But Will It Build? Assessing Student Engineering Designers' Use of Design for Additive Manufacturing in Design Outcomes

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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

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discussed in the literature, few studies have objectively assessed the integration of DfAM in student engineering designers' design outcomes. Furthermore, more research is needed to explore how DfAM use affects the students' AM designs' achievement of design task objectives. This research explores this gap through an experimental study with 301 undergraduate students. Specifically, participants were exposed to either restrictive DfAM or dual DfAM (both opportunistic and restrictive) and then asked to participate in a design challenge. The participants' final designs were evaluated for (1) build time and build material (2) the use of the various DfAM concepts, and (3) the features used to manifest these DfAM concepts. The results show that the use of certain DfAM considerations, such as the part complexity, number of parts, support material mass, and build plate contact area (corresponding to warping tendency) correlated with the build material and build time of the AM designs – minimizing both of which were objectives of the design task. The results also show that introducing participants to opportunistic DfAM leads to the generation of designs with higher part complexity and lower build plate contact area but a greater presence of inaccessible support material.

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 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 the specific manufacturing process. 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 [7]. This integration of DfAM in engineering design has the potential to impact the performance of AM designs while ensuring manufacturability.

Several academic institutions have integrated AM and DfAM educational interventions in the engineering curriculum, with several researchers presenting methods of introducing opportunistic and restrictive DfAM. However, more research is still needed to investigate the use of objective metrics to assess the effects of DfAM education on the students' incorporation of DfAM considerations into their AM designs. This includes exploring the relationship between DfAM integration in the students' designs and the corresponding effect on the designs' achievement of task objectives. Understanding this relationship is important as one of the crucial contributions of AM technologies is its ability to improve design performance through added complexity [8–10]. Therefore, the present study aims at exploring this gap. Further, the study also investigates the features used by the students to execute the various DfAM concepts.

The next section discusses prior research in the field that was used to motivate and inform the present study. The specific research questions investigated in this study are discussed in Section 3. The details of the experiment conducted to answer these research questions are presented in Section 4. The analysis of the data collected from the experiment and their results are presented in Section 5 followed by a discussion of the implications of these results in Section 6. Section 7 provides concluding remarks along with the limitations of the study and potential directions for future work.

2. RELATED WORK

The aim in this research is to explore the effect of DfAM integration on the designs' achievement of design task objectives, and the role of DfAM education in bringing these effects. Therefore, previous research related to the various DfAM guidelines and the current practices in DfAM education were surveyed. Further, current techniques for assessing engineering design outcomes were explored to help develop the metrics used in the study. 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 [6,11–17], of which Laverne, et al. [6] classifies 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 the literature (R: restrictive, O: opportunistic)

	DfAM consideration	Examples
R1	Support structure accommodation	[18–22]
R2	Warping due to thermal stresses	[23–26]
R3	Delamination and material anisotropy	[4,27,28]
R4	Stair-stepping and surface roughness	[29–35]
R5	Minimum feature size	[36–39]
O1	Free complexity – geometric and hierarchical	[40–43]
O2	Material complexity and multi-material printing	[44–47]
O3	Part consolidation and printed assemblies	[9,48]
O4	Mass customization	[49–52]
O5	Functional complexity and embedding	[53–56]

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 [18–22]. 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 [23–26]. 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 [4,27,28]. 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 [29–35]. Therefore, parts that have assembly features and need geometric exactness are oriented parallel to the build platform [32]. 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 [36–39].

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” [40]. AM not only provides designers with the freedom to include complex geometries but also extend this complexity at the hierarchical, and functional levels [41–43]. 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 [44–47]. 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 [9], and design and build assemblies [48] 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

[49]. This enables designers (and consumers) to design and manufacture products that are customized for each user, a concept commonly known as mass customization [50–52]. 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 [53–56].

In summary, several techniques have been developed that help leverage the capabilities and accommodate the limitations of AM. However, given this unique dual nature of DfAM, it is also important to integrate these techniques into the engineering design curriculum. To meet this need, several educational institutions have introduced AM and DfAM educational initiatives, as discussed next.

2.2. DfAM Education and Integration in Engineering Design

While research in AM is constantly refining DfAM methods and providing better tools for engineers and designers [57], it is also important that future engineers are trained in integrating DfAM in the engineering design process [58]. 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 as reviewed in [59].

Early examples of AM integration in the curriculum are presented by Bøhn [60] and Jensen and coauthors [61] where the authors demonstrate the utility of AM to enhance education through (rapid) prototyping. Further examples of formal AM interventions are the AM courses 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 [62]. Employing a more self-directed approach, Yang [63] 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. [64] 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 [65,66]. Similarly, Williams et al. [67] 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. A similar use of problem-based learning can also be seen in the graduate-level course developed by Ferchow and coauthors [68] based on their experience transfer model of learning [69].

In contrast to these formal initiatives, several academic institutions are constantly working towards providing students access to AM processes to encourage self-learning [70]. For example, the 3D printing vending machines at Virginia Tech [71] and UT at Austin [72] allow 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 [40,73–75]. 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 [75]. Further, universities such as MIT and Case Western provide students with access to both AM and traditional manufacturing through a network of interconnected makerspaces [76,77]. The Poorvu Center for Teaching and Learning at Yale further encourages instructors to use AM as an instructional tool and provides a compiled set of educational resources [78]. 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, a limited emphasis is given to the opportunistic aspects of AM.

To meet this need for design tools that help integrate opportunistic DfAM in the design process, Blösch-Paidosh and Shea present the use of opportunistic DfAM-based design heuristics [79]. These process-independent, high-level heuristics [80], 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 studies in [79,81] use qualitative analyses to assess the AM designs for their use of the various heuristics, and the authors further demonstrate the effect of these heuristics in increasing the AM novelty and AM flexibility of designs in [82]. However, the studies used in demonstrating the utility of these heuristics are limited to the redesign of an existing product and do not inform of their use in encouraging creative solution generation.

Perez and coauthors present a similar use of heuristic cards – derived through crowdsourcing [83] – to encourage AM integration. The heuristic cards – presented in [84] – introduce AM concepts related to (1) product innovation, (2) business process, (3) design process, and (4) printing and manufacturability. The authors – in [85] – demonstrate the perceived utility of these heuristic cards towards encouraging creativity and discuss the integration of these heuristics in a design innovation framework in [86]. The authors further demonstrate the positive influence of these DfAM principle heuristics in increasing the novelty and quality of ideas in a two-step brainstorming session, with no increase in the quantity of ideas [87].

A similar use of design principles is presented by Valjak and Bojčetić [88]. These design principles are aimed at encouraging the integration of DfAM by introducing the various DfAM concepts using a mix of a sample CAD model, manufacturability data with respect to different processes, and some examples employing the design principle. Schumacher and coauthors [89] also present the use of design principle cards that provides designers information on the DfAM concepts' ability to help or hamper the achievement of certain design functions. For example, the principle card discussed in the paper informs designers that material complexity introduced through friction-based bearing surfaces has a positive influence on design functions of aesthetics and ergonomics, but has a negative influence on production effort and robustness.

