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# BUT WILL IT PRINT? ASSESSING STUDENT USE OF DESIGN FOR ADDITIVE MANUFACTURING AND EXPLORING ITS EFFECT ON DESIGN PERFORMANCE AND MANUFACTURABILITY

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## ABSTRACT

*Additive manufacturing (AM) enables engineers to improve the functionality and performance of their designs by adding complexity at little to no additional cost. However, AM processes also exhibit certain unique limitations, such as the presence of support material, which must be accounted for to ensure that designs can be manufactured feasibly and cost-effectively. Given these unique process characteristics, it is important for an AM-trained workforce to be able to incorporate both opportunistic and restrictive design for AM (DfAM) considerations into the design process. While AM/DfAM educational interventions have been discussed in the literature, limited research has investigated the effect of these interventions on students' use of DfAM. Furthermore, limited research has explored how DfAM use affects the performance of students' AM designs. This research explores this gap through an experimental study with 123 undergraduate students. Specifically, participants were exposed to either restrictive DfAM or dual DfAM (both opportunistic and restrictive) and then asked to participate in an AM design challenge. The students' final designs were evaluated for (1) performance with respect the design objectives and constraints, and (2) the use of the various aspects of DfAM. The results showed that the use of certain DfAM considerations, such as minimum feature size and support material mass, successfully predicted the performance of the AM designs. Further, while the variations in DfAM education did not influence the performance of the AM designs, it did have an effect on the students' use of certain DfAM concepts in their final designs. These results highlight the influence of DfAM education in bringing about an increase in students' use of DfAM. Moreover, the results demonstrate the potential influence of DfAM in reducing build time and build material of the students' AM designs, thus improving design performance and manufacturability.*

**Keywords:** design for additive manufacturing, additive manufacturing education, manufacturability

## 1. INTRODUCTION

Additive manufacturing (AM) defines a set of manufacturing processes that use layer-by-layer deposition of material to build parts [1]. This enables designers and engineers to produce complex parts at little to no additional cost. Here, complexity could be in the geometry of the designs, the features used in their assembly, or the materials used to fabricate them [2]. Companies, such as General Electric, have demonstrated the use of AM capabilities to improve the performance of their products, most notably the nozzle for the GE9X engine [3]. To encourage the use of AM capabilities during design, researchers are constantly exploring novel design methods, tools, and techniques, resulting in the emergence of *opportunistic* design for AM (DfAM). Opportunistic DfAM enables designers to capitalize on the unique capabilities of AM through techniques such as material complexity, multi-material printing, and part consolidation.

In addition to these unique capabilities, AM also introduces certain process limitations. For example, parts manufactured with AM present anisotropic material properties due to the layer-by-layer deposition technique [4]. These limitations, if not

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accounted for, have the potential to decrease the feasibility of AM designs, increase their manufacturing cost, or even lead to build failure. Therefore, to overcome these limitations and reduce build failures, researchers are developing limitation-based DfAM guidelines. These guidelines, known as *restrictive* DfAM, help designers ensure that their designs can be manufactured feasibly, with minimal material waste and build failure. The restrictive DfAM concepts also show similarities to traditional design for manufacturing and assembly (DFMA) guidelines [5] in terms of their focus on the limitations of a specific manufacturing processes. For example, DFMA provides designers with recommendations such as simplifying designs and providing draft angles for sharp corners to improve the manufacturability of their parts with traditional processes.

In addition to the opportunistic and restrictive DfAM concepts, some frameworks [6] suggest the combination of these two aspects of DfAM resulting in dual DfAM. This dual nature of design techniques is unique to AM, and therefore, it is important for engineering design processes to shift from traditional limitation-based DFMA, towards integrating both the opportunistic and restrictive aspects of DfAM. This integration of DfAM in engineering design has the potential to impact the performance of AM designs while ensuring manufacturability.

While several academic institutions have integrated AM and DfAM educational interventions in the engineering curriculum, limited research has explored their effects on the students' incorporation of DfAM considerations into their AM designs. Further, limited research has explored the relationship between DfAM integration and the performance and manufacturability of designs. Understanding this relationship is important as one of the crucial contributions of AM technologies is its ability to improve design performance through added complexity [3,7–9]. Therefore, the present study aims at exploring this gap by evaluating the effects of DfAM education on the participants' DfAM use, and its relationship with the performance and manufacturability of students' AM designs.

## 2. RELATED WORK

The aim in this research is to explore the effect of DfAM use on the performance and manufacturability of AM designs when introduced in an educational intervention. Therefore, previous research related to the various DfAM guidelines was explored. In addition, current practices in DfAM education were surveyed to help develop the educational intervention. The key findings from the survey of the literature are summarized in this section.

### 2.1. Design for Additive Manufacturing

The unique characteristics presented by AM has resulted in the emergence of design considerations specifically developed for AM. These DfAM considerations have been applied using several frameworks [6,10–13], of which Laverne, et al. [6] classifies these DfAM considerations into restrictive DfAM and opportunistic DfAM. Restrictive DfAM, as the name suggests, emphasizes on the restrictions or limitations of AM processes and provides design considerations to accommodate them. On the other hand, opportunistic DfAM emphasizes the opportunities or unique capabilities of AM processes and how best designers can leverage them. A summary of the different opportunistic and restrictive DfAM concepts is seen in Table 1.

