COBEM 2023 27TH INTERNATIONAL CONGRESS OF MECHANICAL ENGINEERING

ABCM Brazilian Society of Mechanical Sciences and Engineering
27th ABCM International Congress of Mechanical Engineering
December 04-08, 2023, Florianópolis-SC, Brazil

# COB-2023-1218
# DESIGN FOR ADDITIVE MANUFACTURING GUIDELINES FOR MATERIAL EXTRUSION: A REVIEW

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***Abstract.*** *Additive Manufacturing (AM) technologies have grown since their inception in the late 1980s. Material extrusion (MEX) is a technology with a considerable variety of feedstock materials and is cost-effective. Due to technological advances, research in this area has recently increased, especially regarding metallic materials and hardware improvements. These processes generally have characteristics that users constantly seek to improve, such as surface finishing, geometrical and dimensional precision, mechanical strength, time, cost, and material consumption. In this manner, users can employ Design for Additive Manufacturing (DfAM) techniques to improve these characteristics through development guidelines that aid the preliminary stages of product development, considering the aspects of a specific AM technology. Based on a good understanding of the main boundary conditions of each AM process, DfAM's main objective is to define operation rules and guidelines to apply them effectively. The lack of methods to help users design parts considering MEX process characteristics is still a major limiting factor to the wide adoption of this technology in the industry. Several studies in the literature claim to use DfAM rules to optimize and improve the results of the AM processes. However, it still needs to be determined how users employ them and whether they are valid for all cases. Therefore, this study contributes to the literature by presenting an integrative review of scientific papers available on different academic platforms to investigate whether end users are applying DfAM techniques in MEX. Research has shown that it is challenging to construct a global guideline that addresses all AM technologies simultaneously. Although there are sets of recommendations and best practices to follow, there is still room for improvement regarding design in MEX. Despite researchers affirming the use of DfAM, one perceives that designers indirectly acknowledge it by designing parts considering the manufacturing results instead of following a specific set and order of rules. In discussing MEX and DfAM further, this work aims to contribute by increasing the range of applications of this technology in the industry due to the information presented by this review.*

***Keywords:*** *Design for Additive Manufacturing, DfAM, material extrusion, MEX, guidelines, design methods.*

## ACRONYMS

| | |
|---|---|
| ABS | Acrylonitrile Butadiene Styrene |
| AM | Additive Manufacturing |
| CPLA | Conductive Polylactic Acid |
| DED | Directed Energy Deposition |
| DfAM | Design for Additive Manufacturing |
| DfM | Design for Manufacturing |
| MEX | Material Extrusion |
| PBF | Powder Bed Fusion |
| PETG | Polyethylene Terephthalate Glycol |
| PLA | Polylactic Acid |
| SLM | Selective Laser Melting |
| SLS | Selective Laser Sintering |
| TPU | Thermoplastic Polyurethane |

## 1. INTRODUCTION

Additive Manufacturing (AM), also known as 3D printing, has become a key technology for the manufacturing industry due to its ability to produce complex and functional parts that would be difficult or impossible to make using traditional methods (Volpato et al., 2017). Currently, AM is being applied in industries like aerospace, medical, automotive, and consumer goods. It is increasingly being used to produce end-use parts and products, prototypes, and tooling. Although it is constantly evolving to improve quality and performance, it has yet to become competitive with serial processes. Complex manufacturing has slowly shifted from conventional manufacturing to AM technologies

(Bandyopadhyay & Heer, 2018). In this sense, Diegel et al. (2020) state that AM technologies should be only used if we are “truly adding value to our product”.

Currently, the AM processes are defined by the ISO/ASTM 52900:2021 standard, which divides the technologies based on seven principles of addition. Material extrusion (MEX), also known as fused filament fabrication (FFF) when processing polymers, is one of the most common AM processes because of its cost-benefit and ease of control compared to others (Stano et al., 2022). It is compatible with a wide range of materials, including thermoplastics, composites, and even some metals combined with polymers, which can produce functional parts with specific mechanical properties.

Advances in metal MEX are very recent. The first patent involving metallic filaments was filed by Markforged® in 2014, protecting a continuous manufacturing process composed of three main steps: standard 3D printing, debinding, and sintering. Since then, technological advances have facilitated the creation of metallic filaments of several materials such as aluminum, bronze, copper, Inconel®, iron, stainless steel, tool steels, tungsten, and titanium (Markforged, 2023; Virtual Foundry, 2023).