In summary, prior research presents several initiatives that integrate AM and DfAM into the engineering design curriculum through formal and informal educational interventions as well as DfAM design tools. The studies reviewed in this section also demonstrate the utility of the discussed interventions in successfully enhancing design attributes such as novelty and quality. Despite providing important insights, more research is needed when considering how to assess the influence of DfAM education on students' integration of DfAM in their designs. Specifically, additional study into the use of objective metrics is needed to explore the relationship between DfAM integration and the performance of a design with respect to the design task objectives. 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. In addition, while several techniques have been developed for assessing the effectiveness of engineering design outcomes, few methods exist that assess the integration of manufacturing considerations into the designs, especially DfAM considerations. The next section discusses techniques currently in use for assessing engineering design outcomes.

2.3. Techniques for Assessing Engineering Design Outcomes

Several methods for assessing engineering design outcomes have been presented in the literature, and these methods comprise both objective and subjective metrics. Shah, Vargas-Hernandez, and Smith (SVS) [90] introduce a four-component metric for *objectively* assessing ideation effectiveness of engineering design outcomes. This metric assesses an idea based on its (1) novelty, (2) variety, (3) quality, and (4) quantity. While novelty aims at capturing the unusualness or uniqueness of an idea, variety aims at capturing an individual's or a group's ability to think divergently. Further, the quality of an idea assesses the extent to which an idea meets the functional requirements of the problem, and quantity aims at capturing the number of ideas generated by an individual or a group. Despite being widely used, the SVS metrics of novelty and variety only capture variations in the embodiment of the different features of a design and do not capture variations at higher levels of abstraction. For example, in a situation comparing the variety of 3 designs that utilize two physical principles against 3 designs that utilize three different physical principles, the idea set utilizing fewer physical principles scores higher on overall variety despite having a lower variety. To address this issue, Nelson et al. [91] present a refined technique for assessing variety by accommodating for variations in higher levels of abstraction of the features of a design. Similarly, Johnson et al. [92] present a modification of the SVS novelty metric aimed at including ideas defined at a higher level of abstraction.

In contrast to these objective metrics, Amabile [93,94] presents the Consensual Assessment Technique (CAT), a *subjective* technique for assessing the creativity of design outcomes. The CAT relies on the assumption that an expert in a certain domain is best qualified to assess the creativity of an idea in that specific domain. This assumption is often validated through the achievement of high inter-rater reliability [95] between multiple experts and/or quasi-experts [96–98]. Derived from the CAT, Besemer [99,99] discusses the breakdown of creativity into three components: novelty (original and surprising), resolution (value and usefulness), and elaboration and synthesis (well-craftedness and elegance), thus demonstrating similarities to the SVS metrics. Similar to the CAT, Linsey et al. [100] present the use of a subjective approach towards assessing the variety of ideas in a solution pool by categorizing similar ideas into bins and investigating relative frequencies of each bin.

While these measures capture the functional and creativity-related characteristics of an idea, they do not give sufficient emphasis on the manufacturability of an idea, particularly through the integration of DfAM. To address this need, Booth et al. [101] developed the DfAM worksheet to help designers assess AM designs for their manufacturability and 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: (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 typically not encouraged to leverage the design freedoms enabled by 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. To address this lack of emphasis on opportunistic DfAM, the authors' previous work [102,103] used 'AM technical goodness', a subjective metric derived from the CAT. Technical goodness aims at capturing designers' use of both opportunistic and restrictive DfAM in their design outcomes, as assessed by experts and quasi-experts in the DfAM domain. While this metric addresses the lack of emphasis on opportunistic DfAM in existing assessment techniques, it is often difficult to accurately describe the rater's mental model due to its subjective nature.

In summary, while several measures for the assessing engineering design outcomes have been discussed in the literature, few measures *objectively* assess the integration of DfAM considerations – both opportunistic and restrictive – in the associated design outcomes. Therefore, the aim in this research is to present the use of metrics that assess design outcomes for their DfAM use and to understand their role in predicting the designs' achievement of design task objectives. This is achieved through the investigation of the research questions presented in Section 3.

3. RESEARCH QUESTIONS

The goal in this study is to investigate the role of DfAM education in bringing about the integration of DfAM in engineering students' designs outcomes and its effect on the design outcomes' achievement of design task objectives. The study aims to achieve this by exploring the following research questions (*RQ*):

- *RQ1: How does the participants' use of DfAM relate to the design's ability to achieve the design task objectives – minimizing build material and build time?* Prior research has demonstrated the role of integrating DfAM concepts, especially opportunistic DfAM concepts such as part consolidation and geometric complexity, in minimizing build material and build time [9,104]. Therefore, we hypothesize that the participants' use of DfAM in their designs would correlate with lower build material and build time, thus achieving the design task objectives. However, this hypothesis could vary based on the choice of design task objectives beyond build material and build time, for example, part strength relates to build orientation and material anisotropy [4,27,28].
- *RQ2: How does the DfAM educational intervention affect the participants' designs' achievement of design task objectives and the integration of DfAM in the participants' design outcomes?* Since effective learning is shown to correlate with the ability to use the knowledge to solve problems [105,106], we hypothesize that introducing participants to DfAM, either restrictive or dual, would result in greater use of the respective concepts in their final designs. Further, given the ability of opportunistic DfAM to minimize build material and build time [9,104], we hypothesize that participants who received opportunistic DfAM training will generate ideas with lower build material and build time. Similar to the hypothesis in RQ1, this hypothesis could vary based on the choice of design task objectives.
- *RQ3: How do the various DfAM concepts manifest in the participants' designs and is this influenced by the DfAM educational intervention?* We hypothesize that introducing opportunistic DfAM concepts to the participants would encourage the integration of features such as part complexity towards achieving design task objectives. Further, introducing restrictive DfAM concepts would result in the incorporation of features such as warping and support material accommodation, making the designs more feasible. This is based on prior research where effective learning has been shown to correlate with an ability to apply the new knowledge towards solving problems [106].

4. METHODOLOGY

To answer these research questions, an experiment was conducted that involved a short-duration intervention lecture and an AM design challenge. The details are discussed next.

4.1. Participants

The experiment was conducted at a large northeastern public university, where participants (N = 301) were recruited from a junior-level mechanical engineering course focused on product design and engineering design methods. The experiment was conducted in both the fall and spring semesters with N_f = 123 participants in the fall semester and N_s = 178 participants in the spring semester. The participants approximately consisted of juniors (N_f = 78, N_s = 134), seniors (N_f = 41, N_s = 15), and 5th year seniors (N_f = 2, N_s = 4). The remaining participants did not specify their year of study. While this sample can be used to represent mechanical engineering students in their higher classes, the results of the study could be different for students from lower classes such as freshmen and sophomores, as well as higher levels of education such as graduate students and professionals, and future research must extend the study to these samples. The participants' self-reported previous experience in AM and DfAM was collected at the beginning of the study as summarized in Figure 1. As seen in the figure, the participants' AM and DfAM experience showed similar distributions between the two semesters.