**Table 1 Summary of DfAM concepts discussed in literature (R: restrictive, O: opportunistic)**

| | DfAM consideration | Source |
|---|---|---|
| R1 | Support structure accommodation | [14–18] |
| R2 | Warping due to thermal stresses | [19–22] |
| R3 | Delamination and material anisotropy | [4,23,24] |
| R4 | Stair-stepping and surface roughness | [25–31] |
| R5 | Minimum feature size | [32–35] |
| O1 | Free complexity – geometric and hierarchical | [36–39] |
| O2 | Material complexity and multi-material printing | [40–43] |
| O3 | Part consolidation and printed assemblies | [8,44] |
| O4 | Mass customization | [45–48] |
| O5 | Functional complexity and embedding | [49–52] |

Restrictive DfAM is a necessary tool for AM designers as these considerations help reduce build failure and minimize waste of time, cost, and material. An important limitation of AM processes is their limited ability to build overhanging features. This necessitates the use of support material or self-supporting angles and bridging limits to minimize support material [14–18]. Since several AM processes rely on high-temperature melting of solid feed material, parts produced with these processes are prone to warping and cracking due to thermal stresses [19–22]. To minimize warping due to thermal stresses, for instance, designers are encouraged to avoid large flat surfaces or adding thermal walls to their designs to enable better heat dissipation.

The layer-by-layer process used in AM results in the parts having anisotropic material properties [4,23,24]. To avoid delamination between the layers, parts are oriented such that the load-critical features do not bear loads in the build direction. AM processes also result in surface roughness in the build direction due to stair-stepping observed on curves [25–31]. Therefore, parts that have assembly features and need geometric exactness are oriented parallel to the build platform [28]. Finally, given the diverse range of AM processes available, each process has a corresponding minimum feature size and a maximum part size the printer can manufacture. These dimensional limitations affect the accuracy and the number of prints needed to fully manufacture a product [32–35].

Alongside these limitations, AM processes offer new design opportunities for improving part performance. Opportunistic DfAM emphasizes these opportunities offered by AM and helps designers further explore the available design space. One of the most well-known aspects of opportunistic DfAM is the concept of "free complexity" [36]. AM not only provides designers with the freedom to include complex geometries but also extend this complexity at the hierarchical, and functional levels [37–39]. Complexity can also be extended towards the materials available in an AM process, where multiple materials with different characteristics such as rigidity, colour, and transparency can be printed in different combinations [40–43]. Further, AM processes also help minimize assembly time and costs by providing the ability to combine different functional components into one part through part consolidation [8], and design and build assemblies [44] that function with minimal post-processing. The digital manufacturing process followed by AM further permits engineers to manufacture several different parts from the same printer at no additional tooling costs [45]. This enables designers (and consumers) to design and manufacture products that are customized for each user, a concept commonly known as mass customization [46–48]. Finally, AM's unique layer-by-layer process also provides designers with the opportunity to embed external components, such as motors or bearings, by pausing the build at any time [49–52].

Given the uniqueness of DfAM and the growing integration of AM in the industry, several educational institutions have launched initiatives for AM/DfAM education as discussed next.

## 2.2. DfAM education

While research in AM is constantly refining DfAM methods and providing better tools for engineers and designers, it is also important that future engineers are trained in integrating DfAM in the engineering design process. To meet the growing demand for a workforce skilled in AM, several academic institutions are introducing formal and informal educational interventions focused on both AM and DfAM [36]. Further, a majority of these interventions employ principles of inductive teaching, such as the problem- and project-based learning techniques recommended at the 2013 NSF workshop on AM [36].

An example of a formal AM intervention is the AM course introduced at the University of Texas at Austin and Virginia Tech, where students are introduced to the various AM processes. In addition, students are also exposed to choosing appropriate processes for particular applications and applying their knowledge of AM processes towards solving a design problem [53]. Employing a more self-directed approach, Yang [54] discusses the use of literature reviews to encourage students' exploration of new and ongoing research in AM technologies and its various applications. Similarly, Diegel et al. [55] discuss the use of a problem-based AM educational initiative, where industry participants are exposed to different DfAM concepts in a 4-day hands-on workshop. The use of workshops for AM education has also been demonstrated as a method for addressing the challenges faced by AM education and leveraging the capabilities of AM, particularly in the ideation phases [56,57]. Similarly, Williams et al. [58] demonstrate the use of a project-based intervention as a method for informally introducing DfAM to students. Through the design of remote-controlled ground and air vehicles, students are engaged in exploring the uses of AM and applying DfAM concepts in their designs.

In contrast to these formal initiatives, several academic institutions are constantly working towards providing students access to AM processes to encourage self-learning. For example, the 3D printing vending machine [59] at Virginia Tech allows students to upload their parts for printing and collect it upon completion. A similar service is offered at the maker spaces set up at both, Penn State and Georgia Tech [36,60–62]. Students can utilize these AM services either by uploading their parts online, as in the case of the Penn State's Maker Commons or by directly interacting with the printers. The use of makerspaces for AM education has also been demonstrated through the development of a mobile makerspace that can be transported to remote locations where access to 3D printers is limited [62]. Further, universities such as MIT and Case Western provide students with access to both AM and traditional manufacturing through a network of interconnected makerspaces [63,64]. While these AM services provide students with guidelines for designing AM parts, a majority of these guidelines focus on the restrictive aspects of AM such as warping, support structures, and infill densities. However, limited emphasis has been given to the opportunistic aspects of AM.

A similar emphasis on restrictive DfAM can be seen in the DfAM worksheet developed by Booth et al. [65]. This worksheet helps designers assess their AM designs and has been demonstrated to minimize material wastage by reducing build failure. The DfAM worksheet uses eight factors for assessing the appropriateness of a design to be manufactured using AM, which include: (1) complexity, (2) functionality (load bearing), (3) support material removal, (4) support material accommodation (unsupported features), (5) minimum feature thickness, (6) stress concentrations, (7) tolerances, and (8) geometric accuracy. Of these eight factors, only complexity belongs to the opportunistic DfAM domain, while the remaining fall into the restrictive DfAM domain. This highlights an important issue: *designers are not encouraged enough towards leveraging the capabilities of AM*. Further, their study demonstrates the application of the DFAM worksheet to predict build failure; no information is provided to assess the performance of the AM designs with the worksheet.

