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BREAK IT DOWN: COMPARING THE EFFECTS OF LECTURE- AND MODULE-STYLE DESIGN FOR ADDITIVE MANUFACTURING EDUCATIONAL INTERVENTIONS ON STUDENTS' LEARNING AND CREATIVITY

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ABSTRACT
Given the growing presence of additive manufacturing (AM) processes in engineering design and manufacturing, there has emerged an increased interest in introducing AM and design for AM (DfAM) educational interventions in engineering education. Several researchers have proposed AM and DfAM educational interventions; however, some argue that these efforts might not be sufficient to develop higher-level skills among engineers (e.g., identifying design opportunities that leverage AM capabilities). Prior work has shown that longer, distributed educational interventions are more effective in encouraging learning and information retention; however, these interventions could also be time-consuming and expensive to implement. Therefore, there is a need to test the effectiveness of longer, distributed DfAM educational interventions compared to shorter, lecture-style interventions. Our aim in this research is to explore this research gap through an experimental study. Specifically, we compared two variations of a DfAM educational intervention: (1) a module-style intervention spread over two sessions with the introduction of DfAM evaluation metrics, and (2) a lecture-style intervention completed in a single session with no evaluation metrics introduced. From our results, we see that students who received the module-style intervention reported a greater increase in their DfAM self-efficacy. Additionally, students who received the module-style intervention reported having given a greater emphasis on part consolidation and feature size. Finally, we observe that the structure of the educational intervention did not influence the creativity of ideas generated by the participants. These findings highlight the utility of module-style DfAM educational interventions towards increasing DfAM self-efficacy, but not necessarily design creativity. Moreover, these findings highlight the need to formulate educational interventions that are effective and efficient.

Keywords: *design for additive manufacturing; creativity; distributed education; external cues*

1. INTRODUCTION
As additive manufacturing (AM) technologies advance, these processes have become ubiquitous in engineering design and manufacturing. Consequently, there has emerged a need for an engineering workforce skilled in leveraging the offerings of AM [1]. Such an AM-skilled workforce must not only be well-versed with the various AM process characteristics but also be adept in designing for AM (DfAM) [2]. Moreover, when designing for AM, designers must not only accommodate AM limitations to endure the feasibility of their solutions; they must also utilize the capabilities of AM to leverage the creative freedoms offered by these processes [3].

To help designers utilize AM capabilities and limitations in engineering design, researchers have proposed several design tools and methods. These DfAM tools and methods can be broadly categorized into opportunistic and restrictive domains [4,5]; while the former helps designers leverage AM capabilities, the latter helps them accommodate AM limitations. Some examples of opportunistic DfAM methods include (1) mass customization [6], (2) part consolidation [7] and printed assemblies [8], (3) freedom of geometric complexity [9–11], (4) embedding external components [12], and (5) printing with multiple materials [13]. Similarly, examples of restrictive DfAM techniques include accommodating for (1) support structures [14], (2) warping due to thermal stresses [15], (3) anisotropy

[16,17], (4) surface roughness due to stair-stepping [18,19], and (5) feature size and accuracy [20].

Despite the growing body of research on DfAM tools and methods, the lack of an AM-skilled workforce has often been identified as a potential barrier to the successful adoption of AM in the industry [21,22]. To meet this need for an AM-skilled workforce, several academic and professional institutions have introduced AM educational initiatives. These initiatives range from informal efforts such as the setting up of makerspaces [23–27] to more formal efforts such as semester-long courses [28,29], graduate programs [30,31], and professional development workshops [32–36]. However, Quinlan and Hart [37] argue that these efforts might not be sufficient to support the development of a workforce skilled in adopting AM. Specifically, they posit that educational efforts should focus on developing higher-level skills (e.g., identifying design opportunities that leverage AM and upskilling) over and above developing lower-level skills (e.g., operating AM processes). Therefore, educators must give a greater emphasis on teaching engineers to *design* for AM, over and above teaching them how to work with AM technologies, a recommendation also made by Simpson et al. [2]. Moreover, given the costs associated with deploying AM/DfAM education combined with the nascency of the understanding of DfAM education, current efforts are limited to standalone interventions as opposed to integrating these concepts in the broader engineering curriculum.

Educators could potentially use a longer, more thorough DfAM educational intervention to support the effective learning of DfAM concepts. However, little research has investigated the effectiveness of such longer, module-style DfAM educational interventions compared to the shorter, lecture-style interventions that are often employed. Such an investigation is important as longer AM and DfAM educational interventions could involve high associated costs (e.g., access to processes and software) [37]. The costs involved in longer interventions are further amplified when implementing them with industry practitioners; participating in these interventions would take time away from employees that could instead have been spent working [37]. Therefore, educators must formulate DfAM educational interventions that are not only effective but also *efficient.*

Our aim in this research is to investigate this research gap by comparing the effectiveness of two structures of a DfAM educational intervention: (1) a longer, module-style DfAM educational intervention and (2) a shorter, lecture-style intervention. Specifically, the module-style intervention differs from the lecture-style intervention in two aspects: (1) it takes place over two sessions, and (2) in the module-style intervention, students are introduced to DfAM evaluation metrics for assessing their designs. We compare the effects of these two intervention structures on (1) students' DfAM self-efficacy, (2) their self-reported DfAM use, and (3) the creativity of their designs. By exploring this research gap, we aim to inform the formulation of effective and efficient DfAM educational interventions.

Next, we discuss prior research that informed this study with the research questions and our corresponding hypotheses presented in Section 3. Our experimental methodology is discussed in detail in Section 4, the results of the experiment are discussed in Section 5, and the educational implications of these results are discussed in Section 6. Finally, we conclude with limitations and directions for future research in Section 7.

