Proceedings of the ASME International Design Engineering Technical Conferences &
Computers and Information in Engineering Conference
IDETC 2019
August 18-21, 2019, Anaheim CA, USA

IDETC2019-97474

COMPLEX SOLUTIONS FOR COMPLEX PROBLEMS? EXPLORING THE EFFECTS OF TASK COMPLEXITY ON STUDENT USE OF DESIGN FOR ADDITIVE MANUFACTURING AND CREATIVITY

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ABSTRACT

The integration of additive manufacturing (AM) processes in many industries has led to the need for AM education and training, particularly on design for AM (DfAM). To meet this growing need, several academic institutions have implemented educational interventions, especially project- and problem-based, for AM education; however, limited research has explored how the choice of the problem statement influences the design outcomes of a task-based AM/DfAM intervention. This research explores this gap in the literature through an experimental study with 222 undergraduate engineering students. Specifically, the study compared the effects of restrictive and dual (restrictive and opportunistic) DfAM education, when introduced through either a simple or complex design task. The effects of the intervention were measured through (1) changes in student DfAM self-efficacy, (2) student self-reported emphasis on DfAM, and (3) the creativity of student AM designs. The results show that the complexity of the design task has a significant effect on the participants' self-efficacy with, and self-reported emphasis on, certain DfAM concepts. The results also show that the complex design task results in participants generating ideas with greater median uniqueness compared to the simple design task. These findings highlight the importance of the chosen problem statement on the outcomes of a DfAM educational intervention, and future work is also discussed.

Keywords: design for additive manufacturing, problem-based learning, task complexity, creativity.

1. INTRODUCTION

Additive manufacturing (AM) processes have revolutionized several disciplines, such as engineering, sciences, and arts [1]. As research is constantly improving the effectiveness of AM processes, there is a simultaneous need for integrating AM into the engineering design process [2–4]. This growing need to integrate AM into engineering design has resulted in the emergence of design principles specifically aimed at designing for AM (DfAM) [5,6]. Further, the development of a workforce skilled in AM has been identified to be of importance [7] as well as a possible obstacle [8] in facilitating this integration of AM into industry [4,9].

In order to enable the successful integration and use of AM processes, it is necessary to develop educational practices that effectively teach DfAM [10]. These educational practices must not only inform students of the characteristics of the different AM processes but also about their capabilities and limitations. In addition, students must also learn how to design for these capabilities through opportunistic DfAM, while accommodating the limitations through restrictive DfAM [11,12]. Opportunistic DfAM encourages the use of the capabilities of AM through design principles such as (1) mass customization [13], (2) part consolidation [14] and printed assemblies [15], (3) free shape complexity [16–18], (4) embedding external components [19], and (5) printing with multiple materials [20]. In contrast, restrictive DfAM helps designers account for the limitations of AM processes. This includes considerations for limitations such as (1) support structures [21], (2) warping due to thermal stresses

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[22], (3) anisotropy [23,24], (4) surface roughness due to stair-stepping [25,26], and (5) feature size and accuracy [27].

To meet this growing need for a workforce skilled in AM and DfAM, an increasing number of institutions, academic and professional, are introducing AM educational interventions. Given the effectiveness of task-based teaching, especially for manufacturing education [28–30], several of these interventions employ some form of problem- or project-based learning techniques. However, limited research has explored the effect of the choice of the design task on the learning outcomes of the AM/DfAM educational intervention. This is important as previous research has demonstrated that the effectiveness of inductive-learning techniques is influenced by the characteristics of the task chosen [31–33], particularly for domain-specific interventions [34]. These characteristics include the level of specificity in terms of the domain and the task, and the number and complexity of constraints imposed. Given the domain-specific nature of AM education, the choice, context, and complexity of the design task could potentially influence the learning effectiveness of a task-based educational intervention. The present study aims at exploring this relationship by investigating AM design tasks with varying functional requirements and manufacturing constraints. The effect of the design task choice is assessed based on the students' DfAM learning and use and the creativity of their design outcomes.

2. RELATED WORK

To investigate the effects of the DfAM task complexity on the students' learning and creativity, prior research in the areas of inductive learning, AM education, and the role of design task characteristics in learning and creativity were explored. Research questions are then posed in Section 3 and our experimental methodology is described in Section 4. Results are presented in Section 5 followed by conclusions in Section 6.

2.1. Task-based learning in engineering education

Engineering continues to play an important role in addressing global challenges such as environment, sustainability, health, and many more [35,36]. To address the constantly changing nature of these challenges, several researchers have recommended a transformation of engineering education [37–41], particularly towards developing problem-solving skills [42]. Researchers in education have shown *meaningful learning* to be characterized by the ability to transfer knowledge to solve problems [43–49] as opposed to the mere reproduction of information [50,51], or rote learning. Similarly, higher levels of learning have been linked to the ability to use knowledge to analyze, evaluate, and create new information [52].

Inductive, task-based teaching techniques have emerged to replace traditional deductive teaching in engineering education to address this need for learning transfer. Deductive teaching techniques present students with theories and is followed by introducing the applications for the concepts.