Other standard AM techniques that process metallic material, such as Powder Bed Fusion (PBF) and Directed Energy Deposition (DED), are usually more expensive, require more extensive infrastructures, and require complex hardware operation and maintenance. Furthermore, another great advantage of MEX is that it is one of the most studied AM technologies (Hamel et al., 2018). A vast literature is available regarding the physicochemical phenomena involved, as well as many free Computer Aided Manufacturing (CAM) programs capable of giving the user total control over the process.

Despite these material and process advances, it is known that MEX processes generally present characteristics that can be constantly improved, such as surface finishing, geometrical and dimensional precision, mechanical strength, time and cost, and material consumption. Additionally, it produces a green part that needs a post-processing stage, which involves debinding and sintering, to reach the final material properties. While MEX presents these limitations, it remains a widely used and accessible technology for prototyping and end-use production.

In that sense, the Design for Additive Manufacturing (DfAM) emerges as a methodology to improve the reach of AM technologies. The term originates from DfM, which is an abbreviation for Design for Manufacture, commonly used in other manufacturing processes to optimize steps, improve quality, create reliability, and, as always, reduce costs and manufacturing times (Asadollahi-Yazdi et al., 2016, 2017; Wiberg et al., 2019).

The concept of DfM was first introduced by Geoffrey Boothroyd (1994), who highlighted the “importance of taking careful account of manufacturing and assembly problems in the early stages of product design” (Boothroyd, 1994). Through correlated methodologies, such as Design for Manufacture and Assembly (DfMA), it is clear to understand that the idea of dedicating more time in earlier stages of development is justified by an overall reduction in the time needed to bring the product to market (Asadollahi-Yazdi et al., 2016; Boothroyd, 1994; Leutenecker-Twelsiek et al., 2016). DfM rules generally guide designers to reduce the complexity of individual components, making them interact in more straightforward ways. These strategies reduce a product's overall cost but can increase the assembly complexity (Boothroyd, 1994).

Finding an immutable and universal definition for the DfAM in literature is difficult. Each paper and study present a suggestion that is usually closely related to the studied problem (Wiberg et al., 2019). However, in a very similar way to DfM, DfAM stands for a set of best practices and suggestions that optimizes designs that will be manufactured through AM technologies to overcome limitations and make the most of the capacity (Leutenecker-Twelsiek et al., 2016). It embraces all the procedures from the first concept to the final product version, aiming to reach the best geometric and material performance by combining cost, time, and quality optimization (Lopez Taborda et al., 2021). For that, users must master different design methods, AM process knowledge, and tools to explore the limits of the technology. The insufficient data available still limits a quicker entry of the AM technologies in industries (Djokikj & Kandikjan, 2022). For Diegel et al. (2020), DfAM consists of a process of thinking and making conscious decisions to maximize the benefits of AM by modifying the form and part function.

A detailed review of DfAM by Lopez Taborda et al. (2021) revealed that several authors have similar considerations about the current limitations of the available methodologies. Some authors, for example, highlight the need for methods to design better assemblies of printed parts. However, in general, there is a consensus that DfAM should contemplate multiple functions, objectives, scales, and approaches to deal with material design.

Fuwen et al. (2017) stated that MEX processes have significant drawbacks compared to other AM processes, such as lower manufacturing speeds, poor surface quality, and limitations regarding the spectrum of available materials, which are generally restricted to polymers.

However, several advances in MEX technologies have been achieved in the last few years. It is possible to state that MEX is one of the technologies that have been most employed and studied (Djokikj & Kandikjan, 2022; Hamel et al., 2018). In the literature, there are several DfAM reviews available (Djokikj & Kandikjan, 2022), and few of them focus specifically on material extrusion processes (Atatreh et al., 2023). The lack of methods to help users design parts considering MEX process characteristics is still a major limiting factor to the wide adoption of this technology in the industry and often prevents AM techniques from reaching their full potential (Adam & Zimmer, 2014, 2015; Djokikj & Kandikjan, 2022; Leutenecker-Twelsiek et al., 2016; Lopez Taborda et al., 2021).

In this way, this article aims to present a literature review of the DfAM guidelines available for MEX processes to investigate whether they are robust enough to meet process requirements and users' applications. The research also aims to understand how the available guidelines are applied and which are the limitations of current materials and process parameters.