2. RELATED WORK

Our aim in this research is to investigate the effects of the structure of DfAM educational interventions on students' learning and creativity. Before doing so, prior work investigating the effects of distributed interventions and external cues on learning is reviewed as discussed next.

2.1. Distributed Information Presentation in Learning

For an educational intervention to be successful, it must provide students with the opportunity to sufficiently process the information provided. Moreover, students must also be able to retrieve said information at appropriate stages of the design process [38]. The distributed presentation of information in educational interventions has been argued to be an effective strategy to encourage learning and information retention [39,40]. For example, Roediger and Pyc [41] review prior research in learning and provide inexpensive recommendations for integrating evidence in cognitive psychology to enhance student learning. The first of the three recommendations provided by the authors is to introduce information in distributed interventions (i.e., introduced over multiple sessions) as opposed to massed interventions [42]. This recommendation is aimed at providing students with (1) multiple opportunities to recall information and (2) sufficient time to consolidate the information in memory, both of which lead to better information retention and recall.

In the context of DfAM education, Ferchow et al. [43] present a distributed DfAM educational intervention based on the experience transfer model [44]. Their proposed intervention is spread over fourteen weeks with a different topic introduced each week. The authors test their proposed intervention with graduate students who report positive feedback on the utility of the intervention. A similar, semester-long intervention is presented by Li [28]; in the proposed course, the author employs a series of design activities combined with a literature review assignment. Students also work on a design challenge in parallel. Diegel et al. [32] present a four-day workshop introduced at Lund University. The workshop, primarily focused on training industry professionals, comprises a series of short exercises to introduce students to concepts such as lattice structures and part consolidation. These exercises culminate into a larger exercise on day four, allowing students to apply their knowledge of the various DfAM concepts. Finally, Prabhu et al. [45] discuss the effectiveness of a distributed workshop to encourage creative ideation and DfAM utilization among industry practitioners. These studies suggest that a longer, distributed intervention is effective for DfAM education; *however, they do not provide evidence to support that distributed DfAM educational interventions are more effective than massed DfAM educational interventions.*

In contrast to these distributed educational interventions, Prabhu et al. present a series of studies discussing the formulation of single-session educational interventions. First, the authors investigate the effects of providing students with opportunistic DfAM training over and above restrictive DfAM training. The authors demonstrate that while dual DfAM training correlates with the generation of ideas of higher DfAM utilization [46], dual DfAM training did not influence the creativity of ideas generated by the students [47]. Next, the authors investigate the effects of the definition and competitive structure of design tasks used in the intervention. The authors demonstrate the effectiveness of employing a complex design task – comprising explicit task objectives (e.g., minimizing build time) and constraints (e.g., maximum build volume) – when encouraging creative ideation in DfAM tasks [48]. Furthermore, the authors argue for the use of a competitive design task rewarding high-performing designs to increase the effectiveness of dual DfAM education [49]. Finally, the authors investigate the effects of the order of dual DfAM education both, on students' concept generation and concept selection behaviors. In their study, the authors demonstrate that teaching students restrictive DfAM first, followed by opportunistic DfAM, correlated with the generation of ideas of higher creativity [50]. Similarly, Bracken et al. [51], in a study with industry professionals, demonstrate the utility of a single-session DfAM educational intervention to increase creative ideation and DfAM utilization. These findings suggest that *if formulated appropriately*, massed, lecture-style interventions are effective in encouraging student learning and creativity. However, as previously discussed, *little research has investigated whether or not longer, module-style interventions are more effective compared to shorter, lecture-style interventions.* Our aim in this paper is to investigate this research gap and, consequently, inform the formulation of effective and efficient educational interventions. Before doing so, prior work on the effect of external cues on learning is reviewed, as discussed next.

2.2. Influence of external cues on learning

In addition to distributed interventions, providing students with design knowledge using external cues (e.g., design heuristics) is also an effective strategy to support learning and information retention [41,52]. Moreover, a distributed educational intervention also provides multiple opportunities to introduce students to external cues. For example, in a series of studies in the context of mathematics education, Lyle et al. [53], Bego et al. [54], and Hopkins et al. [55] discuss the influence of retrieval practice on students' retention of mathematics concepts. In their studies, students were given the opportunity to practice the various concepts covered in the form of quizzes introduced at different time points in the semester. The authors also varied the number of topics covered in the quizzes between groups. They find that introducing quizzes at multiple time points, which provide students with an opportunity to practice cued recall, has a positive effect on both, short- and long-term retention of information. The authors further provide specific recommendations for distributing cued recall and testing [56]; these recommendations focus on (1) identifying appropriate content chunks, (2) formulating appropriate testing questions for the content, and (3) appropriately determining the timing of these tests.

In the context of DfAM education, several researchers have proposed DfAM tools as a method of providing students with external cues. These design tools – proposed for use in the conceptual design stages – can be broadly categorized into two categories: (1) tools for use in concept generation and (2) tools for use in concept evaluation.