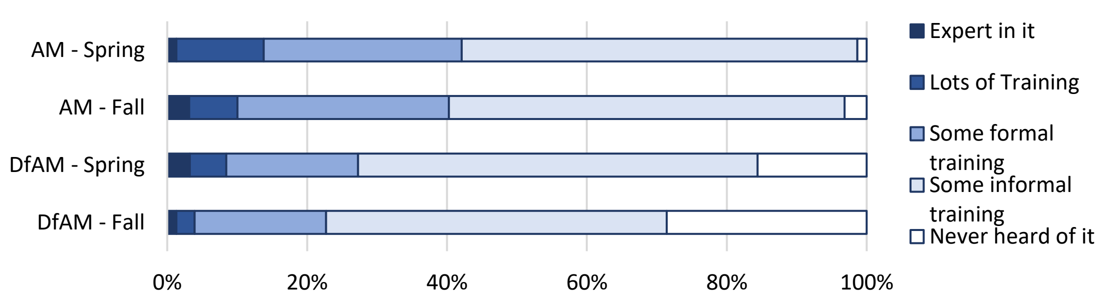


Figure 1 Distribution of participants' previous experience

4.2. Procedure

The experiment was conducted in the second and third weeks of the fall and spring semesters, respectively. Each semester, experimentation was divided into three stages: (1) a pre-intervention survey, (2) a DfAM education lecture, and (3) a design challenge and post-intervention survey. The study was approved by the Institutional Review Board, and implied consent was obtained from the participants before conducting the experiment in both semesters. Figure 2 summarizes the progression of the different experimental stages.

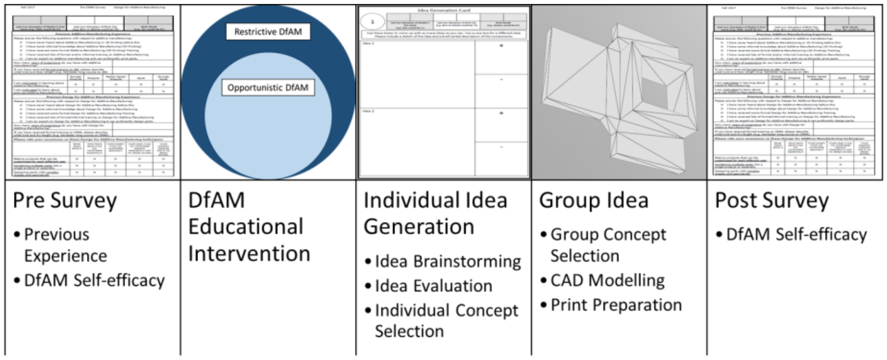


Figure 2 Summary of the experimental procedure

4.2.1. DfAM Education Lectures

Participants consenting to the study were randomly assigned to one of two educational intervention groups: (1) restrictive DfAM ($N_f = 67$, $N_s = 103$) or (2) opportunistic and restrictive (dual) DfAM ($N_f = 56$, $N_s = 75$). 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. The lecture slides can be accessed here: [107]. While this order and distribution of lectures were chosen given the importance of restrictive DfAM in ensuring design printability [101], the order of lectures could potentially influence students' learning and future research must investigate these effects. Additionally, the short length of the lecture could also have limited students' learning of the various DfAM concepts.

4.2.2. Post-intervention Design Challenge

Participants in both fall and spring semesters were given a design task that asked them to:

"Design a fully 3D printable free-standing tower for a down-scaled 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 satisfying the following set of constraints. 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"."*

This task was chosen for the experiment as it requires minimal domain-specific knowledge beyond AM (as suggested by [93]) and given its explicit inclusion of task objectives and constraints [108]. However, the specificity of the design task could have limited students' applications of certain DfAM concepts such as mass customization, and future research must explore the use of an open-ended design task.

Participants from both semesters were first asked to spend 10 minutes individually brainstorming their own solutions using an idea generation card to record each idea for consistency, with 7 minutes allocated for sketching, and 3 minutes allocated for describing each idea in words. The participants were then given 5 minutes to evaluate each idea and note down their 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. These times – approximately determined based on [109] and pilot studies – were intended to keep the participants moving through the various stages of the experiment and were not strictly reinforced. Further, this breakdown also worked towards accommodating the experiment within the class/lab time of the course in which the experiment was conducted. However, we acknowledge that the short duration of the design task could have limited participants from applying multiple DfAM concepts at once. Therefore, future research must explore the effect of the length of the design task especially since prior research has demonstrated the effect of the time spent on prototyping on design outcomes [110]. After completing the design challenge, the participants were asked to complete a post-intervention survey with the same DfAM self-efficacy questions as in the pre-intervention survey.

4.2.3. Concept Selection and Build Preparation

After completing the individual concept generation, participants were split into groups of 3 or 4 participants each. This resulted in 44 groups in the fall semester – 24 groups receiving restrictive DfAM training and 20 groups receiving dual DfAM training – and 48 groups in the spring semester – 28 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+ systems. 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 STL files and .thing (Makerbot build preparation) files were collected from the participants at the end of the experiment. The build files were then assessed using the metrics discussed in Section 4.3. Some sample designs generated by the participants can be seen in Figure 5.

Since the main objective of the study is to investigate the effect of DfAM integration on the design' achievement of design task objectives, only the final designs from each group were used for the analyses. Therefore, we do not expect the team size to have a major influence on the outcome. However, we acknowledge that differences in the group size could have influenced the quantity of ideas generated in the conceptual stage, therefore potentially affecting the creativity of the ideas [111]. In addition, the factors employed by the teams in selecting their final ideas [112] and their individual differences such as risk-taking attitudes [113] could also have influenced the characteristics of the final selected designs [114] and future research must investigate the effect of concept selection on the teams' final design outcomes. Finally, it should be noted that 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.

4.3. Metrics

To explore the integration of the various DfAM concepts in the participants' designs and to understand the effect of this DfAM integration on the achievement of design task objectives, the following metrics were developed.

4.3.1. Achievement of Design Task Objectives

Successful engineering designs are characterized by several attributes such as strength, weight, cost, creativity, and market success [115]. Of these various metrics, the participants' designs were assessed with respect to their build material and build time and minimizing both of these were used as the objectives of the design task. 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 [116]. Further, the weight of parts is also an important criterion for assessing design performance in several industries, including aerospace and automotive engineering [117]. The build time and build material were obtained from the build files submitted by the participants. However, we acknowledge that while build material and build time are important indicators of engineering design success, these two factors might not be an all-encompassing assessment. We limited the objectives of the design task – and therefore the assessment of the design outcomes – to build time and build material to avoid overwhelming the participants with too many objectives and constraints.