## 2. DISCUSSIONS

This article is an integrative literature review with three guiding questions elaborated through a critical analysis of the DfAM theme in MEX processes. The article search was done in some databases and academic platforms such as Portal Periódicos Capes, Science Direct, SciELO, Scopus, and Google Scholar, with the following keywords DfAM, Design for Additive Manufacturing, material extrusion, and their possible Boolean combinations. In total, 23 papers were selected from the results found through the keywords used.

Table 1 presents the selected papers using the mentioned criteria. These were published between 2011 and 2023.

Table 1. Scientific papers selected for the study.

| Authorship | Title |
|---|---|
| Allum et al. (2023) | Extra-wide deposition in extrusion additive manufacturing A new convention for improved interlayer mechanical performance |
| Oliveira et al. (2023) | Production of an Office Stapler by Material Extrusion Process, using DfAM as Optimization Strategy |
| Atatreh et al. (2023) | Evaluation of the infill design on the tensile properties of metal parts produced by fused filament fabrication |
| Oliveira et al. (2023) | Production of an Office Stapler by Material Extrusion Process, using DfAM as Optimization Strategy |
| Kedziora et al. (2022) | Strength Properties of 316L and 17-4 PH Stainless Steel Produced with Additive Manufacturing |
| Spiller, Kolstad, et al., (2022) | Fabrication and characterization of 316L stainless steel components printed with material extrusion additive manufacturing |
| Spiller, Berto, et al. (2022) | Mechanical behavior of Material Extrusion Additive Manufactured components: an overview |
| Djokikj & Kandikjan (2022) | DfAM: development of design rules for FFF |
| Haruna & Jiang (2022) | Adaptability analysis of design for additive manufacturing by using fuzzy Bayesian network approach |
| Prajapati et al. (2022) | Supportless Lattice Structure for Additive Manufacturing of Functional Products and the Evaluation of Its Mechanical Property at Variable Strain Rates |
| Stano et al. (2022) | Additive manufacturing for capacitive liquid level sensors |
| Beltrán et al. (2021) | Estimation and improvement of the achievable tolerance interval in material extrusion additive manufacturing through a multi-state machine performance perspective |
| Nurhudan et al. (2021) | Additive manufacturing of metallic based on extrusion process: A review |
| Diegel et al. (2020) | A Practical Guide to Design for Additive Manufacturing |
| Rane et al. (2019) | Rapid surface quality assessment of green 3D printed metal-binder parts |
| Bandyopadhyay & Heer (2018) | Additive manufacturing of multi-material structures |
| Hamel et al. (2018) | Characterizing the effects of additive manufacturing process settings on part performance using approximation-assisted multi-objective optimization |
| Asadollahi-Yazdi et al. (2017) | Integrated Design for Additive Manufacturing based on Skin-Skeleton Approach |
| Lim et al. (2017) | Design for additive manufacturing of customized cast with porous shell structures |
| Leutenecker-Twelsiek et al. (2016) | Considering Part Orientation in Design for Additive Manufacturing |
| Adam & Zimmer (2015) | On design for additive manufacturing: evaluating geometrical limitations |
| Adam & Zimmer (2014) | Design for Additive Manufacturing - Element transitions and aggregated structures |
| Zimmer & Adam (2011) | Direct Manufacturing Design Rules |

After selecting the articles, main questions were elaborated and grouped, as presented in Table 2, to investigate the existing guidelines' scope and understand how and whether researchers and AM final users are applying them.

Table 2. Guiding questions.

| | |
|---|---|
| **1** | Are there DfAM guidelines available in the literature ready to be applied? Are they suitable for all AM technologies? |
| **2** | How have researchers employed DfAM guidelines in their studies? |
| **3** | Does DfAM have the capability to improve parts produced in MEX? How could DfAM expand the range of applications of the MEX technology? |

## 2.1 Analysis and discussion of the papers

In general, researchers highlight that DfAM can improve the cost-effectiveness of production by custom-fitting the needs to an available AM system (Lim et al., 2017). Previous and similar methodologies, such as DfM, have proven essential to quantify and mitigate costs at the early stages of product development (Boothroyd, 1994). Exploring the process parameters and creating a manufacturing plan are crucial tasks to optimize the parts' mechanical properties, quality, and final roughness, ensuring the parts' usability (Oliveira et al., 2023). In addition, the post-processing time can be reduced by using the DfAM principles (Prajapati et al., 2022).