For example, Laverne et al. [5] study the effects of introducing DfAM knowledge using memos. They observe that designers who were given access to AM knowledge, either through memos generated more original ideas. Another example of a design tool developed to help idea generation is the set of 29 DfAM heuristics developed by Blösch-Paidosh and Shea [57]. The process independent heuristics provide designers with visual and verbal information about the various DfAM concepts and the authors study the effectiveness of the heuristics in encouraging DfAM utilization [57] and creative redesign [58]. These DfAM heuristics have also been tested with experienced and inexperienced designers using different modalities [59] and have been refined for domain-specific applications such as aerospace [60]. Additionally, researchers have proposed variations of DfAM principles to support idea generation. For example, Perez et al. [61,62] present a set of 23 crowdsourced design principles for AM and they observe that the design principle cards help designers generate more creative ideas [63]. Similar to the DfAM heuristics, these DfAM principles have also been tested with experienced and inexperienced designers [64,65], converted into different modalities [66], and employed in educational interventions [67,68]. *These studies suggest that design tools in the form of heuristics and principles are an effective medium for providing external DfAM cues in educational interventions and can be used to support creative concept generation.*

In contrast to these DfAM tools that support ideation, researchers have also proposed DfAM tools to support concept evaluation and selection in educational interventions. For example, Booth et al. [69] present the DfAM Worksheet to help designers evaluate concepts in the early and later stages of design. The worksheet, developed with a focus on the material extrusion process, assists designers in evaluating the suitability of solutions for manufacturing with AM. Moreover, the authors test the use of the worksheet in educational settings with novice designers and demonstrate that the use of the worksheet results in fewer build failures. Bracken et al. [70] present another similar tool – the Geometry for Additive Part Selection Worksheet – for part evaluation in DfAM tasks and educational interventions. The authors introduce the worksheet to industry practitioners in the form of a DfAM educational workshop and report that a majority of the participants find the worksheet to be useful in part selection. *These findings suggest that design tools can not only be used to provide external cues at the concept generation stage but also can be used to support concept evaluation and selection in DfAM tasks and educational interventions.*

In summary, repeated information recall supported by external cues (e.g., DfAM evaluation metrics) could be used to further augment student learning in longer, module-styled interventions. However, it is important to understand if such longer DfAM educational interventions are, in fact, more effective compared to shorter, lecture-style interventions. Such an understanding can support the design and formulation of DfAM educational interventions that are effective *and efficient*. Our aim in this research is to investigate this research gap and towards this aim, we seek answers to the research questions discussed next.

3. RESEARCH QUESTIONS

Our aim in this study is to study the effects of the structure of a DfAM educational intervention on students' learning, DfAM use, and creativity. Specifically, we compare the outcomes of a module-style intervention – comprising multiple lectures and the introduction to design evaluation metrics – to those of a lecture-style intervention. By exploring this research gap, we aim to inform the formulation of DfAM educational interventions that are effective *and efficient in time*. Towards this aim, we seek answers to the following research questions (*RQs*):

- *RQ1: How does the structure of a DfAM educational intervention influence the changes in students' DfAM self-efficacy?* We hypothesize that students who receive the module-style intervention would report a greater increase in their DfAM self-efficacy. This hypothesis is based on prior research suggesting the greater effectiveness of distributed educational interventions with periodic feedback in causing student learning [41].
- *RQ2: How does the structure of a DfAM educational intervention influence students' self-reported DfAM emphasis in a design task?* We hypothesize that students who receive the module-style intervention would report a greater emphasis on DfAM concepts. We also hypothesize that students would show differences in their emphases on DfAM between the two sessions of the module-style intervention. This hypothesis is based on prior research [57,63] suggesting the effectiveness of external cues (e.g., design heuristics) in encouraging DfAM use in engineering design.
- *RQ3: How does the structure of a DfAM educational intervention influence the creativity of students' design outcomes in a DfAM task?* We hypothesize that a module-style intervention would result in the generation of ideas of greater creativity. This hypothesis is based on prior research [58,65] suggesting the utility of external cues provided through DfAM tools to encourage creative idea generation. Furthermore, this hypothesis is based on prior work suggesting that distributed interventions and external cues enhance information retention and retrieval [41]. Effective retrieval and use of opportunistic DfAM could, in turn, support creative ideation [45,57].

4. EXPERIMENTAL METHODS

To answer these research questions, we performed an experiment in the form of an educational intervention comprising lectures and a DfAM task. The experimental protocol was reviewed and approved by the IRB before the experiment was performed. The details of the experiment are discussed next.

4.1. Participants

The participants in the experiment were recruited from a junior-level undergraduate course on AM and a graduate-level course on DfAM. While participants from the junior-level course (N = 14) were given the module-style intervention, students from the graduate-level course (N = 11) received the lecture-style intervention. It should be noted that of the fourteen participants who received the module-style intervention, seven participants were in their junior year of study and seven participants were in their senior year. Additionally, of the twelve participants who received the lecture-style intervention, one participant was in their senior year, ten participants were graduate students, and one participant did not report their year of study.

Before the experiment was conducted, we collected participants' prior AM, DfAM, and CAD experiences through a pre-intervention survey. The distribution of participants' prior experience is summarized in Figure 1. As seen in the figure, while students from both groups demonstrated similar levels of prior DfAM experience, students who received the lecture-style intervention reported higher levels of AM and CAD experience. Additionally, the participants' baseline DfAM self-efficacy, collected before the experiment, was compared using independent-sample t-tests. We observed no significant differences ($p > 0.05$) in the baseline self-efficacy between the participants from the lecture- and module-style interventions.

