DESIGN FOR ADDITIVE MANUFACTURING - A REVIEW

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Abstract
Design for manufacturing involves the practice of designing products to reduce manufacturing difficulties and cost, by optimizing the component for a particular manufacturing process. Design for additive manufacturing (DFAM) intends to design a part for additive manufacturing to obtain the advantages additive manufacturing offers by reduction in cost of production. DFAM allows the product to be visualized as a function which is intended to be performed with the only constraint being the size of the product. The advantage of additive manufacturing cannot be extracted to the fullest extend if DFAM is not utilized. As additive manufacturing processes are expensive compared to conventional processes the cost advantage can be achieved only through savings in material and reduced cycle time for production. Since the time required to manufacture a product by additive manufacturing is directly related to the amount of material required to produce the part, the objective of cost savings can be achieved only when lesser amount of material is consumed. The objective can be achieved by utilizing topology optimization. Topology optimization existed even before additive manufacturing came into existence as a commercial manufacturing process. But the ease with which optimization can be performed increased with the increase in computing power and speed. A study categorized DFAM for three categories, manufacturing, assembly and performance. The main objective is to meet the desired mechanical properties with minimum material and thereby minimizing the cost of product. This study summarizes the DFAM guidance rules which are qualitative and quantitative in nature. The qualitative ones are comparable to traditional DFM rules by Boothroyd and Dewhurst. Different design rules framed by different authors have been studied to find a consensus converging towards achieving a primary design objective.

Key words: Design for additive manufacturing, DFAM, Optimization, Additive manufacturing

Introduction
Design rules have been framed by practicing designers based on their experience in AM which focused on the printability of the part designed rather than utilizing the unique capabilities of AM. The rules framed were generic considering all AM processes as a separate group of manufacturing process [22]. But each AM processes are unique since the underlying physics of the process in creating the part layer by layer is different in each process. It also depends to a greater extend on the material used in creating the desired part layer by layer. AM no longer can be considered as a process to be utilized only for prototyping, since companies have started utilizing it for small scale production of critical components. The word critical can be elaborated as criticality of the design of the part which cannot be produced by any of the traditional manufacturing process. In some cases the criticality can be considered as the time and cost involved in producing the part which is not possible economically by any traditional processes. It has to be remembered that since the legacy of traditional manufacturing dates back to more than 100 years and they are very much cost effective in a mass production setup. It is not possible to efficiently design components if the sensitivities of the process are clearly understood, hence the DFAM is not an optional but a mandatory knowledge to be acquired by designers utilizing AM capabilities in their design [22]. Design for manufacturing intents to design a component to reduce the manufacturing difficulties and cost associated with the production of the part. Design for additive manufacturing helps to design a part which can be effectively manufactured utilizing AM capabilities to the best possible extend knowing the limitations of AM process [22].

DFAM strategies
Yang and Zhao proposed that DFAM can be categorized for manufacturing, assembly and performance. They also proposed three categories of AM related design methods comprising general design guidelines, modified conventional design theories and methodologies and DFAM. The focus of their analysis was in attaining the desired mechanical properties by optimization of the structure of the component [36]. Kumke, Watschke, and Vietor (2016) classified DFAM guidance into two categories based on their main purpose and application, and named them as ‘DFAM in the strict sense’ and ‘DFAM in the broad sense’. ‘DFAM in the broad sense’ refers to guidance which are not directly related to the design process itself such as selecting the appropriate AM process. On the other hand ‘DFAM in the strict sense’ includes ‘AM design rules’ which ensures that parts are printable as well as ‘AM design potentials’ to take advantage of capabilities of AM [15]. Jänsch and Birkhofer 2006 points out that research results in designing are implemented in the design guidelines with the intention of implementing them in practice. This has paved way for the descriptions and guidelines of individual designers to take a back seat. They also state the necessity for science, industry und teaching in coming together to bridge
the design synthesis phase [25].

Yang and Zhao 2015 presents specific design guidelines, whereas Gibson, Rosen, and Stucker 2010 focused on AM capabilities while Laverne et al. 2015 discusses about ‘opportunistic DFAM’ [37]. Rosen proposes to use cellular structures in his design strategy which links functional requirements to part properties [28]. Ponche et al. states a methodology which begins with the definition of functional and empty volumes. This is followed by establishing minimum and maximum part dimensions. Minimum part dimensions are the smallest dimensions needed to contain all functional volumes. Maximum dimension takes into consideration the proposed use of the part like their fit in an assembly or mobility requirements desired for the products use. Now the constraints related to functional and empty volumes are used for screening suitable processes and materials [24].