On the other hand, it is clear from the literature that developing a single standard guideline for all seven principles of addition is practically impossible due to the large number of details and singularities of each approach (Djokikj & Kandikjan, 2022). Much of the available information still circulates mainly in academic environments, making the creation of a methodology based on industrial experiences a challenge (Leutenecker-Twelsiek et al., 2016).

As mentioned, research on MEX technologies has increased during the last few years, most likely due to the fall of invention patents. This situation leveraged research that started to explore open-access equipment (Djokikj & Kandikjan, 2022). The emergence of new materials also pushes this development's boundaries. Each material has a different behavior and demands specific treatments and post-processing steps. Among the read articles, researchers have used materials such as thermoplastic polyurethane (TPU), polylactic acid (PLA), conductive polylactic acid (CPLA), acrylonitrile butadiene styrene (ABS), nickel-chromium alloys (Inconel®), and polyethylene terephthalate glycol (PETG) (Lim et al., 2017; Oliveira et al., 2023; Prajapati et al., 2022; Stano et al., 2022).

The advancement of AM leads to improvements in customization and personalization. However, the lack of knowledge of AM process activities and the increase of AM industrialization have brought instabilities and unpredictability (Haruna & Jiang, 2022). In this sense, it is understandable to imagine that the guidelines for designing for AM may not cover all the specificities of each material processed via MEX and each actual application. Therefore, some adjustments to the existing guidelines are expected.

One found line of research has explored the application of DfAM techniques in conjunction with other optimization tools. The combination results in a powerful strategy to obtain, for example, models with higher resistance to a given stress. The approach can reduce the product's loaded mass by identifying zones not loaded in various applications, from engineering to health areas. Computational simulation helps create more efficient and faster models to be manufactured. Lim et al. (2017) developed a custom elbow orthosis with vent holes to replace conventional plaster orthoses, which can promote skin problems. The authors were able to create reinforcement in loaded areas by combining scanning, optimization, and simulation techniques.

Other studies have explored the reduction in the amount of manual labor and post-processing required during the construction of low-cost capacitive liquid level sensors (Stano et al., 2022). Among the MEX features, Stano et al. (2022) explored the multi-material facility combined with the geometrical freedom of construction. In the DfAM applied, the authors analyzed the ideal nozzle size to manufacture the conductive sensor tracks. The capacitance equation shows that the smaller the track width, the better this property. However, this condition contradicts the printability property of the conductive material used, CPLA, which is very brittle and tends to clog the extruder nozzle.

In addition to the presented works, another approach to the use of DfAM has been identified in the literature. Beltrán et al. (2021) proposed using DfAM techniques as a tool for a dimensional compensation strategy, in which dimensional parameters are changed to compensate for process manufacturing deviations. In the study, the authors elaborated an algorithm capable of creating several CAD files of the same component, each with its pack of dimensional corrections based on the tray position. To assess the deviations, some previous printings and measurements must be performed to create a history of dispersions and calibrate some sensibility coefficients that carry some system performance information. The strategy reduced the deviation between the mean size manufactured and the CAD dimension from 0.555 to 0.130 mm (equivalent to a class IT14 to IT11).

As the studies regarding DfAM point out different directions, it is fair to affirm that the guiding questions assist the understanding of the considerations on a standard basis.

#### 2.1.1 Are there DfAM guidelines available in the literature ready to be applied? Are they suitable for all AM technologies?

Currently, there are few authors who have dedicated themselves to studying the DfAM topic and implementing guidelines (Djokikj & Kandikjan, 2022; Hamel et al., 2018; Lopez Taborda et al., 2021) when compared to the number of papers that claim using DfAM rules to their studies (Beltrán et al., 2021; Lim et al., 2017; Oliveira et al., 2023; Prajapati et al., 2022; Rane et al., 2019; Stano et al., 2022). In general, finding proper design rules available in the literature is a difficult task since they are based on the practical experiences of developers (Leutenecker-Twelsiek et al., 2016).

As mentioned, DfAM techniques emerged from a need to expand the range of applications of the AM techniques and increase the efficiency of these processes to achieve production rates similar to conventional production processes (Asadollahi-Yazdi et al., 2017). In that way, it is possible to state that the importance of DfAM is tied to more recent events, especially due to the technological advances in MEX technologies regarding new materials.

In that way, Djokikj & Kandikjan (2022) proposed a specific methodology to create parts to be manufactured by MEX. To do that, they first conducted a survey that revealed that many of the problems with AM results are directly related to the lack of standardized procedures, which prevents the users from accessing the proper knowledge to control MEX processes.