In contrast to the restrictive-based DfAM worksheet, Blösch-Paidosh and Shea present the use of opportunistic DfAM-based design heuristics [66]. These heuristics, specifically developed for use in early stages of the design process, emphasize the following opportunistic DfAM concepts: (1) part consolidation, (2) customization, (3) conveying information, (4) material complexity, (5) functional embedding, (6) weight reduction, (7) material distribution and (8) reconfiguration. The study uses qualitative analyses to assess the AM designs for their use of the various heuristics. While this study provides important insights into the participants' use of the various heuristics, little emphasis is given to its effect on the manufacturability and performance of AM designs.

In summary, prior research presents several initiatives that integrate AM and DfAM into the engineering design curriculum. However, limited research has investigated the role of these initiatives on the students' use of DfAM in their designs. Further, limited research has explored the relationship between DfAM use and the manufacturability and performance of the students' AM designs. This is particularly important as integrating DfAM into engineering design has the potential of not only improving design performance through opportunistic DfAM but also ensuring design feasibility through restrictive DfAM. Therefore, the aim in this research is to explore these gaps in research.

## 3. RESEARCH QUESTIONS

Based on the current state of the literature, this study aims to explore the relationship between students' use of DfAM and the performance of their final designs. To do this, we seek to answer the following research questions:

*RQ1: How does the participants' use of DfAM relate to the performance and manufacturability of their final designs?* As opportunistic DfAM concepts aim at aiding designers in improving their design performance, we hypothesize that the participants' use of opportunistic DfAM would correlate with lower build material and build time. Further, given the role of restrictive DfAM in improving design feasibility, we hypothesize that students' use of restrictive DfAM would correlate with the generation of designs with better manufacturability.

*RQ2: How does the participants' use of DfAM in their designs vary with the content of DfAM education?* Since effective learning is demonstrated to correlate with the ability to use the knowledge to solve problems [67,68], we hypothesize that introducing participants to DfAM, either restrictive or dual, would result in greater use of the concepts in their final designs.

*RQ 3: How does the performance and manufacturability of participants' designs vary with the content of DfAM education?* Given the ability of opportunistic DfAM to improve design performance, we hypothesize that participants who received opportunistic DfAM training will generate ideas with lower build material and build time. Further, the introduction of restrictive DfAM will enable participants to generate designs with better additive manufacturability.

## 4. METHODOLOGY

To answer these research questions, an experiment consisting of a short intervention lecture followed by a design challenge was conducted. This section discusses the relevant details of the experiment, which was performed as a part of a larger study.

### 4.1. Participants

The participants (N = 123) in the study were recruited from a junior-level mechanical engineering course at a large public university in the northeastern part of the United States. The course focused on mechanical engineering design methodology, and the experiment was conducted in the fall semester. The participants included juniors (N = 78), and seniors (N = 41), and 5th-year seniors (N = 2) with some participants not reporting their year of study. The participants' previous AM and DfAM experience was collected in a pre-intervention survey and is summarized in Figure 1. As seen in the figure, a majority of the participants had received some formal or informal training in AM. By comparison, fewer participants had received formal or informal training in DfAM.

### 4.2. Procedure

The experiment was conducted during the second and third weeks of the semester and was broken into two main parts: (1) a DfAM educational intervention and (2) a design challenge. The study was approved by the Institutional Review Board, and informed consent was obtained from the participants before their participation in the study.

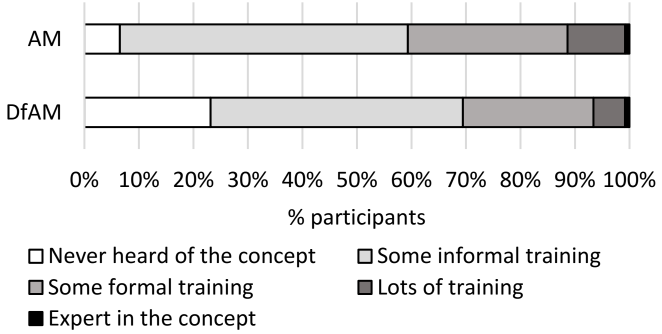


**Figure 1 Distribution of participants' previous experience**

#### *4.2.1. DfAM educational intervention*

Participants consenting to the study were randomly assigned to one of two educational intervention groups: (1) restrictive DfAM (N = 67) or (2) opportunistic and restrictive (dual) DfAM (N = 56). All participants were first given a 20-minute overview lecture on the AM process characteristics. This lecture discussed the material extrusion process available for the design challenge, the contrast between AM and subtractive manufacturing, the digital thread, the Cartesian coordinate system, and filament materials. Next, all participants were given a 20-minute lecture on restrictive DfAM, including build time, minimum feature size, support material, anisotropy, surface finish, and part warping. Finally, the dual DfAM group was given a 20-minute lecture on opportunistic DfAM, which included geometric complexity, mass customization, part consolidation, printed assemblies, multi-material printing, and embedding.

#### *4.2.2. Design challenge*

After attending the appropriate DfAM intervention lecture, the participants were asked to complete a design challenge, where they were asked to:

> *"Design a fully 3D printable free-standing tower for a downscaled wind turbine. The tower must support a motor-blade assembly and must attach to the assembly through a T-slot of given dimensions. The assembly must be able to slide into the slot and stay in place. The motor-blade assembly will include the male side of the t-slot. The objective of the challenge is to minimize the print material and the print time as much as possible while following the constraints listed below. Given the scaling factors of the turbine, the tower must meet the following constraints:*
>
> 1. *The height of the tower must be at least 18 inches (as measured from the ground to the motor).*
> 2. *The tower must support the motor (150 grams) assembled with the blades (150 grams).*
> 3. *The tower can have a maximum base footprint of 3.5" X 3.5".*
> 4. *All components necessary must be completed in one build within the build volume of 11.6" X 7.6" X 6.5"."*

The design task was chosen such that minimal domain-specific knowledge, outside of AM, would be required to generate solutions (as suggested by [69]). Further, the wind turbine problem was chosen given the ease with which functional and manufacturing constraints could be placed on the solution space. For example, the task constrains the build volume to 11.6”x7.6”x6.5”, though the participants are expected to build a tower 18” tall within this volume.