The differences in participants' prior AM and CAD experience are a potential limitation of our study; however, since our aim in this research is to study the effects of variations in a

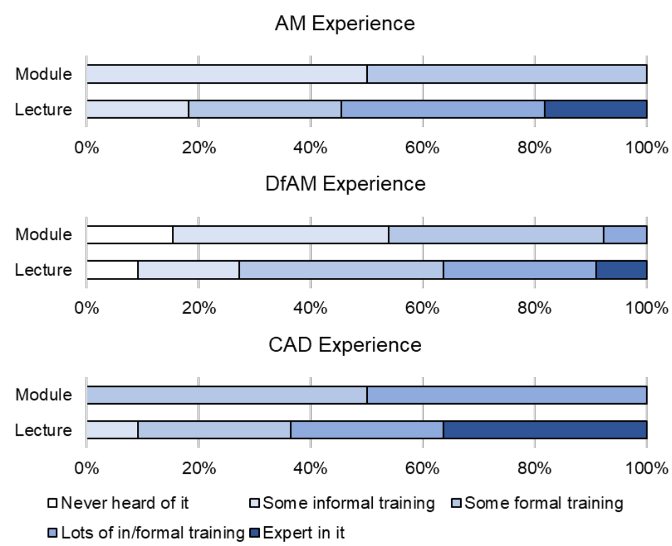


Figure 1 Comparing students' prior experience in AM, DfAM, and CAD

DfAM educational intervention, we believe that these differences should not have a significant effect on our results. We also acknowledge the need for future work to replicate our findings with participants with similar experience levels. Moreover, we only collected participants' prior experience with AM, DfAM, and CAD; however, the two groups of participants could have differed in their prior knowledge with other engineering concepts such as traditional manufacturing. These differences were not captured in the pre-intervention survey and future research must measure and control for the effects of these differences.

To further reduce possible effects of the graduate students' prior AM experience, the experiment with the juniors was conducted half-way through the semester to ensure that these students had some experience with AM. On the other hand, the experiment with the graduate students was conducted in the first week of classes to minimize any external effects and possible exposure to DfAM-related content in the rest of the semester.

4.2. Procedure

The overall experiment comprised four main components: (1) a pre-intervention survey, (2) a DfAM educational intervention, (3) a DfAM task, and (4) a post-intervention survey. The details of each component and the metrics used are discussed next. Furthermore, the two educational intervention structures differed in two aspects: (1) the distribution of the lectures and design task, and (2) the introduction to DfAM evaluation metrics for design evaluation. The details of these distinctions are also discussed in this section.

4.2.1. Overall experimental method:

The experiments in the two educational structure comprised four common elements:

1. *Pre-intervention survey:* In the first stage of the experiment, participants were asked to complete a pre-intervention survey. In the survey, participants were asked to report their prior experience with AM, DfAM, and CAD. Participants were also asked to report their DfAM self-efficacy on the ten-item scale developed by Prabhu et al. [46]. The participants' responses to the pre-intervention survey worked as a baseline for their experience with AM, DfAM, and CAD.
2. *DfAM educational intervention:* After completing the pre-intervention survey, the participants were introduced to the DfAM educational intervention, which was comprised of two elements: (1) DfAM educational lectures and (2) a DfAM task. Specifically, the educational lectures consisted of three parts: (1) an overview on AM, (2) restrictive DfAM, and (3) opportunistic DfAM, in that order. The order of the lectures was chosen based on prior findings [71] suggesting the greater effectiveness of teaching restrictive DfAM first, followed by opportunistic DfAM, towards increasing student learning and creativity.
3. *DfAM task:* After receiving the educational lectures, participants were asked to complete a DfAM task. They were given the complex, wind turbine tower design prompt from [48] given the demonstrated utility of the task to encourage creativity. Additionally, the design task was introduced as a competition based on the recommendations from [49]. The design task was broken into three stages: (1) initial brainstorming, (2) final idea generation, and (3) CAD modeling. In the first stage, participants were asked to brainstorm for solutions with the freedom to generate as many ideas as they liked. Next, participants were asked to generate one final solution with the freedom to brainstorm for a completely new idea, combine previous ideas, or select one of their previous ideas. After generating a final solution, participants were asked to report the emphasis they gave to the various DfAM scale on a scale of 1 = 'not important at all' to 5 = 'absolutely essential'. It should be noted that in the module-style intervention, students were asked to report the DFAM emphasis at the end of both design sessions. These responses were used to answer RQ2. Finally, participants were asked to generate CAD models for their solutions using any CAD software of their choice.
4. *Post-intervention survey:* After completing the DfAM task, participants were asked to complete a post-intervention