Djokikj & Kandikjan (2022) contributed by presenting 10 General Design Rules (GDR) and 27 Specific Design Rules (SDR). The rules were created based on the literature and the authors' own experiences. After that, they validated it through experimental research. The GDR are considerations that must be checked before every AM design process, and the SDR contains the exact boundary values for essential parameters considering the MEX equipment they have used.

In their study, other available methodologies were found (Adam & Zimmer, 2015; Teitelbaum et al., 2009; Urbanic & Hedrick, 2016; Zimmer & Adam, 2012), but they highlight that, in general, they are simple packs of design rules without an in-depth focus on the physical phenomena behind the print parameters. Among some MEX parameters, such as printing speed, extrusion speed, and hatch spacing, layer height is the one that most impacts the surface quality of the parts, producing better results with lower values (Rane et al., 2019). Other vital parameters in MEX are hedge line and filament width (Zimmer & Adam, 2012). Only after considering all these MEX constraints in the design process, it will be possible to use the total capacity of the technology (Leutenecker-Twelsiek et al., 2016) .

It was possible to identify other DfAM methods through an in-depth literature search, summarized in Table 3. Some of them were exclusively developed for MEX, and others claim to be suitable to more than one principle of material addition.

Table 3. Summary of DfAM guidelines for MEX found in literature.

| Authorship | Description | Suitable for all AM technologies? |
|---|---|---|
| Djokikj & Kandikjan (2022) | Review and a survey made in the university where the study was completed. It presents 10 General Design Rules (GDR) and 27 Specific Design Rules (SDR). | Focused on MEX. Therefore, it is not appropriate for all AM technologies. |
| Diegel et al. (2020) | Set of 7 rules as general guidelines. | Claim that these are principles that can be applied to almost any AM principle. |
| Leutenecker-Twelsiek et al. (2016) | Framework for design guidelines that distinguish between process characteristics, design principles, and design rules focusing on determining part orientation in early design stage. | The presented design guidelines primarily focus on AM processes to produce end-user parts, especially on SLS, SLM, and MEX. |
| Asadollahi-Yazdi et al., (2016, 2017) | Proposed to provide an integrated and complete DfM approach for AM to manage new manufacturing criteria coming from AM. Used DfM-Skin and Skeleton approach. | MEX is the AM technology chosen to be analyzed comprehensively, considering different attributes, criteria, and constraints due to process and machine. |
| Adam & Zimmer (2014, 2015); Zimmer & Adam (2012) | Proposed a set of rules through the research project called "Direct Manufacturing Design Rules" based on standard geometrical elements, element transitions, and aggregated structures. | Design rules were developed based on geometrical standard elements for PBF (SLS, SLM), and MEX. |

From a different point of view, Diegel et al. (2020) explain that AM can be employed in three different levels of depth, as shown in Figure 1. The first level considers the case in which AM is just used as a substitute for another conventional manufacturing process, as can occur in direct parts replacement. In the second level, both process and forms are characteristics that want to be changed, in the way that a specific component is just adapted so any AM technology can manufacture it. Finally, in the last level, the whole design process is done based on the premise that manufacturing will occur by adding material, which leads to an entire redesign of form and function.

In their study, Diegel et al. (2020) propose a set of seven rules as general guidelines claiming that they can be applied to almost any form of AM. Generally, the rules alert the user to always ask whether the AM should be the first alternative. Other recommendations include the facility to always round off all sharp corners, design for minimizing support materials and mass, and plan print orientation since the first design stage.

Accordingly, Leutenecker-Twelsiek et al. (2016) recognize the importance of determining part orientation in the early design stage on MEX. The authors state that the designer should master the characteristics of the MEX working principle since the design is directly conditioned to them. To facilitate this process, the authors present a technique to analyze which design components are most impacted by orientation individually, presented in Figure 2. After the first evaluation, a global orientation is defined for the part, and the necessary adaptations are made.

Other works, such as Zimmer & Adam's (2012), have also greatly contributed to the theme. They proposed a set of rules through the "Direct Manufacturing Design Rules" research project. These rules were developed based on a study of the thickness and length of a plate and the layer cycle times of a MEX process. To reach this objective, the authors adopted geometrical standard elements for PBF (SLS, SLM), and MEX (Zimmer & Adam, 2012).