As part of the design challenge, the participants were first asked to spend 10 minutes individually generating and recording ideas on an idea generation card, with 7 minutes allotted for sketching, and 3 minutes for describing ideas in words. The participants were then given 5 minutes to evaluate their own ideas and note each’s strengths and weaknesses. The participants were then given 7 minutes to individually design a final idea with the freedom to redesign, combine, or brainstorm again.

#### *4.2.3. Concept selection and build preparation*

After completing the individual concept generation, participants were randomly split into groups of 3 or 4 participants each. Since only the final designs from each group were used for the study, we do not expect the team size to have a major influence on the outcome. Further, while the groups are assigned for a semester-long project within the course, the participants were informed of their groupings for the first time on this day. These groups were formed such that schedule, commute, and commitment levels were matched for similarity, while writing skills, hands-on skills, and shop skills were diversified. This resulted in 44 groups, with 24 groups receiving restrictive DfAM training and 20 groups receiving dual DfAM training.

After being split into groups, each member was given time to present their individual final ideas to the other group members. The team then selected one final idea for the group. Participants were then asked to create a 3D solid model of their group’s final idea using Solidworks, prepare a build file using MakerBot Desktop software, and submit it to the university’s 3D printing service, which consists of several Makerbot Replicator+ machines. The complete design challenge was conducted within a 3-hour lab session, and participants were not allowed to make any further modifications after submitting their design files. The 3D printed structures, STL files, and .thing (Makerbot build preparation) files were collected from the participants after two weeks. The build files and printed parts were then assessed for their performance using the metrics discussed next.

### 4.3. Metrics

To assess the performance of the designs, metrics were developed that could evaluate both the performance of the final designs and the participants’ use of DfAM. The metrics developed are discussed next.

#### *4.3.1. Manufacturability and Performance of Students’ Designs*

The manufacturability and performance of the students’ designs was assessed with respect to the objectives of the design prompt - minimizing the build material and minimizing the build time. Build time and build material were used as objectives for the design challenge since these factors have a strong influence on the cost of an AM product [70]. Further, the weight of parts is also an important criterion for assessing design performance in several industries, including aerospace and automotive engineering [71].

The build time and build material were obtained from the build files submitted by the participants. In addition to the objectives of the task, the designs were also evaluated based on their adherence to the design challenge constraints. These constraints were developed based on the general requirements of a wind turbine with the height scaled down to 18”. It should be noted that the designs that failed to build successfully, either due to poor design or build preparation, were given zero for all subsequent constraints. A summary of the performance criteria (O = objectives and C = constraints) is shown in Table 2.

**Table 2 Metrics used for assessing the manufacturability & performance of the designs (O: objectives, C: constraints)**

| # | Metric |
|---|---|
| O1 | Build material (g) |
| O2 | Build time (min) |
| C1 | Did it print successfully? |
| C2 | Can it be assembled successfully? |
| C4 | Is the design free standing and can support its own weight? |
| C5 | Does the t-slot attach to the tower? |
| C6 | Does the motor assembly stay in place? |
| C7 | Does the tower bear the motor assembly load? |
| C8 | Is the tower greater than 18” tall? |
| C9 | Is the base footprint within 3.5”x3.5”? |
| C10 | Is the tower built in one build? |

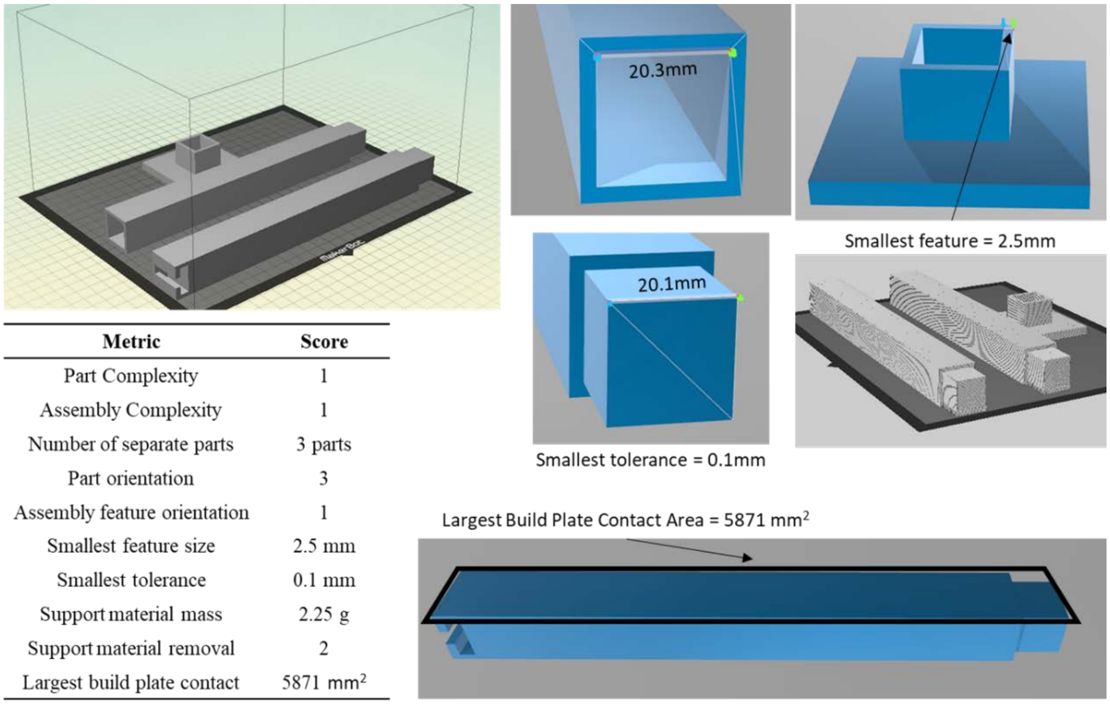
#### *4.3.2. Students’ Use of DfAM in the design*