In contrast, inductive teaching presents students with a problem or a task and encourages them to seek and apply the information needed to solve it [28,53]. Stemming from the Deweyan theories of constructivism [54], inductive teaching has been evaluated to be at least as effective as, and in several cases better than, deductive teaching [28]. This teaching technique has been adopted in several forms including (1) inquiry-based learning [55–59], (2) problem-based learning (PmBL) [60–64], (3) project-based learning (PjBL) [65–67], (4) case-based teaching [68,69], (5) just-in-time teaching [70], and (6) discovery learning [71,72]. Of these techniques, PmBL and PjBL have been used widely in engineering education, particularly manufacturing education [28,73]. PmBL suggests the generation of solutions to open-ended problems, facilitated by the instructor [74]. Similarly, PjBL employs an open-ended project statement, and students are tasked with solving the project by designing and developing an artifact over a period of time, individually or in groups [75]. With the increase in the use of inductive task-based learning techniques in several disciplines, researchers have also demonstrated the role of the characteristics of the task in its effectiveness as a learning tool, as discussed next.

2.2. Role of characteristics of the design task in learning and creativity

The characteristics of the problem statement have been found to play an important role in the success of inductive learning [31–33] since the cognitive strategies used for problem-solving are often task-specific [34]. Depending on an individual's understanding and proficiency in problem-solving, problem solvers transition from the initial problem state to the solution state through the use of certain process operators [76]. Specifically, higher levels of expertise are shown to correlate with the development of the ability to identify the domain of a problem and generate specific solutions for it. This technique opposes that of non-experts who tend to use a generic problem-solving strategy for all problems [77]. The generation of such a domain-specific problem-solving technique is particularly important when developing a DfAM educational intervention. The intervention must encourage students to contextualize the problem within the capabilities and limitations of AM. Further, students must be engaged in applying DfAM knowledge to solve the problem.

In addition to the domain of a problem, the 'structuredness' of the problem influences the process followed to attain a solution. Jonassen [78] contrasts well-structured problems from ill-structured problems and presents the differences in the implications for instructional design for the two. Well-structured problems are described to have limited rules and a convergent solution. These problems are specific to the domain to which they are designed for and are often predictable. Ill-structured problems, in contrast, have multiple solutions and fewer rules that define them [79]. These problems, often termed 'puzzles', are open-ended and do not rely on domain knowledge for the attainment of a solution. While some researchers suggest the use of ill-structured problems in design challenges given their resemblance to real-world, 'messy' problems [80,81], others suggest using well-structured problems for domain-specific learning given their effectiveness [77].

The role of the design task characteristics, particularly the constraints, has also been explored in the context of creativity

[82]. The abstraction and specificity of the task have been shown to influence the creativity of idea generation. Some researchers argue that a moderate amount of constraints imposed both externally and internally, correlate with increased creativity [83,84]. On the other hand, researchers have demonstrated that tasks with greater specificity result in ideas with lower novelty [85]. This reduced creative production has been attributed to the preferred access of known factual knowledge in the idea generation process [86], potentially resulting in fixation [87,88].

These studies highlight the influence of design task characteristics such as the domain, specificity, and constraint complexity on the solutions generated for the task. Given this influence and the domain-specific nature of AM education, it is important for researchers and educators to choose appropriate tasks for AM/DfAM education. However, limited research has explored this relationship between design task characteristics and AM design outcomes. The next section discusses the current practices in AM/DfAM education and the use of task-based learning in these initiatives.

2.3. Current teaching practices in AM education

In the case of manufacturing education, inductive learning techniques have been extended to the use of (rapid) prototyping as a proven method for developing manufacturing skills [30]. Given the success of inductive teaching techniques for engineering education, especially manufacturing education, several AM/DfAM interventions employ task-based learning. This use of inductive learning is further supported by the recommendations from the 2013 NSF workshop on AM education [4]. One of the key recommendations from the workshop was the need for AM education to not just encourage the learning of AM process knowledge, but also develop the ability to apply this knowledge towards new product design.

To meet this need for an AM-skilled workforce, several academic institutions have introduced PmBL and PjBL interventions for teaching AM. One such initiative is the AM course introduced at the University of Texas at Austin and Virginia Tech. This course presents students with a design problem, teaches them to choose the appropriate process for it, and then apply AM process knowledge to solve the problem [89]. Similarly, Williams et al. [90] discuss the use of a vehicle design competition as an effective PjBL technique for teaching DfAM skills. Previous research has also explored the use of workshops for DfAM education for industry professionals that encourage them to leverage the potential of AM [91,92]

Complementing these formal educational avenues, academic institutions have also taken up initiatives to provide students with access to AM. These initiatives rely on hands-on self-guided learning through direct or indirect interaction with AM. Initiatives that provide students with indirect access to AM include the 3D printing vending machine [93] deployed at Virginia Tech, and the maker commons established at Penn State [94] and Georgia Tech [95]. Students can get their AM design printed by submitting their print files online, or in person. These initiatives help students experience the design process involved in manufacturing parts using AM. On the other hand, initiatives that encourage learning through direct interaction with AM include Penn State's mobile maker space [96], and MIT's and Case Western's networks of maker spaces [97,98]. These initiatives provide students with direct hands-on interaction with AM, where students can not only design but also print their AM designs themselves. Further, the maker spaces at MIT and Case Western also allow students to combine AM with traditional manufacturing processes for building their parts. These self-learning initiatives give students the freedom to choose their own project and apply AM and DfAM knowledge to solve them.