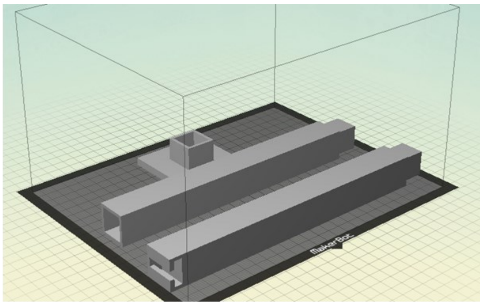
4.3.2. Assessment of Participants' Integration of DfAM in their Designs

To assess the participants' use of DfAM in their designs, metrics were developed for both opportunistic and restrictive DfAM considerations. Of the design considerations discussed in Section 2.1, those that were within the scope of the experimental setup were chosen. For example, given the limitations of the 3D printing facilities available through the university, participants would not be able to embed components or use multi-material printing. Furthermore, given the structure and specificity of the task, participants 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 opportunistic DfAM considerations used in the assessment 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. The measurement scales for geometric complexity and support material removal were adapted from the DfAM worksheet developed by Booth et al. [101] as these items required subjective scales of measurement. Similar scales were developed for measuring assembly complexity and part and assembly feature orientation. Subjective scales were used for these items as (1) in the real world, decisions related to some of these DfAM concepts are often made by experts using their subjective assessments and opinions [118], and (2) it is difficult to obtain quantitative data about these DfAM concepts directly from the CAD and build files. Quantitative measures were used for the remaining DfAM concepts – (1) number of parts, (2) smallest feature size, (3) tolerance, (4) support material mass, and (5) build plate contact area – as these measurements could directly be obtained from the final CAD and print files. The metrics and corresponding DfAM considerations are consolidated in Table 2. Figure 3 presents an example of the assessment of a design using the DfAM metrics.

Table 2 Metrics used for assessing the participants' 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 traditional 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 the process can build (~0.5mm for material extrusion [119]).
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

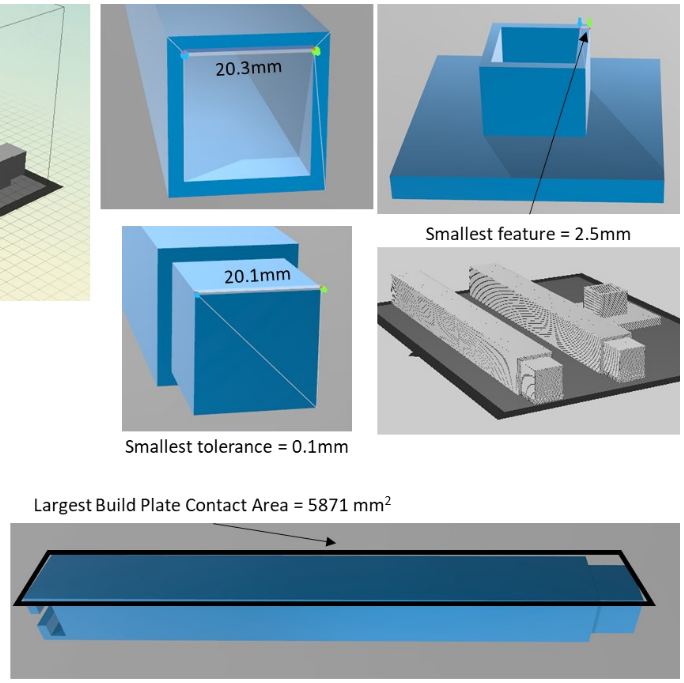


Figure 3 Example of assessment of a design using the DfAM metrics

4.3.3. Feature Analysis of the Participants' Designs

To investigate the manifestation of the various DfAM concepts in the participants' designs, a detailed feature analysis was performed. First, all ideas were dissected for features such as material removal (bulk vs. patterned) and incorporation of different assembly components. These features were then grouped to develop a genealogical tree [92]. Specifically, genealogical trees resented in Figure 4 were developed for part (shape) complexity, assembly (functional) complexity, support material accommodation, and warping accommodation based on work by [120].

After developing the genealogical trees, each design was assigned to a node at the detail design level in the feature tree and the frequency distributions were obtained at each hierarchical level (design detail, embodiment, working principle, and physical principle). For example, the idea shown in Figure 6(a) incorporates shape complexity through the rectangular-shaped bulk removal of material. On the other hand, the idea shown in Figure 6(b) incorporates shape complexity through the patterned cuts that are rectangular in shape. First, 20% of the ideas were independently rated by two raters, and they obtained an inter-rater reliability of 0.75, 95% CI [0.59, 0.84] as measured by an average measures Intraclass Correlation Coefficient [121]. The remaining ideas were rated by one of the two raters.

