issues whereas mechanical strength is not considered. Moreover, there could be other design and topology constraints in product development as well. Also, DFAM constrained topology optimization based method only focuses on support structure reduction. Thus a more integrated approach combining other important design factors can be developed. The effect
of build orientation is a critical factor in AM. Often guideline violations can be avoided just by changing the build orientation. Thus, analyzing orientation effects on manufacturability can be another avenue for future research.
6. REFERENCES


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