Alongside these self-learning interventions that focus on AM processes, researchers have also attempted to provide tools for conceptual learning and application of DfAM. One such example is the DfAM Worksheet developed by Booth et al. [99] which assists students in assessing the AM appropriateness of a design. Similarly, Bloesch-Paidosh and Shea [100] demonstrated the use of DfAM heuristics as a tool for encouraging the use of opportunistic DfAM in the early stages of the design process. Researchers have also attempted to merge traditional tools such as the theory of inventive problem solving (TRIZ) [101] into DfAM to improve the manufacturability of AM designs [102]. These tools encourage students' learning of the various DfAM concepts by engaging them in applying these concepts towards solving problems.

In summary, the various AM and DfAM interventions reviewed here employ design activities, either to teach the different DfAM concepts or to assess the learning effectiveness of the intervention itself. However, limited research has explored the effect of variations in the problem statement on the students' AM design outcomes. This is important as previous research has demonstrated the influence of design task characteristics on design and learning outcomes. Therefore, the present study explores this gap in literature by investigating the interaction between the design task and the students' learning and use of DfAM, as well as the creativity of the design outcomes.

3. RESEARCH QUESTIONS

Based on the review of the literature, this study explores the influence of task complexity, particularly manufacturing and functional constraints, on students' learning and the creativity of their AM design outcomes. To do this, we seek to answer the following three research questions.

RQ1: How does the design task complexity affect the participants' self-efficacy in using DfAM? We hypothesize that the greater number of constraints in the complex design task would encourage more use of DfAM to satisfy the constraints. This engagement with DfAM would translate into an increase in their self-efficacy with the concepts of DfAM. This hypothesis is based on previous research where the use of well-structured problem statements have been shown to correlate with greater learning of domain knowledge [77].

RQ2: How does the design task complexity affect the participants' self-reported emphasis on opportunistic and restrictive DfAM? Similar to the previous research question, we hypothesize that the greater number of functional and manufacturing constraints in a complex design task would encourage greater use of DfAM. This application of DfAM concepts would translate into a greater self-reported emphasis on DfAM by the participants who undertook the complex task.

RQ3: How does the design task complexity affect the creativity of the participants' AM designs? We hypothesize that the freedom provided by a simple design task would result in the generation of ideas with greater uniqueness, as suggested by [85]. On the other hand, the constraints placed by a complex design task would result in the generation of more useful ideas enabled by the learning and use of DfAM knowledge [77].

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 = 222) 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 $N_s = 99$ participants in the spring semester. The participants consisted of sophomores ($N_f = 0$, $N_s = 1$), juniors ($N_f = 78$, $N_s = 83$), seniors ($N_f = 41$, $N_s = 7$), and 5th year seniors ($N_f = 2$, $N_s = 0$). The remaining participants did not specify their year of study. The participants' self-reported previous experience in AM and DfAM was collected at the beginning of the study as summarized in Figure 1.

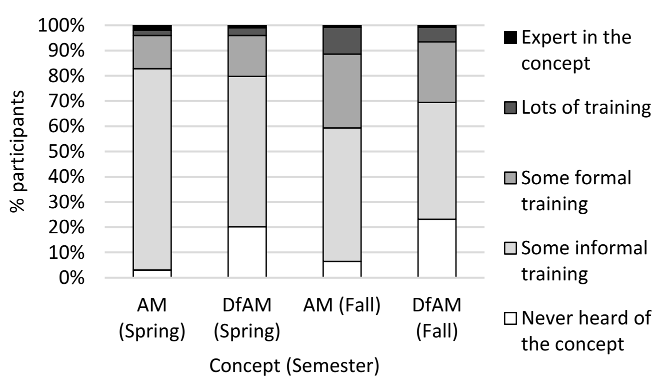


Figure 1 Distribution of participants' previous experience

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) an AM design challenge and a 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.

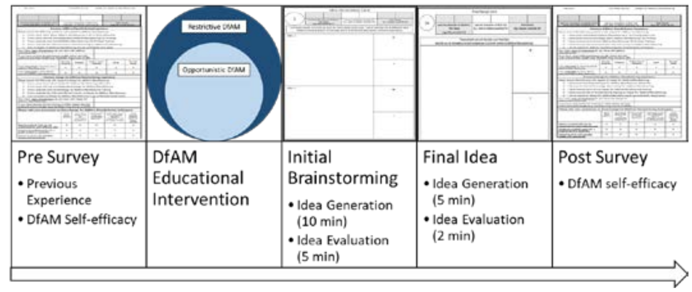


Figure 2 Summary of the experimental procedure

4.2.1. Pre-intervention survey:

At the beginning of the experiment, the participants were asked to complete a pre-intervention survey. The survey captured their previous experience in AM and DfAM, and their self-efficacy with DfAM concepts (see Section 4.3.1). This data provided a baseline for their initial knowledge and comfort levels with DfAM before participating in the experiment.