Some years later, the authors summarized their results on a "Design Rule Catalog" considering element transitions and aggregated structures such as the thickness and edges of transitions of firmly bonded elements, gap heights of transitions of non-bonded elements, gap widths and lengths of transitions of non-bonded elements, lengths of overhangs, starting positions of islands, and dimensions of material accumulations (Adam & Zimmer, 2014). In their most recent study on this area, they chose eight individual attributes to analyze the geometrical limitations and possible derivations for the Design Rules to construct walls, cylinders, and bores (Adam & Zimmer, 2015).

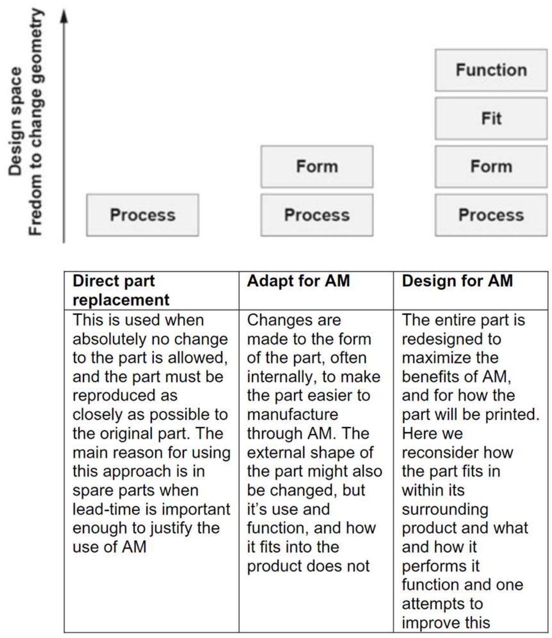


Figure 1. Different levels of design adaptation to meet AM technologies. Source: Diegel et al. (2020)

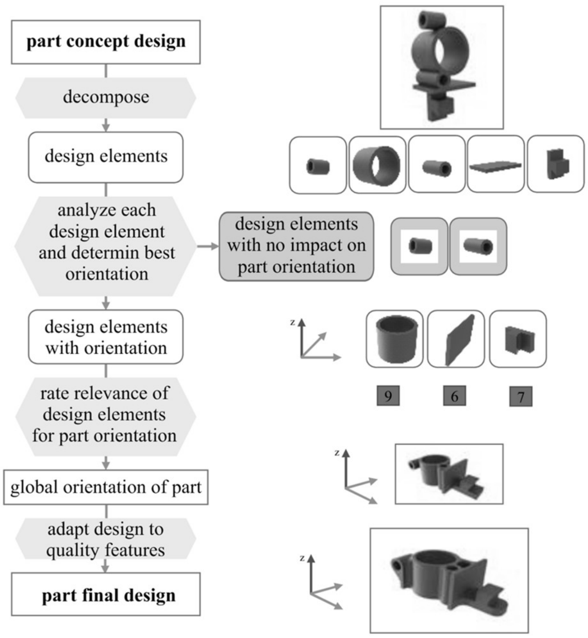


Figure 2. Defining part orientation in early design stages. Source: Leutenecker-Twelsiek et al. (2016)

In the research conducted, another interesting work emerged. Haruna & Jiang (2022) proposed a framework based on the Fuzzy Bayesian Network (FBN) to create a DfAM decision-making tool. The study analyzed twenty impact factors, leading to relationships and dependencies between the correlated impacts. An arm claw was designed and printed to examine the method's effectiveness. With that, the authors validated the methodology as a tool that provides a recommended method for designers to explore AM technologies in the industry.

### 2.1.2 How have researchers employed DfAM guidelines on their studies?

After reading the papers, it became clear that there has yet to be a consensus about what is DfAM among researchers. There are papers in which the authors claim to employ DfAM guidelines and recommendations, but they simply use topology optimization and generative design tools.

Oliveira et al. (2023), for example, claim using a DfAM strategy to manufacture a stapler. In the article, the authors explain the use of topology optimization software to create functional parts with minimum mass and acceptable safety factors. By doing that, it is possible to identify the regions loaded from the application and calculate how much material is needed to resist such loads. In that way, the design was not optimized to address the specific requirements of an AM process. Despite this, the authors evaluated the best printing parameters before manufacturing. Planning on doing that, the authors evaluated the print time and the amount of material and support in the process planning program.