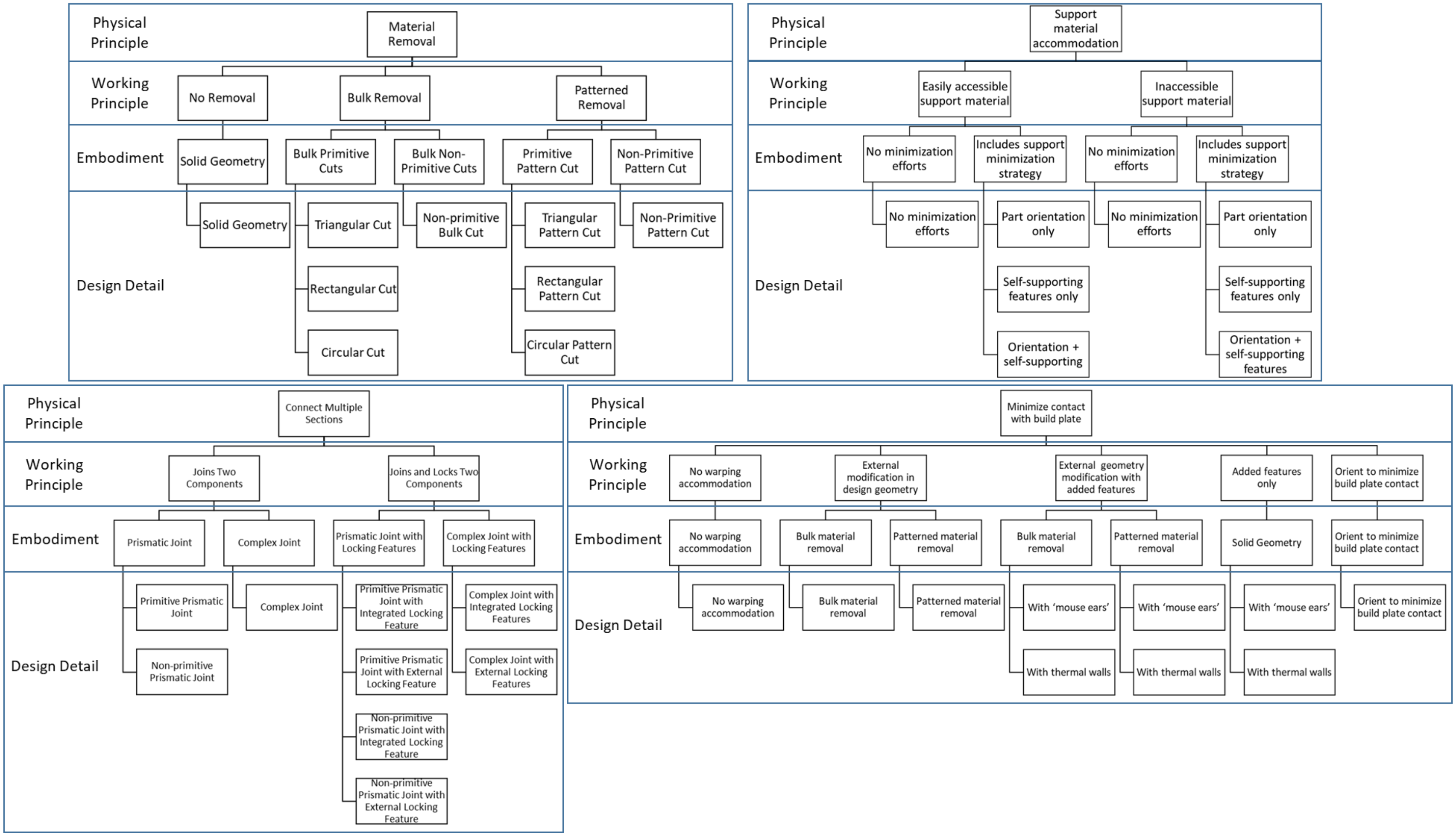


Figure 4 Genealogical trees used for the feature analyses

5. RESULTS

To answer the three research questions presented in Section 3, the collected data was analyzed. Before the analysis was performed, any data points with missing values (such as missing components or build files) were removed, leading to a sample size (N) of 86 groups with 39 groups in the fall (N_f) and 47 groups in the spring (N_s). In this sample size, the educational intervention groups were distributed as: restrictive DfAM only = 49 ($N_f = 21$, $N_s = 28$), and dual DfAM = 37 ($N_f = 18$, $N_s = 19$). Further, it should be noted that the data from both fall and spring semesters was combined for the analysis and the effect of the intervention semester was checked and controlled for where necessary. The remainder of this section discusses the results for each research question.

5.1. RQ1: How does the participants' use of DfAM relate to the design's ability to achieve the design task objectives – minimizing build material and build time?

To answer the first research question, hierarchical linear regressions were performed. All ten DfAM metrics were used as the input predictors in the first model, and the intervention semester and educational intervention group were added as a block to the second model. Build material and build time were used as the dependent variables. The results of the linear regression showed no significant effect of either the intervention semester ($\beta_{In} = -0.09$, $t(73) = -0.80$, $p = 0.43$) or the educational intervention group ($\beta_{In} = 0.17$, $t(73) = 1.63$, $p = 0.10$) on the build time of the designs, with an R^2 change of 0.028 upon adding the second block. Similarly, the results showed no significant effect of either the intervention semester ($\beta_{In} = -0.03$, $t(73) = -0.35$, $p = 0.73$) or the educational intervention group ($\beta_{In} = 0.06$, $t(73) = 0.70$, $p = 0.49$) on the build material, with an R^2 change of 0.004. Therefore, the second block of independent variables (intervention semester and educational intervention group) was removed from the model. The results of the linear regressions after removing the second block of variables are summarized in Table 3.

Table 3 Correlation coefficients between the DfAM metrics and the design build time and build material

DfAM consideration	Build Material			Build time		
	B	SE_B	*p*	B	SE_B	*p*
Part Complexity	-40.40	14.41	0.01**	10.21	54.62	0.85
Assembly Complexity	-5.20	12.17	0.67	-59.51	46.16	0.20
Number of parts	11.00	4.06	0.01**	36.64	15.39	0.02**
Part orientation	-11.59	13.00	0.38	-78.07	49.28	0.12
Assembly feature orientation	7.15	10.89	0.51	73.67	41.30	0.08
Smallest feature size	7.85	3.42	0.02**	22.68	12.96	0.08
Tolerance	-10.08	12.67	0.43	-28.28	48.03	0.56
Support material mass	1.34	0.34	<0.001**	5.08	1.28	<0.001**
Support material removal	35.57	19.21	0.07	99.61	72.82	0.18
Largest build plate contact area	0.01	0.00	<0.001**	0.02	0.01	0.002**

**indicates $p < 0.05$

From these results, we see that the *number of parts in the design, the support material needed, and the build plate contact area have a significant correlation with build material and build time.* Specifically, the greater the number of parts, the higher the build material and time. Further, the build material and build time increased with the amount of support material mass required. Finally, a larger contact area between the parts and the build plate corresponded to a greater build material and build time. In addition to these results, we see that the c*omplexity of the parts and the size of the smallest feature in the design had an effect on the build material of the design.* Specifically, parts with greater complexity and small features correlated with lesser build material consumed by the design. The implications of these results are discussed in Section 6.1.

5.2. RQ2: How does the DfAM educational intervention affect the participants' designs' achievement of design task objectives and the integration of DfAM in their design outcomes?

To answer the second research question, a series of Mann-Whitney U tests [122] were performed with the DfAM educational intervention group (restrictive and dual DfAM) as the between-subjects factor. Build time, build material, and each DfAM concept from Table 2 was individually taken as the dependent variable. The results from the analyses are summarized in Table 4.

The results show that, while there were no significant differences between the build material and build times of the designs generated by the two educational intervention groups, the groups did show a significant difference in their use of certain DfAM concepts. Specifically, the results showed that the restrictive DfAM group incorporated more appropriate tolerances between their mating features (mean = 0.44mm, median = 0.25mm) compared to the dual DfAM group (mean = 0.15mm, median = 0.05mm). The tolerances provided by the restrictive DFAM group were closer to the 0.5mm tolerance guideline given during the lecture. Furthermore, the results show that the group that received restrictive DfAM training generated designs with better access to support material which could be removed easily, compared to the dual DfAM group. Finally, the group that received the restrictive DfAM training designed parts with larger build plate contact area (mean = 9355.73 mm^2, median = 7921.00 mm^2) compared to the dual DfAM group (mean = 6343.92 mm^2, median = 7045.11 mm^2). In addition to these statistically significant results, we also see that print files from the restrictive DfAM group presented better part and assembly feature orientation and needed lower support material. However, it must be noted that these results were significant to the $p <$ 0.1 level. Some representative examples of the designs from each group are shown in Figure 5.