4.2.2. DfAM educational intervention:

The DfAM educational content was presented to the students after they completed the pre-intervention survey. The participants each semester were split into two different groups: (1) restrictive DfAM and (2) opportunistic and restrictive (dual) DfAM. The distribution of the participants in each semester is shown in Table 1. These groups were chosen given the need for restrictive DfAM in ensuring the manufacturability of AM designs, which limits the usefulness of investigating the use of opportunistic DfAM on its own.

Table 1 Distribution of participants between semesters

	Restrictive DfAM	Dual DfAM
Simple Design Task (Spring)	47	52
Complex Design Task (Fall)	67	56

All participants were first given a 20-minute overview lecture on general AM process characteristics. This lecture discussed topics including the material extrusion process (the AM process available to the students in the AM design challenge), differences with subtractive manufacturing, the digital thread, the Cartesian coordinate system, and common filament materials. Next, all participants were given a 20-minute lecture on restrictive DfAM considerations, including build time, feature size, support material, anisotropy, surface finish, and warping. The restrictive DfAM group was then asked to leave the room during the final DfAM lecture. The dual DfAM group was then given a 20-minute lecture on opportunistic DfAM considerations, including geometric complexity, mass customization, part consolidation, printed assemblies, multi-material printing, and embedding. The lecture slides can be accessed at [103].

4.2.3. Design challenge and post-intervention survey:

In the final part of the experiment, all participants were asked to individually participate in a design challenge. The participants in the spring were given a simple design task, with fewer manufacturing constraints and functional requirements. The design task asked the participants to:

> *"Design a fully 3D-printable solution to enable hands-free viewing of content on a smartphone. You can design your solution to fit any phone of your choice. Design such that you use the least amount of print material as possible. It should also print as fast as possible."*

Participants in the fall semester were given a more complex design task, with a greater number of manufacturing constraints and functional requirements. Specifically, the design task in the fall semester asked the participants 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"."*

These tasks were chosen for the experiment as they require minimal domain-specific knowledge beyond AM (as suggested by [104]). Further, the simple task was chosen such that it would impose fewer constraints on the solution space and reduce the specificity of the task. As a result, students are given the freedom to employ a wide range of working principles to solve the stated problem. On the other hand, the wind turbine problem was chosen given the ease with which functional and manufacturing constraints could be placed on the solution space. One such example is the constraint of building an 18" tall structure that would fit in a build volume with a maximum dimension of 11.6".

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 (see Figure 3), 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. 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.

4.3. Metrics

To measure the effect of the complexity of the design task on the participants' learning and the creativity of the outcomes from the AM design challenge, the following metrics were developed.

4.3.1. DfAM Self-efficacy

Previous research has demonstrated the role of self-efficacy [105] and meta-cognition [45] in predicting effective learning. Self-efficacy has also been shown to predict ones' performance in engineering design [106], computer science [107,108], and sports [109,110]. Therefore, the self-efficacy survey from [10,111] was used to assess participants' learning of DfAM. The survey focusses on both the opportunistic and restrictive DfAM domains [12] as summarized in Table 2. Further, it uses a 5-point scale (see) derived from Bloom's Taxonomy [52] to measure participants' DfAM self-efficacy. A difference between the participants' pre- and post-intervention self-efficacy scores was calculated to measure the change in their self-efficacy.

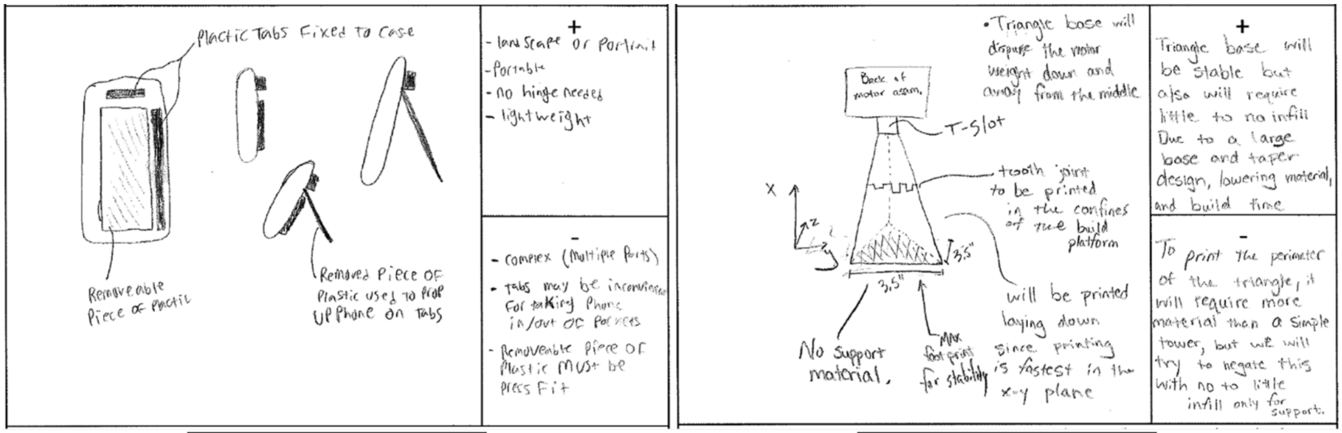
Table 2 Items from the DfAM self-efficacy survey (O: opportunistic, R: restrictive)