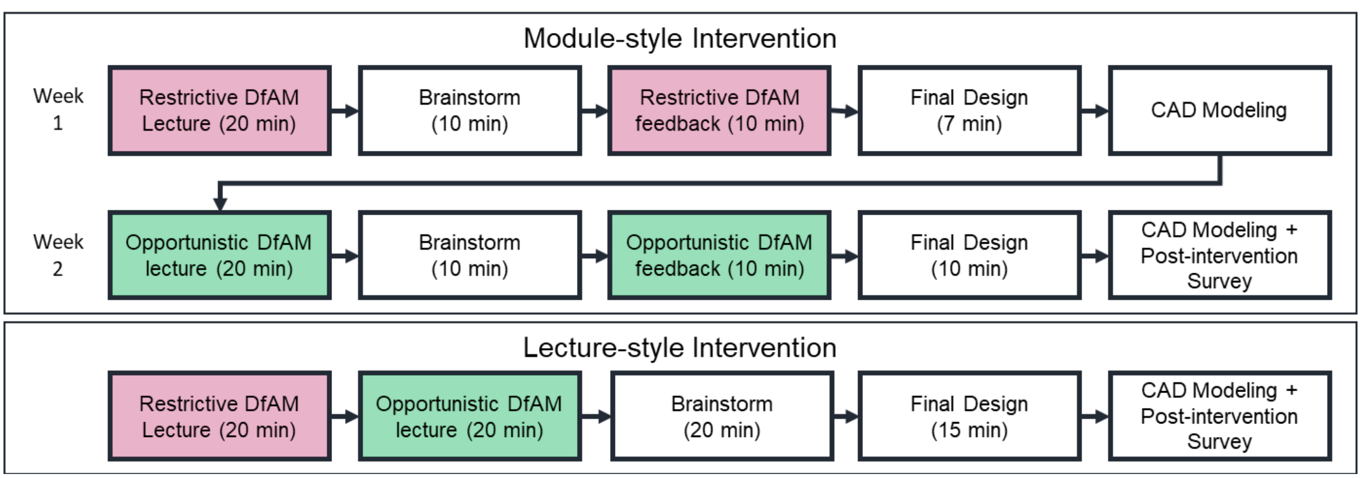


Figure 2 Overview of the procedure followed in the two educational intervention formats

survey. In the survey, participants were asked to respond to the same ten-item DfAM self-efficacy scale as the pre-intervention survey.

4.2.2. Differentiating elements between the two structures:

In this study, we want to investigate the effects of distributing the educational intervention into multiple sessions and introducing students to design evaluation metrics during each session. Therefore, these two elements were varied in the module-style intervention, and the details of these variations are discussed next. It should be noted that the lecture-style intervention was developed in prior work (e.g., see [48–50]). Additionally, the timing of the different stages of the module-style intervention was determined such that cumulatively, students had a similar amount of time to complete the various stages.

1. *Distribution of lectures and design task:* The first key difference between the structure of the two educational interventions was the distribution of the lectures and the design task. In the module-style intervention, the lectures and design task were split into two sessions. In the first session, participants were introduced to restrictive DfAM and were then asked to participate in the design task. In the second session, participants were introduced to opportunistic DfAM and then were asked to continue with the same design task. On the other hand, in the lecture-style intervention, the entire intervention was completed in a single session. We present an overview of the two educational intervention formats in Figure 2. Furthermore, it should be noted that the total time given to complete the design task was kept approximately constant between the two formats to avoid possible confounding effects due to the time available to the students.
2. *Introduction to DfAM evaluation metrics:* The second key difference between the two educational intervention formats was in providing external feedback. In the module-style intervention, participants were provided with the DfAM evaluation metrics proposed in [72] to evaluate their designs between the initial brainstorming and final design stages. These metrics were developed to assess the DfAM utilization in AM solutions and have been demonstrated to successfully predict the build time and cost of AM solutions. Participants were only provided with the opportunistic and restrictive parts of the metrics in the corresponding stages of the intervention, as presented in Figure 2. Specifically, in the first week, participants were given the metrics corresponding to the restrictive DfAM concepts of (1) part and assembly feature orientation, (2) feature size, (3) tolerances, (4) support material minimization and removal, and (5) build plate contact/warping. In the second week, participants were provided with the metrics corresponding to the opportunistic DfAM concepts of (1) part complexity, (2) assembly complexity, and (3) part consolidation. Participants were provided the corresponding metrics and were asked to self-evaluate their solutions generated in the brainstorming stage. Since our aim in this research was to investigate the utility of introducing students to design evaluation metrics in DfAM educational interventions, participants in the lecture-style intervention were not provided with the DfAM evaluation metrics. A subset of the evaluation metrics provided to the students is presented in Figure 3 and the complete set of metrics is available at [73] and in [72].

4.3. Metrics Used to Assess Design Creativity

Participants' final conceptual ideas were evaluated for their creativity using the Consensual Assessment Technique (CAT) [74–76], and these ratings were used to answer RQ3. An AM expert and a novice with some background in AM (as recommended in [77,78]) independently rated participants' ideas on a scale of 1 = 'least creative' to 6 = 'most creative'. The novice rater was trained in forming their mental model through discussions with the expert rater to ensure the reliability of the ratings [79]. The raters were provided the following metrics (developed in prior work in [48–50]) based on the three-factor model of assessing design creativity [80,81]:

- *Uniqueness*: Using this component, the raters assessed the originality of each design idea in comparison to other ideas generated in the sample [76]. This is analogous to the measure of originality [82] and novelty [83] in other metrics.
- *Usefulness*: Using this component, the raters assessed each idea's ability to solve the given design problem along with its

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.

Figure 3 Example of metrics used to provide external cues in the module-style intervention (complete set at [73] *and in* [72] *)*

value and appropriateness. This component is analogous to the measure of quality seen in other measures [84].

- *Technical Goodness*: Using this component, raters assessed the extent of DfAM use in an idea in terms of AM capabilities and limitations [46,47]. This component was developed in prior studies for assessing creativity in DfAM tasks.
- *Overall Creativity*: Using this component, the raters provided a subjective evaluation of the overall creativity of an idea.

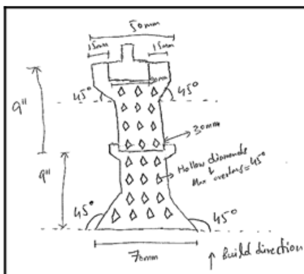
A mean of the scores provided by the two raters was calculated and the mean scores for each design were used in the analyses for RQ3. Examples of ideas generated by the participants and the corresponding creativity scores are presented in Figure 4. It should be noted that although the novice rater in this study was trained through repeated interactions with the expert (as suggested in [77,78]), the use of a novice rater as opposed to one or more experts is a potential limitation of this research.