To assess the students’ use of DfAM in their designs, metrics were developed for both opportunistic and restrictive DfAM considerations. Specifically, of the design considerations discussed in Section 2.1, those that were within the scope of the experimental setup were chosen. Specifically, the opportunistic DfAM considerations used were: (1) geometric complexity (2) assembly (functional) complexity, and (3) part consolidation. Meanwhile, the following restrictive DfAM considerations were used: (1) surface roughness and stair-stepping, (2) warping and thermal stresses, (3) support material accommodation, and (4) feature size.

Given the limitations of the open printing facilities available through the university, students would not be able to embed components or use multi-material printing. Furthermore, given the structure and specificity of the task, students have limited scope to generate ideas that can be mass customized, as they are constrained to a specific motor-turbine assembly design. Therefore, these design considerations were excluded from the evaluation. The measurement scales for geometric complexity, feature size, and support material removal were adapted from the DfAM worksheet developed by Booth et al. [65]. The metrics and corresponding DfAM considerations are listed in Table 3. A 3-point scale was used to ensure uniformity across metrics. The results of an analysis based on these metrics is discussed next.

**Table 3 Metrics used for assessing the students' use of DfAM in the design challenge and the DfAM consideration associated with each metric.**

| Metric | Score | | | DfAM Consideration |
|---|---|---|---|---|
| | *1* | *2* | *3* | |
| Part Complexity | Primitive geometry (ex. square, cylinder) | Complexity/curves that can be machined | Complex/curves that cannot be machined | AM designs can have complex geometries to improve performance as opposed to tradition manufacturing. |
| Assembly Complexity | Prismatic joint | Prismatic joints with locking features | Unidirectional joints with locking features | AM designs can have complex functional features such as assembly components. |
| Number of separate parts | -------------------------- Number/value -------------------------- | | | Designers can reduce part count by combining, thus reducing build time, assembly time and cost. |
| Part orientation | ZX/ZY (largest dimension in Z-direction) | XZ/YZ (second-largest dimension in Z-direction) | XY/YX (smallest dimension in Z-direction) | AM processes are typically slowest when printing in the z-direction. |
| Assembly feature orientation | ZX/ZY/XZ/YZ (critical mating features in X or Y planes) | | XY/YX (critical mating features in the Z-plane) | The orientation of a part affects its surface finish. Stair stepping is observed when rounded features are printed vertically (along X or Y planes) |
| Smallest feature size | --------------------------- Value in mm --------------------------- | | | AM processes have a minimum feature size that can the process can build (~0.5mm for material extrusion [72]). |
| Smallest tolerance | --------------------------- Value in mm --------------------------- | | | Adequate tolerances must be given between mating features. |
| Support material mass | -------------------------- Value in grams -------------------------- | | | AM designs with overhanging features need support material. Support material mass can be reduced using self-supporting angles and bridging limits. Internal cavities must have access for ease of support material removal. |
| Support material removal | Internal cavities with support difficult to remove | Easily accessible support material | No support material | |
| Largest build plate contact | ---------------------------- Value in $mm^2$ ---------------------------- | | | Large flat surfaces are prone to warping due to inadequate heat dissipation and thermal stresses. |



| Metric | Score |
|---|---|
| Part Complexity | 1 |
| Assembly Complexity | 1 |
| Number of separate parts | 3 parts |
| Part orientation | 3 |
| Assembly feature orientation | 1 |
| Smallest feature size | 2.5 mm |
| Smallest tolerance | 0.1 mm |
| Support material mass | 2.25 g |
| Support material removal | 2 |
| Largest build plate contact | 5871 $mm^2$ |

**Figure 2 Example of assessment of a design using the DfAM metrics**

## 5. DATA ANALYSIS AND RESULTS

To answer the research questions posed in Section 3, we performed statistical analyses with a statistical significance of $\alpha = 0.05$ and a confidence interval of 95%. A sample size of 39 groups was used after accounting for missing data, either due to participants not submitting their built parts or their build files. Among these, 21 groups received restrictive DfAM education and 18 groups received dual DfAM education.

### RQ1: How does the participants' use of DfAM relate to the performance and manufacturability of their designs?

The first research question was developed to understand whether participants' use of DfAM had an effect on the performance of their final designs. To answer the research question, first, a multiple linear regression was performed with each objective criteria (i.e., build material and build time) as the dependent variable, and each DfAM criteria (see Table 3) as the independent variable. Before conducting the analysis, all assumptions (e.g., homoscedasticity, normality of residuals) were verified. An outlier was identified based on Cook's distance and the centred leverage values, and the data point was removed from further analysis. The results showed that as a group, the DfAM metrics successfully predicted both build material ($F(10,27) = 4.56$, $p = 0.001$, $R^2 = 0.63$, $R^2_{adj} = 0.49$) and build time ($F(10,27) = 2.74$, $p = 0.02$, $R^2 = 0.50$, $R^2_{adj} = 0.32$). The correlation coefficients, standard errors, and standardized coefficients are as summarized in Table 4.