#	*DfAM Self-efficacy Item*
O1	Making products that can be customized for each different user
O2	Combining multiple parts into a single product or assembly
O3	Designing parts with complex shapes and geometries
O4	Embedding components such as circuits in parts
O5	Designing products that use multiple materials in a single part or component
R6	Using support structures for overhanging sections of a part
R7	Designing parts to prevent them from warping and losing shape
R8	Designing parts that have different material properties (e.g. strength) in different directions
R9	Accommodating desired surface roughness in parts
R10	Accommodating for min and max feature size permitted by a process

The internal consistency of the scale was validated by performing a reliability analysis and a high Cronbach's α was observed [112] (pre-intervention α = 0.93, post-intervention α = 0.86). Similarly, the individual opportunistic and restrictive sections of the scale also showed a high internal consistency, as determined by Cronbach's α (opportunistic: pre-intervention α = 0.88, post-intervention α = 0.77, and restrictive: pre-intervention α = 0.88, post-intervention α = 0.80).

Table 3 Scale used for DfAM self-efficacy

Never heard about it	Have heard about it but not comfortable explaining it	Could explain it but not comfortable applying it	Could apply it but not comfortable regularly integrating it with my design process	Could feel comfortable regularly integrating it with my design process



Semester: Spring (simple task)	
Participant ID	NEIA10
Usefulness	3.5
Uniqueness	3.25
Technical goodness	3.5
Overall Creativity	3.5

Semester: Fall (complex task)	
Participant ID	RIVE02
Usefulness	4.5
Uniqueness	4.75
Technical goodness	4.5
Overall Creativity	5

Figure 3 Examples of design outcomes from the design challenge with respective CAT scores

4.3.2. Self-reported use of DfAM

The items shown in Table 4 were used to capture the participants' self-reported emphasis on the different DfAM techniques during the AM design challenge. This scale was developed in [10,111] using the same set of items as the self-efficacy scale. Participants were asked to rate the importance they gave to each DfAM technique on a 5-point Likert-type scale, with 1 = 'Not important at all' to 5 = 'Absolutely essential'.

Table 4 Scale used for measuring participants' self-reported emphasis on DfAM.

#	*DfAM Emphasis Item*
1	The product can be customized for each different user
2	The design combines multiple parts into a single part or assembly
3	The design contains complex shapes and geometries
4	The design contains embedded components such as circuits
5	The design uses multiple materials in a single part or component
6	The design accommodates for support structures in overhanging sections
7	It is designed to prevent warping and losing shape during manufacturing
8	It is designed to accommodate variations in material properties (e.g. strength) in different directions
9	The design accounts for desired surface roughness in the parts
10	The design considers minimum and maximum feature size permitted by a process

4.3.3. Consensual Assessment Technique (CAT) for assessing creativity

The creativity of the outcomes from the AM design challenge was assessed using the Consensual Assessment Technique (CAT) [104,113,114]. The AM design outcomes were independently evaluated by two quasi-experts with a background in DfAM (as suggested by [115,116]). A moderate to high inter-rater reliability was observed between the two raters, as verified by a Cronbach's $\alpha = 0.71$ [112]. The following metrics were provided to the raters, as suggested by the three-factor model [117,118]. The raters were asked to rate the ideas on a scale from 1 to 6, where, for example, 1 = least useful and 6 = most useful:

- *Usefulness*: Assesses the quality of the design in its ability to solve the given design problem. This metric focusses on the value and appropriateness of the resulting solution.
- *Uniqueness*: Assesses the originality and novelty of each solution. The uniqueness is evaluated in comparison to the pool of solutions generated in the sample [104].
- *Technical Goodness*: Assesses the level to which each solution suits the AM processes, both in terms of capabilities and limitations.
- *Overall Creativity*: Provides a subjective evaluation of the overall creativity of the idea as measured by experts.

An average score for each metric was then calculated by taking a mean of the scores from the two raters for each design (see Figure 3 for examples of ideas and their assigned CAT scores).

5. DATA ANALYSIS AND RESULTS

To answer the three research questions, a statistical analysis of participant data was performed using a statistical significance level of $\alpha = 0.05$ and a 95% confidence interval. After accounting for missing data, a sample size of 180 (vs. the original sample of 222) was used. Of these, 90 participants received restrictive DfAM education ($N_f = 47$, $N_s = 43$), and 90 participants received dual DfAM education ($N_f = 45$, $N_s = 45$). All reported results are either mean (M) ± standard deviation, or median (Mdn) unless otherwise specified.