Similarly, Stano et al. (2022) have used DfAM principles but without mentioning the guideline adopted. In the study, the authors designed a sensor with thin electrode tracks with a width that matches the printer's nozzle size. The thinner and the closer the tracks are to each other, the higher the capacitance. In this approach, the major problem stated in the article is the breakage of the filament being deposited due to the brittle behavior of the CPLA material. To address it, the authors had to study the forces involved during manufacturing by adjusting the extrusion flow and nozzle displacement. Using MEX made it possible to manufacture a completely customizable sensor in a unique processing step.

Beltrán et al. (2021) created a method, shown in Figure 3, that aims to improve a tolerance achievement within an interval by defining global and local compensations in the 3D files. The strategy allows the user to create a series of tailored designs that best match the equipment and the position on the printer tray, reducing manufacturing deviations. Therefore, a batch with some units of the same component is priorly manufactured and measured. After that, an analysis of the dispersion is conducted to compensate the models and reduce the deviation between the mean size. Results allowed the reduction of the tolerance interval from IT14 to IT11. This general approach uses a limited number of physical experiments to answer a specific DfAM question of interest, and the results can then be used to design functional parts without needing additional data.

Another study proposed a multi-objective optimization method, presented in Figure 4, that best fits the AM parameters based on a limited batch of physical experiments. The method allows the user to understand which parameter or combination leads to a specific result in the available AM equipment through a cause-and-effect characterization process. Using a genetic algorithm and a Pareto analysis, it is possible to identify the impact of several parameters, such as infill, shell, layer thickness, and velocity in the final part strength (Hamel et al., 2018).

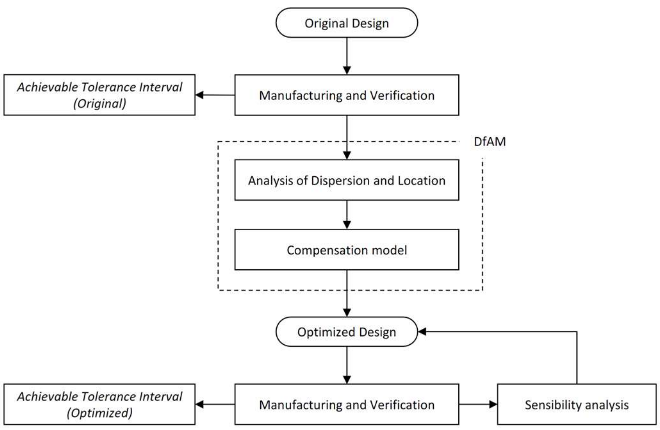


Figure 3. Compensation strategy to reduce manufacturing dispersion in MEX processes coupled to DfAM. Source: Beltrán et al. (2021)

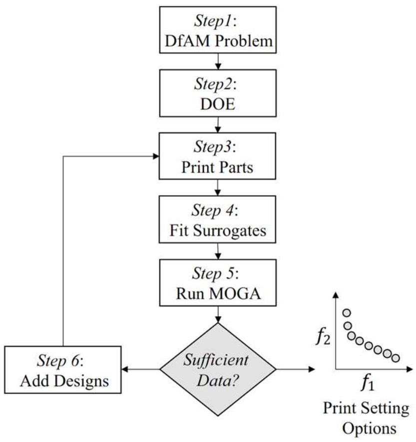


Figure 4. Multi-objective optimization approach for DfAM. Source: Hamel et al. (2018)

DfAM has also been used to create assistive technology products. Some features, such as textures and porosity, can be user-defined by understanding the process parameters that influence those characteristics. Lim et al. (2017) have used the DfAM concept to create a customized upper limb orthosis with a porous orthosis. After the first concept, a simulation was conducted, considering the properties of a material printed via MEX. Based on the results, modifications in the structure were made. The authors did not mention which methodology was applied and how the process characteristics were input into the design process.

Another study explores a MEX process to avoid support use during manufacturing (Prajapati et al., 2022). They aimed to construct lattice structures with PETG, filling them with PU foam in a hybrid MEX system. The frame absorbs impact energy in crash situations. In this case, the authors studied the maximum angle the AM system can manufacture without support structures and the maximum bridging distance. Some tests were performed for this analysis, and some parameters in the process planning software were adjusted. Through DfAM, the authors created a support-free structure by understanding the equipment and process limitations.

#### 2.1.3 Does DfAM have the capability to improve the parts produced in MEX? How could DfAM expand the range of applications of the MEX technology?