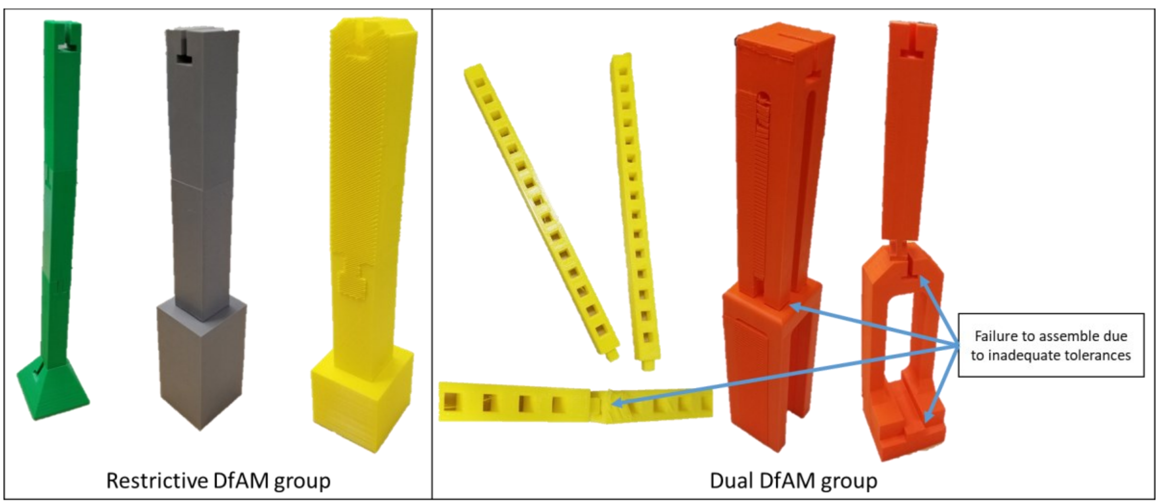


Figure 5 Sample printed parts: Solid 'blocky' designs with large surfaces by the restrictive DfAM group vs complex designs with poor assembly tolerances by the dual DfAM group

Table 4 Comparing manufacturability and DfAM use between the DfAM educational intervention groups (significantly higher values highlighted)

Metric	*p*	*U*	*z*	Mean Rank (Mean Score)	
				Restrictive DfAM	**Dual DfAM**
Build material	0.71	864.00	-0.37	44.37 (255.30)	42.35 (241.86)
Build time	0.32	1020.50	0.99	41.17 (807.69)	46.58 (886.49)
Part complexity	0.46	986.00	0.73	41.88 (2.14)	45.65 (2.26)
Assembly complexity	0.85	926.50	0.19	43.09 (1.67)	44.04 (1.68)
Number of separate parts	0.31	1016.50	1.02	41.26 (3.69)	46.47 (3.84)
Part orientation	0.05*	739.00	-1.95	46.92 (2.71)	38.97 (2.41)
Assembly feature orientation	0.07*	712.50	-1.82	47.46 (2.24)	38.26 (1.89)
Smallest feature size	0.12	729.50	-1.55	47.11 (4.61)	38.72 (3.55)
Smallest tolerance	<0.001**	551.50	-3.20	50.74 (0.44)	33.91 (0.15)
Support material mass	0.09*	1099.00	1.68	39.57 (11.34)	48.70 (27.99)
Support material removal	0.04**	696.50	-2.01	47.79 (2.42)	37.82 (2.14)
Largest build plate contact	0.03**	654.00	-2.20	48.65 (9355.73)	36.68 (7045.11)

*Statistically significant to 0.1 level
**Statistically significant to 0.05 level

In summary, we see that the dual DfAM education does not sufficiently encourage the generation of designs with better integration of opportunistic DfAM. Further, we see that dual DfAM education results in the generation of designs with poor integration of restrictive DfAM compared to only restrictive DfAM education. The implications of these findings are discussed in Section 6.2.

5.3. RQ3: How do the various DfAM concepts manifest in the participants' designs and is this influenced by the DfAM educational intervention?

The third research question sought to understand how various DfAM concepts manifested in the participants' designs. To answer this research question, a feature analysis was performed where each design was dissected into its features and categorized using genealogical trees defined in Section 0. The frequency of occurrence of designs in each node at the second-lowest level of detail (embodiment) was investigated using Fisher's Exact Tests [123]. Further, exact tests were used since several cells had frequencies less than 5 [124]. The results of the analysis are summarized in Table 5, and the frequency distribution of the designs is presented in Figure 7. The results show that there was a statistically significant difference in the multinomial probability distribution of the *part complexity* and *warping accommodation* in the designs generated by the two educational intervention groups ($p < 0.05$). Further, there was a significant difference in the distribution of the *support material accommodation* between the two educational intervention groups but only at the $p < 0.1$ level.

Table 5 Summary of Fisher's Exact Tests comparing the frequency of occurrence at the nodes between the two educational groups.

DfAM Feature	**Fisher's Test Statistic**	**Exact 2-sided Significance**
Part Complexity	9.70	0.03**
Assembly Complexity	1.28	0.94
Support Material Accommodation	6.28	0.07*
Warping Accommodation	8.35	0.03**

*Significant to 0.1, **Significant to 0.05

Further investigation into the distribution of part complexity shows that while a majority (73%) of the designs in the dual DfAM group incorporated material removal strategies, this was only seen in about 46.9% of the designs from the restrictive DfAM group. The remaining designs – 27% in the dual DfAM group and 56.1% in the restrictive DfAM group – consisted of solid geometries with no material removal efforts. Of the designs that incorporated some part complexity through material removal, only 10.2% of the designs in the restrictive DfAM group had patterned cuts in primitive shapes compared to 29.7% in the dual DfAM group, a three-fold increase in usage by teams exposed to the opportunistic aspects of DFAM.

Next, an investigation into the features that help minimize warping showed that while only 26.5% of the designs in the restrictive DfAM group presented features that aided the minimization of warping, this number was much higher in the dual DfAM group (56.8%). This difference was primarily due to the greater number of designs from the dual DfAM groups that incorporated bulk material removal, which helps minimize warping. While only 16.3% of the designs in the restrictive DfAM group presented bulk material removal to aid warping minimization, these features were seen in 35.1% of the designs from the dual DfAM group, a two-fold increase by the teams exposed to the opportunistic aspects of DFAM. Additionally, we also see that a greater number of designs from the dual DfAM group (18.9%) present patterned material removal, which can help reduce warping, compared to only 8.2% of the designs in the restrictive DfAM group.

The results for the analysis of the complexity of the assembly features used in the designs showed no significant differences between the educational intervention groups. A majority of the designs from both groups employed simple prismatic joints with some designs from both groups incorporating locking features in their prismatic joints.