RQ1: How does the design task complexity affect the participants' self-efficacy in using DfAM?

To answer the first research question, a two-way analysis of variance (ANOVA) was performed. Specifically, the task complexity and the educational intervention group were taken as the between-subject variables, and items from the self-efficacy scale in Section 4.3.1 were used as dependent variables. While there were no outliers in the data as verified using three standard deviations, the data was not normally distributed as assessed by the Shapiro-Wilk test [119]. Despite this violation of normality, the test was performed, given the robustness of the ANOVA to deviations from normality.

Table 5 Main effects of task complexity on participants' DfAM self-efficacies (higher mean values highlighted)

DfAM concept	*p*	*F*	Means (S.D.)	
			Simple task	Complex task
Mass Customization	**<0.001**	15.75	1.06 (0.14)	0.32 (0.13)
Part Consolidation	0.112	2.55	0.46 (0.13)	0.74 (0.13)
Free Complexity	0.396	0.73	0.46 (0.12)	0.60 (0.12)
Embedding	0.586	0.30	0.36 (0.11)	0.28 (0.10)
Multi-Material	0.077	3.16	0.56 (0.12)	0.26 (0.12)
Support Structures	0.342	0.91	1.07 (0.13)	0.90 (0.13)
Warping	0.062	3.51	1.40 (1.23)	1.08 (1.20)
Anisotropy	**0.001**	11.54	0.97 (0.13)	0.36 (0.13)
Surface Roughness	**0.002**	9.53	0.90 (0.12)	0.39 (0.12)
Feature Size	Simple main effects discussed in text below			

The results of the ANOVA showed no significant interaction between task complexity and the educational intervention group for 9 of the 10 DfAM items. A significant interaction was only observed for the change in self-efficacy with respect to feature size ($F(1,176) = 4.84$, $p = 0.03$). Therefore, controlling for the educational intervention group, the main effects of the task complexity on DfAM self-efficacy were analyzed. The main effect results in Table 5 show significant differences between the different task complexities for mass customization, material anisotropy, and surface roughness. For these three DfAM concepts, the participants who received the simple design task reported a greater increase in their DfAM self-efficacy compared to those who received the complex design task.

Due to the observed interaction between the educational intervention group and task complexity when predicting self-efficacy with feature size, an analysis of the simple main effects was conducted. The results showed that among the participants who received only restrictive DfAM education, those who participated in the simple design challenge reported a greater increase in self-efficacy ($M = 1.67 \pm 0.21$) than those who were given the complex design challenge ($M = 0.851 \pm 0.20$) ($F(1,176) = 8.27$, $p = 0.005$, partial $\eta^2 = 0.045$). However, this difference was not seen in the group that received dual DfAM education ($F(1,176) = 0.05$, $p = 0.82$, partial $\eta^2 = 0.00$). These results refute our hypothesis that the complex design task would encourage a greater use of DfAM to meet the constraints and requirements.

RQ2: How does the design task complexity affect the participants' self-reported emphasis on opportunistic and restrictive DfAM?

To answer the second research question, a two-way ANOVA was performed. The task complexity and the educational intervention group were taken as the between-subject variables, and the items from the self-reported DfAM emphasis scale discussed in Section 4.3.2 were used as dependent variables. While there were no outliers in the data, the data was determined to be not normally distributed; however, we proceeded with the ANOVA due to its robustness.

The results showed no significant two-way interaction between the task complexity and the educational intervention group on the participants' self-reported emphasis on DfAM. Therefore, an analysis of the main effects of the task complexity was performed, controlling for the educational intervention group. The results showed a significant effect of the task complexity on the participants' emphasis on certain DfAM concepts (see Table 6). Specifically, participants who were given the simple design task reported a higher emphasis on mass customization, multi-material printing, surface roughness, and feature size than those who received the complex design task. On the other hand, participants who were given the complex design task reported a higher emphasis on part consolidation, free complexity, and embedding, compared to those who received the simple design task. These results support our hypothesis that the complex design task would encourage the participants to employ more DfAM concepts, particularly the opportunistic ones, to satisfy the constraints and requirements of the design task.

Table 6 Main effects of task complexity on participants' self-reported emphasis on DfAM (higher mean values highlighted)

DfAM concept	*p*	*F*	Means (Std. Error)	
			Simple task	Complex task
Mass Customization	**<0.001**	23.39	3.00 (0.12)	2.21 (0.11)
Part Consolidation	**<0.001**	43.90	2.86 (0.13)	4.04 (0.12)
Free Complexity	**0.008**	7.15	2.54 (0.12)	2.98 (0.11)
Embedding	**0.001**	10.58	1.14 (0.08)	1.49 (0.08)
Multi-Material	**0.038**	4.36	1.80 (0.10)	1.49 (0.10)
Support Structures	0.109	2.60	3.33 (0.13)	3.61 (0.12)
Warping	0.571	0.32	3.43 (0.11)	3.52 (0.11)
Anisotropy	0.222	1.50	3.10 (0.11)	3.30 (0.11)
Surface Roughness	**0.007**	7.51	2.74 (0.12)	2.28 (0.12)
Feature Size	**0.003**	8.91	3.96 (0.12)	3.45 (0.12)

RQ3: How does the design task complexity affect the creativity of the participants' AM designs?