**Table 4 Coefficients for predicting design performance using the DfAM use (significant effects highlighted)**

| DfAM consideration | Build Material | | | Build time | | |
|---|---|---|---|---|---|---|
| | B | SE$_B$ | β | B | SE$_B$ | β |
| Part Complexity | -10.44 | 19.54 | -0.08 | 58.27 | 73.73 | 0.14 |
| Assembly Complexity | 17.19 | 17.43 | 0.14 | 13.51 | 65.75 | 0.03 |
| Number of parts | 9.54 | 6.89 | 0.21 | **56.68** | **25.99** | **0.38** |
| Part orientation | 0.36 | 16.04 | 0.004 | -16.82 | 60.51 | -0.05 |
| Assembly feature orientation | -1.12 | 14.41 | -0.01 | 63.55 | 54.36 | 0.22 |
| Smallest feature size | **13.78** | **3.90** | **0.51** | **30.70** | **14.70** | **0.35** |
| Tolerance | 39.48 | 43.65 | 0.12 | 179.86 | 164.68 | 0.17 |
| Support material mass | **1.14** | **0.34** | **0.47** | **4.02** | **1.30** | **0.51** |
| Support material removal | 7.81 | 27.45 | 0.04 | 85.34 | 103.58 | 0.14 |
| Largest build plate contact area | **0.01** | **0.003** | **0.37** | 0.004 | 0.01 | 0.06 |

Bold indicates $p < 0.05$

These results support our hypothesis that the various DfAM concepts influence the performance of AM designs. Specifically, we see that the size of the smallest feature and the support material mass positively correlate with the build time and build material. Furthermore, we see that while the number of parts correlates positively with build time, the maximum build plate contact area correlated positively with build material.

### RQ2: How does the participants' use of DfAM in their designs vary with the content of DfAM education?

As seen in the results of RQ1, the participants' use of DfAM influenced the performance of their design. Therefore, the second research question sought to understand the role of DfAM education in bringing about these effects.

To answer the second research question, a series of Mann-Whitney U tests were performed. Specifically, the scores for the designs for each metric discussed in Section 4.3.2 were used as dependent variables, and the educational intervention group was used as the independent variable. The results of the analysis are summarized in Table 5.

**Table 5 Comparing DfAM use between the DfAM educational groups (significantly higher values highlighted)**

| Performance Metric | *p* | *U* | *z* | Mean Rank (Median) | |
|---|---|---|---|---|---|
| | | | | Restrictive DfAM | Dual DfAM |
| Part Complexity | 0.57 | 210 | 0.61 | 19.00 (2.00) | 21.27 (2.00) |
| Assembly Complexity | 0.13 | 244.00 | 1.75 | 17.38 (1.00) | 23.06 (1.75) |
| Number of separate parts | 0.49 | 214.00 | 0.77 | 18.81 (3.00) | 21.39 (3.00) |
| Part orientation | 0.44 | 161.00 | -0.93 | 21.33 (3.00) | 18.44 (3.00) |
| Assembly feature orientation | 0.25 | 147.50 | -1.35 | 21.98 (2.00) | 17.69 (1.00) |
| Smallest feature size | 0.13 | 135.50 | -1.51 | 22.55 (5.00) | 17.03 (2.99) |
| Smallest tolerance | **0.01** | **98.50** | **-2.62** | **24.31 (0.25)** | **14.97 (0.025)** |
| Support material mass | 0.43 | 217.50 | 0.80 | 18.64 (4.0) | 21.58 (6.51) |
| Support material removal | 0.86 | 182.00 | -0.22 | 20.33 (2.00) | 19.61 (2.00) |
| Largest build plate contact | **0.05** | **120.00** | **-1.94** | **23.29 (8174.60)** | **16.17 (6438.9)** |

Bold indicates $p < 0.05$

The results show that while there were no significant differences between the educational intervention groups for 8 out of 10 DfAM considerations, the groups did show a significant difference in their use of assembly tolerances and build plate

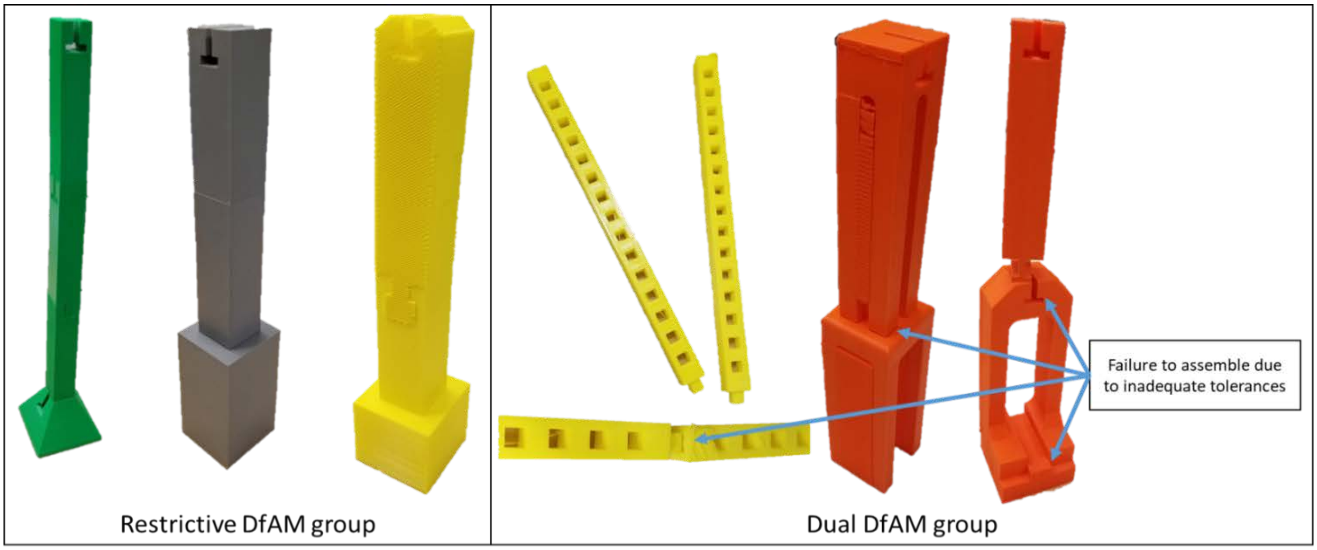


**Figure 3 Sample designs: Solid 'blocky' designs with large surfaces by the restrictive DfAM group vs complex designs with poor assembly tolerances by the dual DfAM group**

