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Teaching Designing for Additive Manufacturing: Formulating Educational Interventions That Encourage Design Creativity

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Abstract

As additive manufacturing (AM) processes become more ubiquitous in engineering, design, and manufacturing, the need for a workforce skilled in designing for additive manufacturing (DfAM) has grown. Despite this need for an AM-skilled workforce, little research has systematically investigated the formulation of educational interventions for training engineers in DfAM. In this article, we synthesize findings from our experiments with 596 engineering design students to inform the development of educational interventions—comprising content presentations and design tasks—that encourage student learning and creativity. Specifically, we investigated the effects of four variations of DfAM educational interventions by manipulating the following: (1) the content of DfAM information presented, (2) the order of presenting the DfAM content, (3) the definition of the AM design task, and (4) the competitive structure of the AM design task. The effects of these variations were experimentally tested by comparing changes in students' DfAM self-efficacy and the creativity of students' design outcomes. Validated measures were also developed as part of our studies to help mature the nascent field of DfAM education. Based on the findings of our experiments, we discuss how task-based educational interventions can be formulated to (1) increase students' DfAM self-efficacy, (2) encourage students to generate ideas of high AM technical goodness, and (3) encourage students to generate more creative ideas when using AM. The novel synthesis of our findings in this article will help educators formulate effective DfAM educational interventions and tasks to foster a workforce skilled in DfAM.

Keywords: designing for additive manufacturing, design education, creativity, assessment

Introduction

Additive manufacturing (AM) processes present engineers with manufacturing capabilities far exceeding those of traditional manufacturing. As these processes become more ubiquitous in several industries, there has emerged a need for an AM-skilled workforce. Moreover, the lack of a workforce skilled in AM and *designing* for additive manufacturing (DfAM) has often been identified as a potential barrier to the successful adoption of AM in industrial applications.[1] For example, Thomas-Seale *et al.*[2] identify the key barriers to the industrial adoption of AM in the United Kingdom through discussions with industry practitioners. In their case study, they highlight the need for ''a paradigm shift in education'' to meet the need for an AM-skilled engineering workforce. A similar argument is made by Quinlan and Hart[3] who argue for the need for an increase in investment in AM education and more collaborative efforts between industry and academia to facilitate effective AM training. Simpson *et al.*[4] further provide recommendations toward preparing a future

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engineering workforce that can effectively adopt AM. In their recommendations derived from an NSF workshop comprising industry leaders and academic researchers, they identify the need for ''design practices and tools that leverage the design freedom enabled by AM'' as one of the key themes for future work in AM education. This recommendation suggests that an AM-skilled workforce must be trained to use the knowledge of AM processes in *designing* for AM, that is, DfAM. Seepersad *et al.*[5] further extend this recommendation to suggest that designers must go beyond accommodating AM process limitations through restrictive DfAM (R-DfAM); they must also sufficiently emphasize opportunistic DfAM (O-DfAM) to leverage the capabilities of AM.

Therefore, to harness the potential of AM processes, an AM-skilled workforce must be adept at leveraging the capabilities of layer-based fabrication methods. To help designers leverage these unique design opportunities presented by AM, researchers have proposed numerous design tools and techniques and these techniques are collectively known as O-DfAM. O-DfAM techniques can be broadly classified into five categories: (1) leveraging the freedom of geometric and hierarchical complexity,[6–8] (2) capitalizing on the ability to mass customize products to varying user requirements,[9–12] (3) consolidating design features into integrated products[13] and assemblies,[14,15] thereby minimizing assembly time and costs, (4) leveraging the freedom of material complexity,[16,17] and (5) tapping into the freedom of functional complexity and embedding.[18–21]

Several industries have leveraged these O-DfAM techniques to improve the functionality and performance of their designs and reduce the production costs associated with these designs. A recent example is General Electric's Advanced Turboprop Engine,[22] which achieved a 20% improvement in fuel efficiency and a 10% improvement in power through weight reductions from combining 855 separate parts into 12 components. Another example is the seat bracket redesign undertaken by General Motors,[23] in which eight different components were consolidated into a single part, resulting in nearly 40% weight reduction and 20% improvement in the strength compared with the original design. Furthermore, to help designers utilize these O-DfAM techniques in the design process, researchers have distilled these techniques into design tools such as heuristics[24] and principle cards.[25,26]