According to Djokikj & Kandikjan (2022), the problems that users usually face during MEX manufacturing can be classified into two groups: those caused by the technology itself and those arising from unsuitable designs for MEX. Analyzing the second group, the authors identified a list of common problems that are related to the task of designing thin vertical walls (1), thin elements (2), inappropriate inclination (3), small features that will be misrepresented in the slicing step (4), poor assembly connections (5), lack of support material when appropriate (6). In that way, creating rules that precisely define boundary values for the critical MEX control parameters is a manner that “should help in familiarization and better understanding” the physical phenomena of the technology (Djokikj & Kandikjan, 2022).

Similarly, Leutenecker-Twelsiek et al. (2016) conclude that using guidelines in conjunction with training can easily change designers' mindsets. For them, MEX facilities can be better exploited once the designers master the process characteristics and the working principles. The complexity of the DfAM strategy is variable. It depends on each specific case, ranging from basic simplification recommendations to considerations that can completely transform the design due to the function.

The authors presented a simple example of the second case. A considerable redesign was conducted in a specific component, shown in Figure 5. After running the suggested workflow, already presented in Figure 2, and identifying the basic elements and analyzing which could be impacted by the manufacturing orientation. Leutenecker-Twelsiek et al. (2016) reinforced that this strategy allows designers to “bypass or avoid certain process restrictions” since the design is adjusted to meet the MEX system capacity.


Figure 5. Design change after a manufacturing orientation study. Source: Leutenecker-Twelsiek et al. (2016)

Integrating manufacturing attributes into the design characteristics is a consistent way to develop a product manufactured by any AM process, including MEX (Asadollahi-Yazdi et al., 2016). Some tools, such as the one developed by Asadollahi-Yazdi et al. (2017), interpret the manufacturing constraints and make them understandable to the designer, who will be able to implement design modifications at earlier stages of development.

From another point of view, the DfAM studies and guidelines also play a role in influencing the acceptance of MEX processes in the industry. Consequently, users can feel more comfortable embracing technologies as robust and reliable manufacturing tools (Zimmer & Adam, 2012).

Diegel et al. (2020) introduce an interesting way to analyze designs in their book. The strategy starts by identifying the AM steps that are indeed being affected by design, which, in the end, directly impacts the cost and time of manufacturing. In the article, an SLS is used as an example, and among the steps identified, the authors mention laser contour and hatch patterns, thermal stress relief, the removal of supports, and heat treatments. Analogously, for MEX processes, the design directly influences the printhead movements, speed, and path, support structures in closed or hard-to-reach areas, and print orientation. Specifically on metal MEX processes, some new concerns may appear, such as the need to add extra support structures to avoid warping and component collapse.

## 3. CONCLUSIONS

The study conducted in this article was essential to understand how researchers and MEX final users adapt the design process during product development to take advantage of the equipment's maximum capacity and compensate for some effects of the process. DfAM should be interpreted as a process of thinking and making conscious decisions to achieve the scenario mentioned.

Some DfAM methodologies exclusively developed for MEX were found, and, in general, all the authors state that the secret of designing for AM is to adopt the strategies since the early stages of development. The faster the process considerations are implemented and integrated into the design, the quicker the outcome will be. The difficulty of developing a single methodology that simultaneously attends all AM technologies is understandable when we need to consider the physical phenomena of each addition principle in depth.

Another common impression of the authors is that the most recent information still circulates mainly in academic environments and might be improved once more industrial experiences are considered. Also, the lack of helpful and comprehensive information is a factor that makes it difficult for industries to make the decision to adopt AM technologies and start analyzing where they can add value.

The new advances in MEX technologies, such as new materials development, are essential drivers to increase efficiency and make the technology competitive compared to conventional manufacturing technologies. Although there are sets of recommendations and best practices to follow, there is still room for improvement regarding design in MEX. Despite researchers affirming the use of DfAM, one perceives that designers indirectly acknowledge it by designing parts considering the manufacturing results instead of following a specific set and order of rules. Future studies should focus on how industry can contribute to the creation of robust guidelines that can cover the full spectrum of parameters and cause-and-effect phenomena.

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## 5. RESPONSIBILITY NOTICE

The authors are the only ones responsible for the printed material included in this paper.

## 6. ACKNOWLEDGMENTS

We thank FINEP for funding part of this research and CNPq for the productivity scholarship in technological development and innovative extension (DT2).