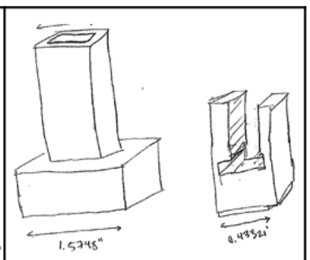
5. DATA ANALYSIS AND RESULTS

The data collected from the experiment were analyzed using statistical tests. The specific details of the tests used to answer each research question and the corresponding results are discussed next.

5.1. RQ1: How does the structure of a DfAM educational intervention influence the changes in students' DfAM self-efficacy?

We hypothesized that students who received the module-style intervention would report a greater increase in their DfAM self-efficacy compared to students who received the lecture-style intervention. To answer the first research question, we first compared participants' pre-intervention DfAM self-efficacy scores between the two educational structures using independent sample t-tests. This comparison was done to test if participants in the two educational structures start with different levels of DfAM knowledge and efficacy. From the results, we observed no significant differences in the pre-intervention self-efficacy scores between participants in the two educational structures ($p > 0.05$).





ATAN05 (Lecture)	NANG08 (Module Week 2)
Uniqueness: 4	Uniqueness: 2.25
Usefulness: 3.75	Usefulness: 3.5
Technical Goodness: 3.75	Technical Goodness: 3
Overall Creativity: 4	Overall Creativity: 3.25

Figure 4 Examples of participants' ideas and corresponding creativity scores

Next, we performed a series of related-samples Wilcoxon Sign-Rank Tests [85]. Specifically, we compared participants' pre- and post-intervention responses on each of the ten DfAM self-efficacy items. These comparisons were independently made for students who received the lecture and module-style interventions. From the results summarized in Figure 5, we see that students who received the module-style intervention reported more positive changes in their DfAM self-efficacies. Specifically, we observed that students who were assigned to the module-style intervention reported a significant increase in their self-efficacies in free complexity and surface roughness at $p < 0.1$ and in warping and feature size at $p < 0.05$. On the other hand, participants who received the lecture-style intervention did not report a significant increase in any of the ten DfAM self-efficacy items. This result supports our hypothesis that the module-style intervention would result in a greater increase in students' DfAM self-efficacy.

5.2. RQ2: How does the structure of a DfAM educational intervention influence students' self-reported emphasis on DfAM in a design task?

We hypothesized that the participants who received the module-style intervention would report having given a greater emphasis on DfAM. We also hypothesized that students who receive the module-style intervention would report different emphases on the various DfAM concepts between the two sessions of the intervention. To test these hypotheses, we performed a series of one-sample t-tests with the participants' self-reported DfAM emphasis as the dependent variable and a hypothesized scale mean of 3. From the results, summarized in Figure 6, we see that students who received the module-style intervention reported a significantly greater emphasis on part consolidation and feature size compared to the hypothesized mean of 3 and this difference was not observed among participants who received the lecture-style intervention. Additionally, students who received the module-style reported a greater emphasis on the restrictive DfAM concepts of support structure accommodation and surface roughness in the first week of the module compared to the second week. Furthermore, students reported a greater emphasis on the opportunistic DfAM concept of functional embedding in the second week of the module compared to the first week.

5.3. RQ3: How does the structure of a DfAM educational intervention influence the creativity of students' design outcomes in a DfAM task?

We hypothesized that students who receive the module-style intervention would generate ideas of higher creativity compared to those who receive the lecture-style intervention. To test this hypothesis, we performed a series of independent-samples Kruskal-Wallis tests [85] with each component of creativity, i.e., uniqueness, usefulness, technical goodness, and overall creativity, as the dependent variable and the intervention structure as the independent variable. From the results,

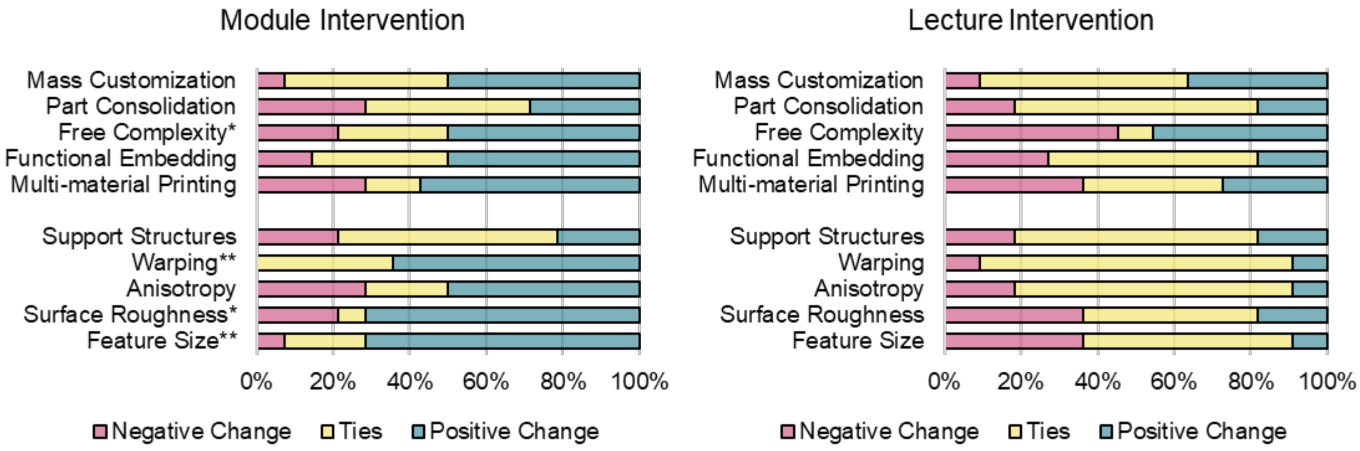


*Figure 5 Comparing changes in students' DfAM self-efficacy between the two educational intervention formats (*indicates p < 0.1 and **indicates p<0.05)*