In addition to leveraging AM capabilities, designers must also accommodate the limitations inherent in these processes. If not accounted for, these AM process limitations could lead to significant losses in time and cost due to build failures and expensive postprocessing.[27] To help designers overcome these process limitations, researchers have proposed design techniques collectively known as R-DfAM. R-DfAM techniques can broadly be classified into the following: (1) accommodating support structures,[28,29] (2) minimizing warping due to thermal stresses,[30–32] (3) accommodating for minimum feature size and maximum build volumes,[33–35] (4) designing for material anisotropy,[36–38] and (5) including appropriate tolerances and surface roughness due to stair-stepping and design tessellation.[39–41] Furthermore, R-DfAM techniques have been distilled into easy-to-use design tools such as (1) worksheets (e.g., the DfAM worksheet by Booth *et al.*[42] and the GAPS worksheet by Bracken *et al.*[43]), (2) process-specific design guidelines (e.g., design guidelines for the Selective Laser Sintering process by Seepersad *et al.*[44]), and (3) process-agnostic design guidelines and benchmarking artifacts.[45–47]

Combining the two domains of O-DfAM and R-DfAM into a dual DfAM approach, researchers have proposed design frameworks that help designers systematically integrate AM and DfAM in the engineering design. For example, Laverne *et al.*[48] study novice and expert designers, revealing that designers perceive the knowledge of AM capabilities (i.e., opportunities) to be useful in the early design stages. On the contrary, designers find that the knowledge of process characteristics and limitations (i.e., restrictions) is more useful in the later stages of design as the embodiment and detailed specifications for a concept to emerge. Researchers such as Chekurov[49] and Yang *et al.*[50] further extend these frameworks to include both additive and traditional manufacturing considerations, thereby helping designers transition between manufacturing technologies.

Despite the growing body of research on DfAM tools and techniques, little research has systematically studied how DfAM educational interventions could be formulated to encourage student learning and creativity. Specifically, little research has explored how variations in the presentation of DfAM content and the definition of design tasks used in formal DfAM educational interventions influence student learning and creativity. Such efforts are important both to train the new engineering workforce in successfully using DfAM and to upskill the existing engineering workforce to transition toward a dual DfAM mindset. Motivated by this research gap, our aim in this article is to synthesize findings from our prior experiments to inform the effective formulation of DfAM educational interventions. Specifically, in our previous experiments, we studied the effects of variations in the presentation of DfAM content and the DfAM tasks that compose DfAM educational interventions. Our research efforts help (1) identify appropriate methods for assessing the effects of DfAM education and (2) evaluate the effects of variations in task-based DfAM educational interventions.

In the Overview of the Current State of AM and DfAM Education section, we review prior studies and current practices in AM and DfAM education that informed our work. Next, in the Overview of Factors Studied in Our DfAM Educational Research section, we summarize the variations in the educational interventions that were studied as part of our research. This overview is followed by a discussion of the generalized experimental methods used in our studies to test the effects of these variations, including details of the metrics developed and used (the Generalized Experimental Methods Used to Test the Variations in the Educational Intervention section). In the Summary of Results and Implications for DfAM Educational Practice section, we summarize our findings and their implications based on the novel synthesis presented in this article. We conclude with suggestions for future work in the Directions for Future Work section.

Overview of the Current State of AM and DfAM Education

As discussed in the Introduction section, several researchers have argued that the lack of an AM-skilled workforce poses a potential barrier to the successful adoption of AM in industry. To meet this lack of an AM-skilled workforce, numerous educational initiatives have been implemented to train engineers at the undergraduate and graduate levels, as well as practicing industry professionals.

We present a summary of past studies investigating the effectiveness of the various educational interventions in Table 1. These educational initiatives can be broadly classified into the following: (1) informal initiatives aimed at giving students access to AM processes (e.g., makerspaces and design competitions), (2) formal educational interventions (e.g., courses and workshops), and (3) DfAM knowledge introduction through design tools (e.g., design guidelines and worksheets). As highlighted in the table, researchers have also studied the effectiveness of these educational interventions by evaluating factors such as (1) students' learning and self-efficacy, (2) the DfAM utilization in students' designs, (3) the creativity of students' designs, and (4) manufacturability of students' designs.