contact area. Specifically, the results showed that the restrictive DfAM group incorporated more appropriate tolerances between their mating features (mean = 0.605 mm, median = 0.25 mm) compared to the dual DfAM group (mean = 0.117 mm, median = 0.025 mm). The tolerances provided by the restrictive DFAM group were closer to the 0.5mm tolerance guideline given during the lecture. Furthermore, the group that received the restrictive DfAM training designed parts with larger build plate contact area (mean = 9622.31 mm$^2$, median = 8174.6 mm$^2$) compared to the dual DfAM group (mean = 6651.76 mm$^2$, median = 6438.9 mm$^2$). Some representative examples of the designs from each group are shown in Figure 3.

### RQ3: How does the performance and manufacturability of the participants' designs vary with the content of DfAM education?

To answer the third research question, first, a one-way analysis of variance (ANOVA) was performed. Specifically, each objective criterion discussed in Section 4.3.1 was used as the dependent variable, and the educational intervention group was used as the between-subjects factor. The data showed no significant outliers or deviations from normality and homogeneity of variances. The results are summarized in Table 6, and we found no statistically significant difference between the two groups for either build material or build time.

Next, Fisher's exact tests [73] were performed for each constraint to check for differences between the educational groups in meeting each constraint. The constraint criteria were used as the dependent variables, and the educational intervention group was used as the between-subjects factor. The results showed that while the group that received only restrictive DfAM education had a greater frequency of success in meeting the constraints, this difference was not statistically significant. In summary, these results refute our hypotheses that the participants who received dual DfAM education would generate designs with lower build time and material.

**Table 6 Summary of results comparing the educational intervention groups for their design performance**

| Performance Metric | *p* | *F* | Means (Std. Error) Restrictive DfAM | Means (Std. Error) Dual DfAM |
|---|---|---|---|---|
| Build material | 0.24 | 1.44 | 276.53 (18.92) | 243.17 (20.43) |
| Build time | 0.57 | 0.33 | 896.71 (63.10) | 843.67 (68.16) |

| Performance metric | *p* | Frequency of success (%) Restrictive DfAM | Frequency of success (%) Dual DfAM |
|---|---|---|---|
| Successful print | 0.21 | 100 | 88.9 |
| Successful assembly | 0.11 | 76.2 | 50 |
| Free standing (supports its own weight) | 0.11 | 76.2 | 50 |
| Attaches to the T-slot | 0.09 | 81 | 50 |
| Keeps the motor assembly in place | 0.34 | 61.9 | 44.4 |
| Supports the motor assembly load | 0.20 | 61.9 | 38.9 |
| Height greater than 18" | 0.34 | 57.1 | 38.9 |
| Base footprint within 3.5"x3.5" | 1.00 | 90.5 | 94.4 |
| Built in one build | 1.00 | 95.2 | 94.4 |

## 6. DISCUSSION

The main goal in this study was to understand the effects of DfAM education on the performance and manufacturability of the participants' designs, as well as the influence of DfAM use on these effects. The key findings from the results were:

1. The participants' use of certain DfAM concepts predicted the performance of their designs towards achieving design task objectives.
2. Participants who received only the restrictive DfAM education incorporate more appropriate tolerances, but also have parts with higher build plate contact area than those who received dual DfAM education.
3. Variations in DfAM education do not have a statistically significant effect on the performance of the participants' final designs.

### Participants' use of certain DfAM concepts predict the performance and manufacturability of their designs

The first research question was developed to understand whether the performance of the participants' designs could be predicted by their use of the various DfAM concepts. The first key observation was that the smallest feature size in their designs correlated with both the build material and build time. This suggests that designs that tend to have large features tend to take longer to build and use more material, which makes intuitive sense. Therefore, designers must take measures to optimize the size of their features to a minimum, while taking into account the resolution of the chosen AM process and the desired strength of the part. This would enable designers to successfully minimize the time and material consumed by the print.

The second key observation was that the support material required in a design correlated with both the build time and build material. This observation suggests the importance of emphasizing design guidelines such as self-supporting angles and bridging limits. Using these guidelines, designers are able to minimize the amount of support material needed to build their designs. This would help minimize both the time and material used to manufacture the design.

Further, we see that the largest build plate contact area for a component correlated with the build material. This suggests that designs that have large flat surfaces tend to consume more build material throughout the whole design. Therefore, designers must aim at avoiding large flat surfaces in their components, potentially by including complexities at the geometric and functional level. This would help minimize not only the build material but also reduce the risk of warping due to thermal stresses. Finally, we also see that a higher number of components in a design correlated to the time it took to build the design. This further supports the findings of past case studies, where part consolidation has been demonstrated as a technique for improving the manufacturability of designs by reducing build time and build material [3,8].

In summary, these results highlight that integrating the various opportunistic and restrictive DfAM guidelines have a positive influence on the manufacturability of designs. While this is a positive outcome, the dominance of the influence of restrictive DfAM suggests the need for a greater emphasis on applying opportunistic DfAM given its ability to improve design performance by minimizing build time and material.

### Variations in DfAM education content affects participants' use of certain DfAM concepts

The second research question was developed to further understand the extent to which variations in DfAM education influenced the use of the various DfAM concepts in the participants' designs. The results showed that participants who received only restrictive DfAM provided *more appropriate tolerances* (closer to the 0.5mm guideline) between assembly mating features compared to those who received dual DfAM education. This suggests a greater emphasis on geometric exactness and interfaces between mating components that could potentially result in their designs being easier to assemble. While this is a positive outcome, given the role of tolerances in improving manufacturability, it also suggests that introducing opportunistic DfAM could potentially reduce the effectiveness of restrictive DfAM education, which supports the findings from previous research [74]. Therefore, educators must ensure that the introduction of DfAM does not dilute students' emphasis on restrictive DfAM. Moreover, this lack of emphasis on restrictive DfAM could be a result of the short duration of the given design challenge. Extending the length of the design activity could potentially provide students with more time and opportunity to apply opportunistic and restrictive aspects of DfAM together.