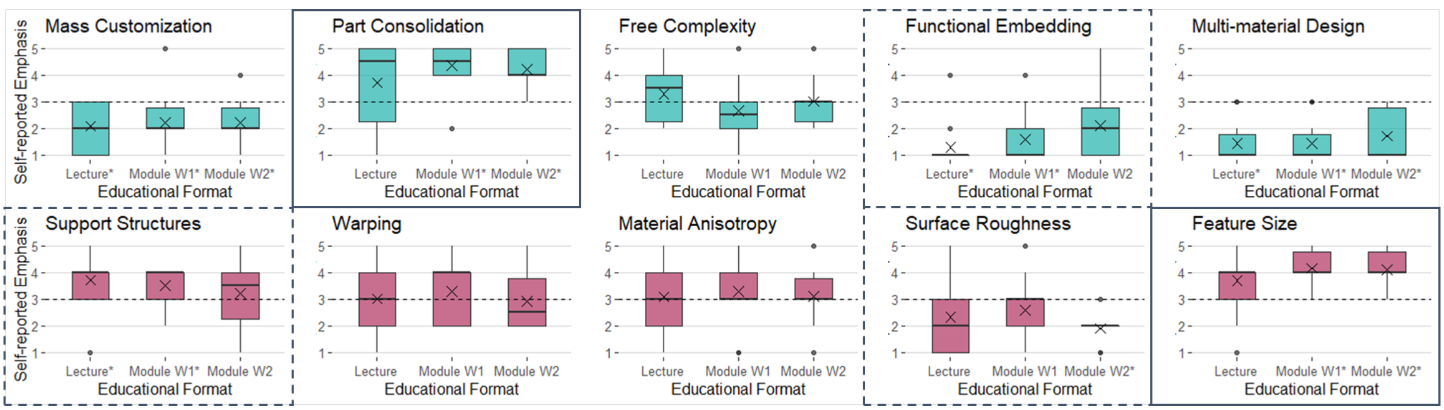


*Figure 6 Summary of self-reported DfAM emphasis responses (*indicates p<0.05, dotted line indicates hypothesized mean of 3, solid box indicates a difference between lecture and module, and dashed box indicates a difference between the two weeks of the module)*

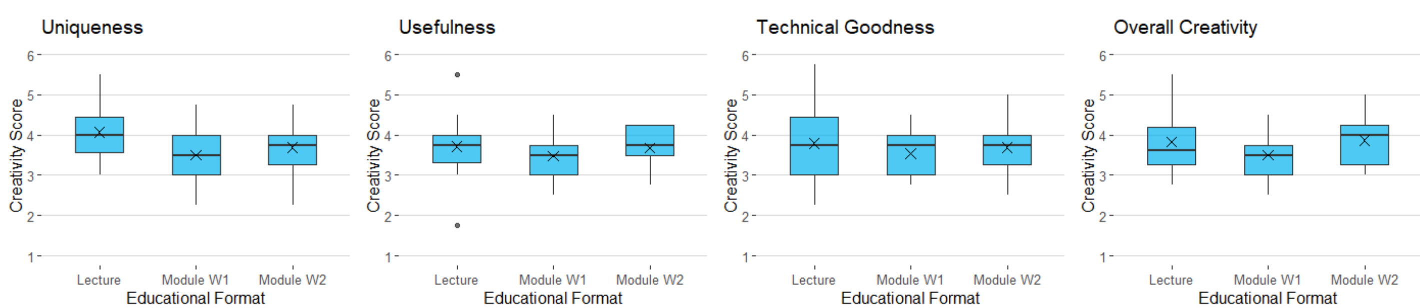


Figure 7 Comparing creativity of designs generated by the participants between the two educational intervention structures

summarized in Figure 7, we see no significant effect of the intervention structure on the creativity of students' design outcomes. Despite the lack of statistically significant differences, we see an increase in the usefulness and overall creativity of ideas generated by students who received the module-style intervention, between the first and second weeks of the intervention. Taken together, these results refute our hypothesis.

6. DISCUSSION AND IMPLICATIONS FOR DESIGN EDUCATION

Our aim in this research is to compare the effects of the structure of DfAM educational interventions on students' learning, DfAM use, and creativity. Specifically, we compared a module-style intervention – distributed over two sessions with the introduction of DfAM evaluation metrics – to a massed lecture-style intervention with no evaluation metrics introduced. The key findings from the results of our study are:

- Students from both groups started with similar levels of baseline DfAM self-efficacy and those who received the module-style intervention reported a greater increase in their DfAM self-efficacy
- Students who received the module-style intervention reported a greater emphasis on part consolidation and feature size
- No differences were observed in the creativity of ideas between the educational intervention structures

The implications of these findings are discussed next.

The first key finding is that students who received the module-style educational intervention reported a greater increase in their self-efficacy with the DfAM concepts of (1) free complexity, (2) warping, (3) surface roughness, and (4) feature size, compared to those who received the lecture-style intervention. This finding supports our hypothesis that students who receive the module-style intervention would report a greater increase in their DfAM self-efficacy. This finding could be attributed to the use of the DfAM metrics to provide students with design feedback during the educational intervention. For example, students were given the cue that 'AM designs can have complex geometries to improve performance as opposed to traditional manufacturing' as part of the part complexity metric. The access to these cues could have helped students easily retrieve, and therefore, apply the various DfAM concepts in their design process. This retrieval and access to these DfAM concepts could have, in turn, increased their confidence with the DfAM concepts. This finding could also be attributed to the distribution of the intervention over multiple sessions. The distributed intervention could have given students more time to deeply process the various DfAM concepts. Moreover, having multiple sessions in the design task could have given students more opportunities to apply the various DfAM concepts. This finding, therefore, supports the use of a distributed, module-style intervention with external cues when compared against massed, lecture-style interventions.