Adam and Zimmer (2015) and Kranz, Herzog, and Emmelmann (2015) presented a set of detailed rules to identify feature types in relation to their dimensions. These feature level rules ensures printability but it doesn’t ensure the conceptual optimality of the part as desired [1]. Almost all studies distinguish between two different types of design guidance: The potential of AM which relates to the qualitative capabilities of the process and the printability of the part which is quantitative in nature focusing on the component features and the constraints of AM [22]. While most of the guidelines are generic in nature, Rosen, 2007 proposed a biomimetic approach and Salonitis (2016) proposed an axiomatic design method to improve current design approach for AM. The former is based on process-structure-property-behavior model which is common in the materials design community. Axiomatic design method utilizes a zigzag decomposition keeping in mind two fundamental design axioms, the independence axiom where each functional requirement has to be independent and the information axiom which intends to select the design alternative which has minimum information content. This method takes into account the manufacturing capabilities and limitations of the process under consideration [28, 29]. These rules tend to apply at the detail design stage to optimize the products geometric features and dimensions according to the capability of the specific AM process [22].

R. Ponche, et al. designed a process-independent global approach which combines process characteristics with functional specifications and context stating what needs to be optimized. He defines new part designs by defining functional surfaces and then volumes of a part and empty volumes that will be occupied by other parts. A drawback of this method is that material and process have to be selected before applying the method since these information were mandatory during the design synthesis phase [25].

Kumke et al. developed a DFAM framework which combine the general procedure for systematic design with DFAM methods and tools. This provides guidance to the designer enabling them a framework to proceed from a design problem to design solution [15].

Rias et al. proposed a 5 stages ‘creative DFAM’ based on AM design features database mostly intended to be used in early design stages [26].

G. Sossou et al. 2017 proposes a top down assembly design methodology for AM. This approach provides guidance in defining the product architecture considering printability and functional requirements. In printability downstream process characteristics such as build orientation is taken into account in the design process. On the other hand functional requirements ensures effective functional Flow of energy, material or signal as desired while the objective is to minimize material and cost. The proposed approach is structured in three main stages comprising of functional analysis, derivation of components control structures and design of components geometries [30].

Research efforts in DFAM can be classified into three major groups: design recommendations, methodologies and tools, and design procedures. The recommendations are derived from the results of empirical studies. They include part shape and dimensions, manufacturing orientation, etc [30]. G. A. O. Adam, D. Zimmer, in a German project ‘Direct manufacturing design rule’ provides the basis for other studies framing design rules. G. A. O. Adam, D. Zimmer, D. Thomas, J. Kranz, has noted that the design rules framed from experiments are AM process and material specific [2, 14, 30, 31].

Gibson et al. states that DFAM should maximize product performance through the synthesis of shapes, sizes, hierarchical structures and material compositions, subject to the capabilities of AM technologies [7].

B. Vayre et al. propose that a component can be defined by a set of functional surfaces, a clearing volume and a specified behavior. The functional surfaces helps to serve the function intended like assembling to other parts or to transfer mechanical/thermal loads and/or fluid tightness. The clearing volume helps the part to prevent from colliding with other parts and to allow fluid transfer through. The specified behavior can be mechanical, thermal or multi-physics [36]. The designer has to start by defining functional surfaces. Then the surfaces are linked to attain the specified behavior. The choice of initial shape can be based on guidelines, expert-based or by automation utilizing topological optimization [36].

Any of the product’s components can be characterized by functional interfaces, possible flows getting through and the design space collectively known as control structures (CS). The whole product is designed by connecting the functional interfaces, allowing adequate conveyance of flows while staying within the prescribed design space and considering the specific AM process constraints [30].

Manufacturing capabilities

B. Vayre et al. states that layer based processes need a plane surface to start the manufacture whereas direct material deposition processes can deposit material on metallic substrate of complex geometries [36]. In direct material deposition to minimize acceleration and
deceleration stages of nozzle movements sharp corners should be avoided in design. But in case of EBM there is no need for minimum fillet radii. The only constraint is that the minimal wall thickness should be larger than the voxel size [36].

**Figure 1:** Functional interface effect on design spaces [30]

### Manufacturing constraints

The major limiting factor in considering AM for making parts is the lack of knowledge in successfully designing printable components and complete utilization of AM capabilities [22]. Kim states that support structures, surface quality, curling/warping, minimal feature sizes, shape accuracy, resolution and anisotropy directly relate to the buildable geometry for certain processes [12].

B. Vayre et al. states that to properly utilise the advantage of AM specific manufacturing capabilities and constraints have to be taken into account during DFAM. They identified two main manufacturing constraints which are that the nozzle must stay parallel to the vertical axis and the speed of deposition which gives the height of the deposited material. Heat dissipation is the biggest constraint in all layer based processes [36].

Tools such as topological optimization tend to focus on mechanical requirements such as strength and stiffness and neglect other important aspects such as maintenance and cleaning ability. There is also a need for guidance at early stage of design to generate innovative concepts that results in cost effective product solutions utilizing AM capabilities [22].