To answer the third research question, four two-way ANOVAs were first performed to check for interaction effects between the educational intervention group and the task complexity. Each creativity metric—uniqueness, usefulness, technical goodness, and overall creativity—was used as the dependent variable, and the educational intervention group and task complexity were used as independent variables. Although the data showed no outliers, the data was found to be not normally distributed. The results of the ANOVA showed no significant two-way interactions between the independent variables (p > 0.05). Therefore, a Mann-Whitney U test was performed to assess if there were differences in the distribution of creativity scores between the two task complexities.

Table 7 Effects of task complexity on the creativity of design outcomes (higher mean values highlighted)

Creativity Metric	p	U	z	Mean Rank (Median)	
				Simple Task	Complex Task
Usefulness	0.91	4011.50	-0.11	90.93 (3.75)	90.08 (3.75)
Uniqueness	**0.001**	5180.00	3.24	77.80 (3.50)	102.92 (4.25)
Technical Goodness	0.11	3490.50	-1.61	96.78 (3.75)	84.36 (3.60)
Overall Creativity	0.11	4609.50	1.61	84.21 (3.50)	96.65 (3.75)

The results of the analysis are summarized in Table 7 and indicate that there was only a statistically significant difference in the distribution of uniqueness scores between the two task complexities. The participants who received the complex design task showed a higher median uniqueness score (*Mdn* = 4.25) compared to those who received the simple design task (*Mdn* = 3.50). However, no significant differences were seen in the scores for usefulness, technical goodness, and overall creativity. These results refute our hypothesis that the lack of specificity in the simple design challenge would result in the generation of ideas with greater variety. The results also refute our hypothesis that the greater functional requirements of the complex task would result in ideas that better meet these requirements, thus being more useful.

6. DISCUSSION

The goal of this research was to explore the role of design task complexity on the participants' DfAM self-efficacy, their self-reported use of DfAM, and the resulting influence on the creativity of the design outcomes. Three main findings were observed from the results of the study:

1. Design task complexity influenced the participants' DfAM self-efficacy, but only with certain DfAM concepts.
2. Design task complexity affects participants' self-reported emphasis on the different DfAM concepts, opportunistic as well as restrictive.
3. Participants who were given the more complex design task generated ideas with greater uniqueness compared to those who were given the simple design task.

The implications of these findings are discussed next.

Task complexity influences participants' DfAM self-efficacy

Previous research has demonstrated the effect of the design task characteristics on the effectiveness of task-based learning [31–33]. Further, self-efficacy has been demonstrated to correlate with effective learning [120]. Therefore, the first research question was developed to explore the influence of task complexity on the change in the participants' self-efficacy with the different DfAM concepts. The results showed that the simple design task, with fewer constraints, was successful in bringing about a greater increase in the students' self-efficacy in *mass customization, material anisotropy,* and *surface roughness*. This result suggests that the simple design task potentially provides participants with the greater opportunities to apply these DfAM concepts, and this rehearsal of concepts could result in the participants feeling greater comfort in using them after the design challenge. For example, several participants from the spring group mentioned that their designs "could fit a phone of any size", thus emphasizing mass customization. Despite being given the freedom to design for any cellphone of their choice, universal fit and customization could be an external constraint added by the participants to improve functionality, as discussed by [121]. This result, therefore, demonstrates the potential advantage of using a simpler, more abstract design task for encouraging students' learning and use of certain DfAM concepts in the design challenge. However, we must be careful in making these inferences given the short duration of the educational intervention. The rapid introduction of several topics in a relatively short time period could have influenced the effectiveness of the intervention, and future research must explore these effects with a refined educational intervention.

Task complexity influenced the participants' self-reported emphasis on DfAM concepts

The results of the first research question demonstrated the influence of task complexity on the participants' DfAM self-efficacy. However, it is important to understand whether these variations in the design task also translated into the participants' self-reported use of DfAM. The second research question was developed to explore these effects.

The first observation from the results was that participants who received the *simple design task* reported a greater emphasis on the opportunistic DfAM concepts of *mass customization* and *multi-material printing*, and the restrictive DfAM concepts of *surface roughness* and *feature size*. These results reinforce the findings of the first research question where the simple design task demonstrated the potential to bring about a greater increase in participants' self-efficacy in mass customization and surface roughness. The participants' emphasis on mass customization could be attributed to the freedom enabled by the simple design task to generate several customizable designs, as demonstrated in previous research [85]. The greater freedom and lack of constraints could have resulted in the participants introducing their own constraints such as universal fit and shock absorption, as suggested by [121]. As seen in the previous research question, several participants mentioned that their designs "could fit any phone”. These external constraints could have encouraged the participants to leverage the capabilities of mass customization and multi-material printing into their solutions.