The second key finding is that students who received the module-style intervention reported having given a greater emphasis on part consolidation and feature size compared to those who received the lecture-style intervention. This is a positive outcome as it suggests that the distributed intervention provides students with greater opportunities to apply these DfAM concepts in their solutions. This opportunity to apply the various DfAM concepts could, in turn, result in better learning of the concepts. Furthermore, this finding could be attributed to the introduction of external cues in the form of DfAM metrics to the students as part of the module-style intervention. For example, one of the metrics asked students to evaluate the number of parts in their solution with the accompanied cue that "[AM processes enable] designers to reduce the part count by combining them, thereby minimizing build and assembly time and cost." Providing these external cues could have helped students retrieve the various DfAM concepts and apply them in the design process.

Another important finding was that students who received the module-style intervention reported a greater emphasis on support structures and surface roughness accommodation in the first week of the module. On the other hand, they reported giving greater emphasis on functional embedding in the second week of the module. This result correlates with the order in which the DfAM content was presented in the study. That is, in the first week, students were introduced to restrictive DfAM whereas they were introduced to opportunistic DfAM in the second week. This is an important finding as it further suggests that distributing the intervention provides students with the time and opportunity to apply the various DfAM concepts in the design task. The experience of applying these concepts in the design process could, in turn, result in better learning outcomes, thereby reinforcing the inference of the first RQ. This inference is also informed by prior work arguing for the role of practice in encouraging better learning outcomes [52]. Taken together, these findings further reinforce the use of distributed, module-style interventions with the introduction of DfAM evaluation metrics for DfAM education.

The final key finding was that no differences were observed in the creativity of the ideas generated by students between the two educational intervention structures. This result refutes our hypothesis that students trained using the module-style intervention would better utilize DfAM, and therefore, generate more creative solutions [45,57]. Furthermore, this result suggests that although students show differences in their self-reported emphasis on DfAM, these differences do not necessarily reflect in the technical goodness of their solutions. This lack of differences could also be attributed to the composite, subjective measure of technical goodness used to evaluate the designs. Using an overall measure could have obscured any granular differences and therefore, future work must employ either objective measures (e.g., [72]) or more granular subjective measures (e.g., [45]).

Despite the lack of statistically significant results, we observe an *increase* in the usefulness and overall creativity of the ideas generated by the students in the first and second weeks of the module-style intervention. This finding is a positive outcome as it suggests that training students in opportunistic DfAM encourage them to generate more creative solutions. This finding corroborates our prior work (e.g., see [49,57]), demonstrating the utility of providing designers with opportunistic DfAM inputs to encourage creative ideation. Furthermore, the increase in usefulness suggests that after being introduced to opportunistic DfAM, students' these techniques to increase the functionality of their solutions, therefore, increasing the usefulness of the solutions. However, we must be careful in making this inference given the lack of statistically significant results.

7. CONCLUSION, LIMITATIONS, AND FUTURE WORK

Our aim in this study was to investigate the effects of the structure of a DfAM educational intervention on students' learning, DfAM use, and the creativity of their design outcomes.

The educational interventions comprised DfAM educational lectures and a DfAM task. In the module-style intervention, the lectures and design task were distributed over two sessions, and students were provided feedback using DfAM evaluation metrics. On the other hand, in the lecture-style intervention, the lectures and design task were completed in one session with no feedback provided. From the results, we see that students who were given the module-style intervention reported a greater increase in their DfAM self-efficacy. We also see that students from the module-style intervention reported having given greater emphasis on part consolidation and feature size. Finally, we see an increase in the usefulness and overall creativity of the ideas generated by participants who received the module-style intervention between the two weeks. Overall, these findings lend evidence to the greater effectiveness of a distributed module-style DfAM educational intervention to increase students' DfAM self-efficacy, but not necessarily design creativity.

These findings provide important insights into the formulation of DfAM educational interventions; however, our study has limitations and several directions for future research still exist. One of the main limitations of the study is the distinction between the lecture- and module-style interventions; the intervention structures not only differ in the distribution of the intervention (i.e., one session vs. two sessions) but also in the introduction of DfAM evaluation metrics. Therefore, it is difficult to establish causality in the results and to point out specific sources for the observed differences in the effects of the two educational intervention structures. Future research is needed to test these effects in isolation to provide stronger causal evidence. Second, the participants recruited in the study primarily comprised upperclassmen and first-year graduate students. However, the participants' prior experience, both, in AM/DfAM and engineering, could have influenced their learning and creativity. Future research must explore these effects. Finally, we used self-reported DfAM emphasis and AM technical goodness to evaluate designers' utilization of the various DfAM concepts in their solutions. Self-reported measures are prone to measurement error, especially with novice users. Furthermore, the subjective measure of technical goodness does not provide sufficient clarity into students' use of the specific DfAM concepts, which could be important to capture [45]. Future work must investigate the use of objective measures to capture students' use of DfAM in their solutions. This line of work could also extend the assessment of students' designs beyond the conceptual design stage (i.e., sketches) and include an assessment of the final CAD models of their solutions [72].

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