(a) Primitive (rectangular) shaped patterned material removal

(b) Primitive (rectangular) shaped bulk material removal

(c) Inaccessible support material

Figure 6 Sample designs demonstrating the various features ((a) and (b): restrictive DfAM group (c): dual DfAM group)

Finally, the design features that helped minimize support material and/or enabled its easy removal were investigated. The results showed that in the dual DfAM group 10.8% of the ideas presented the need for support material with no minimization strategies included and this support material was not easily accessible for removal. No ideas from the restrictive DfAM group presented features that fell in this category. On the other hand, the restrictive DfAM group consisted of 20.4% ideas with easily accessible support but no minimization strategies compared to 10.8% of the ideas from the dual DfAM group falling in this category.

In summary, we see that teaching participants about opportunistic DfAM results in an increase in the generation of ideas with shape complexity through the inclusion of patterned cuts. This added complexity also helps minimize warping tendencies in these designs – primarily achieved through a reduction of build plate contact area due to bulk and patterned material removal. Alongside this incorporation of shape *complexity, we see that participants from the dual DfAM group fail to sufficiently incorporate support material minimization strategies. This could result in higher build time and build material and poor surface finish due to support material removal, especially in mating features. This could, in turn, increase the time and cost spent on post-processing the parts. The implications of these results are discussed in Section 6.3.*

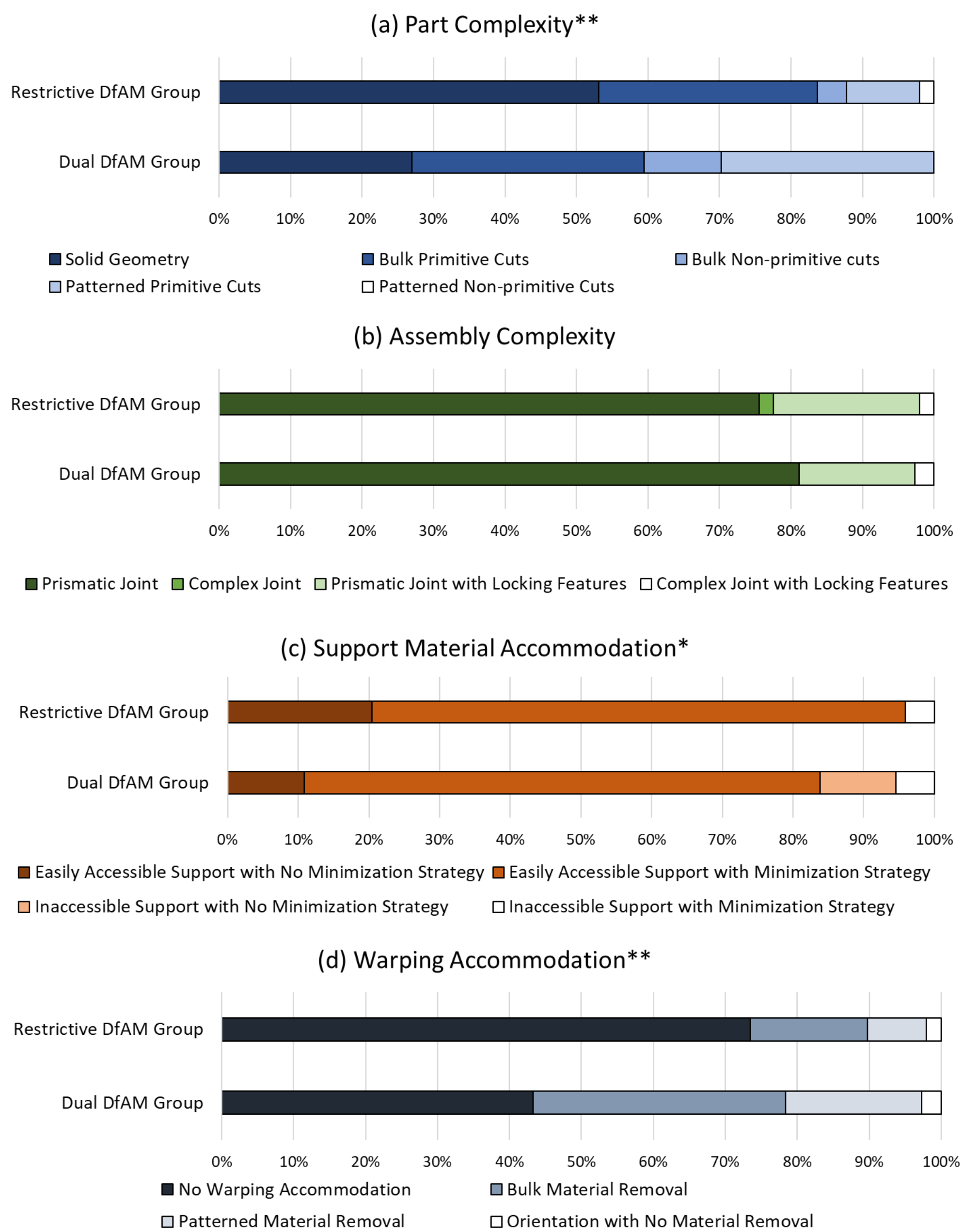


*Figure 7 Distribution of designs between the nodes for each DfAM feature (*significant to 0.1 level, **significant to 0.05 level)*

6. DISCUSSION AND IMPLICATIONS

The main findings from the results were:

- The participants' use of certain DfAM concepts predicted the build material and build time consumed in manufacturing the designs.
- Designs generated by the restrictive DfAM group incorporate more appropriate tolerances with easily accessible support material, but also tend to have higher build plate contact area compared to designs from the dual DfAM education.
- Variations in DfAM education do not have a statistically significant effect on the participants' designs' achievement of design task objectives.
- Dual DfAM education encourages the generation of designs with more shape complexity accompanied by less warping tendency. However, designs from the dual DfAM group also consumed more support material and these support structures were not easily accessible for removal.

The implications of these findings are discussed in detail in the following sections.

6.1. Participants' use of certain DfAM concepts predict the build material and build time consumed in manufacturing their designs

The first key observation from the results was that the size of the smallest feature in a design correlated with both, the design's build material and build time; designs that tend to have large features tend to take longer to build and use more material. 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. Further, we see 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.

Finally, 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 [3,9].

In summary, these results highlight that integrating the various opportunistic and restrictive DfAM guidelines have a positive influence on the build material and build time of the 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, both of which were objectives of the design task.

6.2. Variations in DfAM education content affects participants' use of certain DfAM concepts, but not their designs' achievement of design task objectives

The second key finding was 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 [125]. Therefore, educators must ensure that the introduction of opportunistic 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.

Further, 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 5, 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 the 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.

Finally, we see that the content of the DfAM education did not have a significant effect on the build material and build time of the designs. While the dual DfAM group generated designs with lower mean build time and build material used, as hypothesized, this result was not statistically significant. This result suggests 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 build material and build time of the AM designs. This outcome 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 build material and build time 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 [67]) to engage students in generating better design outcomes.