Tomiyama et al. 2009 suggests that prescriptive type design methods find limited application in industrial context mainly due to the lack of approach specific to the machine and process used in industry. However large corporations which have rigid processes in-house tend to utilise them in their own design methods and processes [33].

D. E. Whitney, in his book titled ‘Mechanical assemblies their design, manufacture, and role in product development’ suggested that consideration of DFAM from an assembly perspective would result in a wider adoption of AM in industries [40].

When considering assemblies the main concern is about the clearance gaps desired to ensure the desired fit needed for the assembly and avoiding support structures and unprocessed material within these gaps. It has been found that it is easy to remove unprocessed material from the gap than to remove cured support structure [30].

### Selecting an AM process

There most important factors to consider while selecting an AM process over another are process capability, machine availability and printing cost [22].

ULLman states that most of the material in a component is used to connect the functional interfaces and hence are not dimensionally critical [34].

Goutier and Ashby proposes to use screening and ranking steps, for both material and process selection [3, 41].

T.H.J. Vaneker suggests that to assess the use of AM, the possible implication of including AM in all stages in a product development have to be considered [35].

It has been reported that laser based processes consumes 50-100 times more electrical energy than injection moulding. It has also been observed that by orienting the part to minimum build height reduces energy consumption for powder bed process [35].

### Lattice structure and topology optimization

M. P. Bendsoe and O. Sigmund, in their book titled ‘Topology Optimization: Theory, Methods, and Applications, states topology optimization as a numerical method optimizes matter distribution within a defined design space, under a set of specified boundary conditions, loads and constraints [42].

L. J. Gibson and M. F. Ashby in their book ‘Cellular Solids: Structure and Properties’, states that lattice structures are numerically generated truss like structures with high strength to weight ratios, good energy absorption, thermal and acoustic insulation characteristics. They are utilized at detail design stage on a part which may be topologically optimized or not to improve a specific performance [43].

Emmelmann, et al. states that while topological optimization results in theoretical best solutions their manufacture may still have issues like too much support, enclosed spaces, etc. [5].

Zegard and Paulino have developed a tool to support their proposed method which creates AM ready topology optimized part where support elimination is considered as a constraint to the TO algorithm [39].

A.Hadi, et al. reviewed different types of lattice structures and utilized them in developing a computational tool to generate them [8].

Fuel nozzle for leap engine from GE is a best example to consider for part consolidation where 855 components were reduced to just a dozen ones [35].

Topology optimization using numerical methods performed by computer determines optimal geometry for the part under consideration based on a set of constraints. To achieve this the solution space is divided into small elements and the solution algorithm is applied along with the constraints to determine which elements are part of final product and which are not [35].

Lindeman among other utilizes topology optimization for weight reduction in airplanes. This helps to reduce wear and increase efficiency due to lesser number of parts involved. He also states that existing DFAM strategies are based on early selection of both AM process and material and proposes an approach which delays this choice allowing designers to test generic applicability of AM [19].
Mirzendehdel et al. observed that standard use of TO strategies utilize mechanical constraints which may result in parts which are difficult to be optimally produced even using AM. They proposed a TO variant which includes the AM process constraints. It balances weight reduction along with low level of support materials to achieve a topology optimized part [20].

B. Vayre et al. recommends to use lattice structures along with topology optimization rather than using the former alone since the combination proved to be an optimal choice the part considered for their study [36].

**Parametric optimization**

In AM, manufacturing duration, raw material consumption, energy utilization and global cost are all linked to the part volume [36].

Current parametric optimization methods involve performing empirical studies which focus on optimization of the response variable under consideration.

**Shape validation**

Availing an optimised part for AM can be achieved by minimizing material usage and the manufacturability can be validated by direct manufacture of the parts [36]. So there lies a research gap facilitating the development of strategies to build an efficient software that will perform virtual shape validation thereby eliminating the need for actual printing to check the manufacturability of the part designed.

**Conclusion**

Different types of DFAM strategies are reviewed and it is found that most of them provide a set of generic rules to abide by while designing. Since each AM process is different from other these generalized rules are difficult to be practiced in industry at machine level. Many industries follow their own DFAM strategies developed from their experience. There is consensus among different authors related to the workflow which has to begin by defining functional interfaces and then connecting the interfaces to achieve the desired material/flow. The necessity to define minimum and maximum dimension of a part is explained. Most DFAM methodologies are devised to be applied at detail design stage while two methodologies have been found to be utilized even at conceptual design stage. There exists a need for collaboration between science, research and industry to produce guidelines which can be utilised directly in industries and in design soft wares. To utilize AM to its fullest capability lattice structures has to be used along with topology optimization

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