The second observation was that participants who received the *complex design task* reported a greater emphasis only on the opportunistic DfAM concepts of *part consolidation, freedom of complexity, and embedding functionalities*. Previous results have shown that students tend to simplify their AM designs when given an opportunity. Therefore, a complex design task potentially encourages participants to employ the capabilities of AM such as freedom of geometric complexity to improve the functionality of their designs. For example, most solutions from the simple task consisted of simple, primitive geometries given the ease with which the requirements of the task could be achieved. On the other hand, the added constraints in the complex task encouraged the use of complex features to meet the constraints. For example, since the participants were expected to build an 18” tall tower in an 11.6”x7.6”x6.5” build volume, most designs employed assembly features to attach multiple components together, adding part and assembly complexities to the solution. This is an interesting observation as it suggests that educators must employ design tasks with greater complexity and constraints to encourage students to fully leverage the capabilities of AM. On the other hand, the participants do not report a corresponding greater emphasis on restrictive DfAM, which could potentially result in the generation of solutions with poor manufacturability. Therefore, when employing a complex design task, educators must ensure a strong emphasis is given to restrictive DfAM concepts to ensure successful fabrication with the AM process. This could possibly be achieved by using a combination of simple and complex design activities to teach different opportunistic and restrictive DfAM concepts.

Participants who received the complex design task generated ideas with greater uniqueness

The third key finding from the study was that the complexity of the design task influenced the uniqueness of the solutions generated by participants. Participants who received the complex design task generated more unique solutions compared to those who received the simple design task. This result suggests that the complex design task better encourages the exploration of the solution space, with participants generating a diverse set of solutions. This result supports previous findings, where a moderate set of constraints have been shown to correlate with greater creative production [82]. The participants could possibly be employing the various opportunistic DfAM concepts to find innovative techniques to improve the functionality of their solutions, as well as meet the requirements of the design task.

This inference also relates to the observed higher self-reported emphasis on *part consolidation* and *free complexity* by participants who received the complex design task. In order to meet the constraints and requirements of the complex task, the participants incorporate complexities at the part and assembly levels, and these complexities manifest in different ways. For example, to fit the tower in the limited build volume, participants split their solutions into several components. These components were connected using a variety of assembly features such as T-slots and prismatic joints with and without locking features. On the other hand, given the ease with which the requirements of the simple task can be met, participants tend to generate single component designs, with similar primitive geometrical features. This result, thus, further supports the findings of the previous research question, suggesting the greater potential of a complex design task in encouraging the generation of unique designs, possible through leveraging the capabilities of AM.

7. CONCLUSION, LIMITATIONS, AND FUTURE WORK

The aim of this research is to explore the effect of design task complexity on the creativity of students’ AM design outcomes and investigating the role of DfAM in bringing about these effects. The results showed that the complexity of the design task affects the change in participants’ DfAM self-efficacy as well as their self-reported use of DfAM in the design challenge. Both, the simple and complex tasks encourage the use of specific DfAM concepts, suggesting the use of a combination of simple and complex tasks to effectively teach different DfAM concepts. Further, the results also show that participants who received the complex design task generated more unique ideas. This could be attributed to the participants’ use of the different DfAM concepts to achieve the constraints and objectives of the design task. Based on these results, AM educators are recommended to use a combination of simple and complex design tasks that engage students in applying the different DfAM concepts, thus resulting in effective learning.

While the present research provides insights into the role of the choice of problem statements in a problem-based DfAM intervention, it has several limitations. First, the design tasks used in the study are not analogous to each other in terms of their working principle. Therefore, future research must use analogically near problem tasks (for example, a marshmallow tower [122] and a wind turbine tower) to eliminate any possible influence due to differences outside of task complexity. Second, the study was conducted with mechanical engineering students in their junior and senior years. These students have a relatively higher level of engineering experience compared to freshmen and sophomores. Since previous experience has shown to influence learning, especially in the context of DfAM education [111], future research must explore the effects of task complexity on students with different levels of engineering experience. Third, the study relies on the participants’ self-reported scores as an indicator of their DfAM use, and these levels of emphasis might not fully manifest in their design outcomes. Therefore, future research must employ objective metrics to not only assess the students’ design outcomes for their use of DfAM but also explore the manifestation of the different DfAM concepts, potentially through an analysis of the features of the designs.

8. ACKNOWLEDGEMENTS

This research was funded by the National Science Foundation under Grant No. CMMI-1712234. Any opinions, findings, and conclusions expressed in this paper are those of the authors and do not necessarily reflect the views of the NSF. We would also like to thank Dr. Stephanie Cutler for her guidance and advice. We would like to acknowledge the help of Dr. Jason Moore, Dr. Joseph Bartolai, the ME 340 TAs, and members of the Brite Lab and Made by Design Lab for helping conduct the experiment.

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