6.3. Dual DfAM training results in the generation of more complex parts but poor support material accommodation

The third key finding from the results was that teaching students about opportunistic DfAM concepts results in an increase in part complexity through patterned cuts, compared to the solid geometries seen in a majority of the designs from the restrictive DfAM group. The finding conflicts with the result from the second research question, where no differences were seen in the part complexity scores between the designs generated by the two educational groups. This could be attributed to the observation that despite the inclusion of patterned cuts, most designs from the dual DfAM group were 2.5D extrusions. These designs could easily be manufactured using conventional manufacturing processes such as milling, and do not fully leverage the freedom of shape complexity offered by AM processes. This finding, therefore, suggests that while the studied intervention helps shift from solid 'blocky' designs towards complex designs with patterned cuts, further efforts must be made towards encouraging complexity beyond 2.5D features.

Next, we see that the introduction of opportunistic DfAM education results in the generation of ideas with a lower warping tendency due to material removal. The lower warping tendency is attributed to bulk and patterned material removal, and it corroborates the finding from the second research question where designs from the dual DfAM group had a lower mean build plate contact area compared to the restrictive DfAM group. While this is a positive outcome, this finding further reinforces the previous inference that the generation of designs with lower warping tendency might not be on account of features added specifically to minimize build plate contact. This outcome could be attributed to the bulk and patterned removal of material aimed towards minimizing build material and build time, as reflected in the analysis of part complexity. Therefore, this result is problematic as it suggests that despite receiving training on the techniques that help minimize warping, the restrictive DfAM group failed to incorporate these techniques into their designs. In summary, while opportunistic DfAM education indirectly helps the generation of ideas with lower warping tendency, efforts must be made to encourage the learning and use of techniques specifically aimed at minimizing warping and build plate contact area.

The final key finding from this research question was that a greater proportion of designs from the dual DfAM group presented the need for inaccessible support material with no support minimization strategies incorporated. This finding corroborates findings from the second research question where designs from the restrictive DfAM group not only required less support material but performed better in terms of their ease of support material removal. Further, this finding suggests that introducing opportunistic DfAM potentially hinders participants' ability to give sufficient emphasis on the *restrictive* aspects of DfAM, particularly accommodation (and removal) of support material. This observation is supported by previous research where only restrictive DfAM education has been shown to have a greater increase in students' self-efficacy with restrictive DfAM compared to dual DfAM education [125]. The lack of emphasis on support material accommodation could be attributed to the short length of the design task, where participants might not have had sufficient time to effectively apply both opportunistic and restrictive DfAM concepts. Therefore, future research must explore these effects with a longer design activity with multiple preliminary and detailed design stages. Furthermore, educators must ensure that, along with encouraging designers to integrate opportunistic DfAM concepts and leverage AM capabilities, equal emphasis must be given to restrictive DfAM integration to ensure that the designs are manufactured feasibly. This is particularly important as the findings of the first research question suggest a positive correlation between support material mass and both build material and build time.

7. CONCLUSION, LIMITATIONS, AND FUTURE WORK

The research and development of AM processes have 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. While several studies have demonstrated methods of introducing DfAM to student designers in ways that successfully enhance design creativity, few studies have objectively assessed engineering design students' use of DfAM and its resulting influence on the designs' achievement of design task objectives. 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 the participants' use of DfAM concepts such as part consolidation, warping accommodation, and support material accommodation influence the build material and build time required for manufacturing the designs – minimizing both of which were objectives of the design task. Further, the results show that while variations in the DfAM educational content (restrictive and dual DfAM) does not influence either the build time or the build material of the designs, it has an influence on the participants use of assembly tolerances and warping considerations. Finally, a feature analysis of the designs showed that a greater number of designs from the dual DfAM group introduced shape complexity and warping accommodations through bulk and patterned material removal compared to the restrictive DfAM group. However, designs from the dual DfAM group also tended to require support material that was not easily accessible or removable. These results, therefore, suggest that the participants' use of the DfAM influences the achievement of design task objectives, thus demonstrating the role of DfAM on improving engineering design outcomes. Further, the results also suggest a decrease in the effectiveness of restrictive DfAM education when introduced with opportunistic DfAM. This could either be attributed to the short length of the lectures or that of the design activity. However, we must be careful when extending the findings of the study as these results could vary if the students' designs are assessed using measures beyond build material and build time, for example, part strength or creativity, or if tested using a participant sample with different levels of experience. These limitations and potential directions for future work are discussed next.

The first limitation of the study is that it assesses the performance of the designs using build material and build time. A successful design could have several other attributes such as strength, ease of assembly, and creativity, and future research must explore the effects of DfAM integration on design attributes beyond build material and build time. Second, the study was conducted with participants primarily in their junior and senior years of study. While this group of participants could have relatively high levels of engineering experience compared to freshmen and sophomores, their prior experience could be lower compared to graduate students and industry professionals. Future research must investigate the effect of engineering experience by comparing students from lower (e.g., freshmen, sophomores) and higher years of study (e.g., graduate and professional students). This comparison could also highlight any influence of CAD skills on the students' ability to translate complex designs from concept to final product. This investigation is important as the current study uses the participants' final CAD designs to assess the integration of DfAM. The participants' CAD skills, as well as the time available to generate the CAD models, could have limited the integration of features such as complex geometries in their designs [126].

The third 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. Fourth, we see that the participants' learning and use of opportunistic DfAM potentially interact with their use of restrictive DfAM. This could be attributed to the short length of the intervention and the design task. While interventions that comprise of a lecture followed by a design task have been shown to be effective for AM education [68], the time spent on prototyping has also been shown to influence design performance [110]. Therefore, future research must compare the effectiveness of a longer, module-style educational intervention to that of the present lecture-style intervention. A longer educational module could provide students with more time and opportunity to apply the various DfAM concepts, resulting in the generation of designs that both, leverage AM design freedoms and demonstrate high manufacturability. Additionally, while the problem statement used in the study has been demonstrated to encourage creativity [108], its complexity could have constrained the design space thus limiting participants' application of opportunistic DfAM. Therefore, future studies muse extend this research to open-ended problems. Finally, the feature analysis employed in this study only captures the design features as they exist in the design, with no information about the participants' *intent* towards incorporating the various DfAM concepts. For example, the results show that designs from the dual DfAM group are less likely to warp due to the bulk and patterned material removal, resulting in lower build plate contact area. However, this outcome could be an indirect effect of material removal aimed at minimizing build material. Therefore, future research must capture the participants' intent of incorporating certain design features and the corresponding relation of these features to the various DfAM concepts.

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NOMENCLATURE

AM	Additive Manufacturing
DFMA	Design for Manufacturing and Assembly
DfAM	Design for Additive Manufacturing
CAT	Consensual Assessment Technique
SVS	Shah, Vargas-Hernandez, Smith Technique
ANOVA	Analysis of Variance
NSF	National Science Foundation

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Figure Captions List

Table Captions List