Finally, the results also show that participants who received only restrictive DfAM education generated designs that had a higher contact area with the build plate. This could potentially lead to a greater risk of build failure due to warping and thermal stresses. While this finding suggests that participants who received restrictive DfAM could have given a lower emphasis on warping and thermal stresses, this outcome could be an effect of the dual DfAM group adding complexity to their AM designs. For example, as seen in Figure 3, participants from the dual DfAM group generated designs with more hollowed out features compared to the restrictive DfAM group where several solid designs were observed. This addition of complexity at the geometric level could have contributed to the reduction in contact area with the build plate without the participants having specifically emphasized this. However, we also observed that despite the added complexity, most designs could still be manufactured using traditional manufacturing processes, thus explaining the lack of difference in the complexity scores between the two educational groups. This could also be attributed to the use of a 3-point scale which might have failed at capturing detailed differences in the complexity of the designs. This inference is further reinforced by the significantly higher contact area among the designs from the restrictive DfAM group, suggesting a potential lack of emphasis on warping by both groups. This finding, therefore, suggests that the current intervention fails to convey the importance of integrating DfAM guidelines for warping and thermal stresses into a design. However, the introduction of opportunistic DfAM, particularly the freedom of complexity, could indirectly help minimize warping.

### Variations in DfAM education did not influence the performance and manufacturability of the participants' designs

The third research question was developed to investigate the effect of variations in the content of DfAM education on the performance of the participants' designs. The results showed that the content of the DfAM education did not have a significant effect on the performance of the designs. While the dual DfAM group generated designs with lower mean build time and build material use, as hypothesized, this result was not statistically significant. The results also show that while the designs from the restrictive DfAM groups showed greater success in meeting the constraints, this difference was not significant. These results suggest that the studied DfAM educational intervention did not succeed in bringing about effective learning or application of the various DfAM concepts. This could be attributed to the nature of the lectures where the rapid introduction of the concepts could have affected the students' learning of the concepts. The large amount of information conveyed to the participants in a short time could have limited their ability to absorb and apply all the different opportunistic concepts. Furthermore, the short duration of the design challenge could have limited the time available to apply the various DfAM concepts towards improving the performance of the AM designs.

This could also be attributed to the nature of the design task chosen. The task might not have provided the participants with adequate opportunity to apply some of the DfAM concepts. The lack of differences in the performance of the design outcomes could further be attributed to a relatively low level of incentive among the participants to generate ideas that fully leverage AM capabilities and improve their design performance. Therefore, future research must explore the use of a design challenge with an element of competition (as suggested by [58]) to engage students in generating better design outcomes. Finally, the study primarily focusses on the performance of the designs based on the objectives and constraints of the design challenge. However, there could potentially be differences in the features incorporated in the designs, particularly at the geometry and assembly levels. For example, in terms of material removal, participants from the dual DfAM group employ a variety of strategies such as shell-like designs, trusses, and bulk removal of material. Therefore, future research must explore the assessment of the different features employed in the designs, particularly in terms of their *variety*.

## 7. CONCLUSION, LIMITATIONS, AND FUTURE WORK

The research and development of AM processes has resulted in an increase in their use in industry, which has consequently developed the need for a workforce skilled in AM and DfAM. Therefore, several academic institutions have undertaken initiatives to integrate AM and DfAM into the undergraduate engineering curriculum. However, limited research has explored the role of DfAM education on the students' use of DfAM in engineering design and its resulting influence on the performance of their design outcomes. The present study explores this gap through an experimental study with undergraduate students consisting of a DfAM educational intervention and a design challenge.

The results of the study show that variations in the content of the educational intervention, namely, restrictive and dual DfAM, does not influence either the build time or the build material of the participants' final designs. However, these variations in the educational content have an influence on the participants' use of assembly tolerances and warping considerations. Finally, the participants' accommodation for feature sizes and support material mass influence the build material as well as the build time. In addition, while the largest build contact area has a small influence on the build material, the number of parts significantly influences the build time. These results, therefore, suggest that the participants' use of the DfAM influences the performance of their design outcomes, thus demonstrating the role of DfAM on improving engineering design outcomes. Further, the results also suggest the low effectiveness of the studied educational intervention, either due to the short length of the lectures and design challenge or due to the choice of the design task.

Although this study demonstrated the effect of DfAM use on the performance and manufacturability of design outcomes, it has several limitations. First, the study was conducted with participants primarily in their junior and senior years of study, with relatively high levels of engineering experience. Future research must compare the effect of engineering experience by comparing students from lower years of study (e.g., freshmen, sophomores). The second limitation of the study is that once the participants were assigned to their groups, they were asked to choose one idea to represent the group; however, the rationale behind the students' selection process is unknown. Future research must explore what factors affect the participants' selection of concepts when engaged in a group design challenge. Such an investigation could not only highlight the participants' emphasis on factors such as manufacturability and creativity but also reflect any biases towards their own ideas. Third, the metrics used in the present study do not provide information on the features used by the participants to manifest the different DfAM concepts. For example, shape complexity could take the form of organic structures, lattice structures, or bulk material removal. This can be seen in the sample designs shown in Figure 3 where the dual DfAM groups employed a variety of strategies such as shells and trusses to introduce complexity to their designs. Future research must explore the design features that are used by the participants to incorporate the different DfAM concepts into their designs. This would help further refine the assessment of their designs.

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