In addition to the studies on AM and DfAM education presented in Table 1, several educational initiatives have been operationalized in the form of undergraduate and graduate programs, and as workshops and courses for industry professionals. Some examples of these initiatives include (1) graduate programs in AM offered at Penn State[51] and Carnegie Mellon,[52] (2) problem-based learning courses in AM and DfAM offered at UT Austin and Virginia Tech,[53] and (3) the professional development courses offered by Penn State,[54] MIT,[55] ASTM,[56] ASME,[57] Purdue,[58] and Wohler's Associates.[59] In addition, several academic institutions have introduced makerspaces to provide students with access to 3D printing and AM technologies,[60–68] and Ford and Minshall[69] review the literature on the use of 3D printing in education more broadly.

Despite the implementation of these educational initiatives to integrate AM and DfAM in engineering and design education listed in Table 1, several gaps still exist in the formulation of formal DfAM educational interventions. Specifically, few studies have systematically investigated how DfAM educational interventions—comprising content presentations and design tasks—could be formulated to encourage student learning and creativity. To explore this research gap, we studied the effects of variations in four factors of a DfAM educational intervention. We present an overview of the factors studied in our research, as well as the specific variations in these factors, next.

Overview of Factors Studied in Our DfAM Educational Research

As discussed in the Introduction section, AM processes present designers with unique capabilities that can support design creativity. However, these processes also impose certain limitations, which, if not accounted for, can lead to build failures and infeasible designs. While several DfAM tools and techniques have been proposed, little research has investigated how designers and engineers can be trained to utilize DfAM in their design process. Motivated by the need for a workforce skilled in AM and DfAM, we conducted a series of experiments with undergraduate engineering students.

In our experiments, we investigated the effects of introducing a DfAM educational intervention—comprising DfAM content presentation and a DfAM task—on student learning and creativity. Specifically, we studied four variations in the educational intervention (Fig. 1): (1) the presented DfAM content, (2) the order of dual DfAM content presentation, (3) definition of the AM design task, and (4) the competitive structure of the task.

As seen in Figure 1, we compared three variations in the content of DfAM education presented to the students: (1) R-DfAM, (2) O-DfAM, and (3) dual DfAM comprising O- and R-DfAM. These variations are presented along the vertical axis in the figure. In preliminary studies conducted in this research, we also compared the effects of no DfAM inputs to R-DfAM inputs and dual RO-DfAM inputs. Second, we compared two variations in dual DfAM education: (1) O-DfAM followed by R-DfAM, and (2) R-DfAM followed by O-DfAM. Third, we investigated the effects of two design task definitions: (1) a simple, open-ended design task, and (2) a complex design task comprising explicit objectives and constraints. These variations are presented in one of the two horizontal axes in Figure 1. Finally, we compared two design task competitive structures: (1) a noncompetitive design task structured as a showcase, and (2) a competitive design task where best-performing designs would be rewarded, and these variations are presented in the second horizontal axis in Figure 1.

The effects of these variations were assessed on two key metrics: (1) changes in students' DfAM self-efficacy and (2) the creativity of their design outcomes from the said design task. We discuss specific details of each of these variations in the remainder of this section. It should be noted that each of these variations were tested in isolation, as opposed to a design of experiments approach, given the limited availability of a homogenous participant sample. This is a potential limitation of this work and future efforts must work toward exploring interactions between the various factors using a full factorial experimental design. Such an investigation would require a $4\times2\times2$ design, with the first factor being the DfAM content presented (R, O, dual-OR, and dual-RO), the second factor being the design task definition (simple and complex), and the third factor as the task competitive structure (competitive and noncompetitive).

Content of DfAM information presented

In the first set of experiments, we investigated whether introducing students to O-DfAM over and above R-DfAM, that is, dual RO-DfAM, influenced their learning and creativity when compared with no DfAM training. In these experiments, students were categorized into three groups: (1) no DfAM education, (2) R-DfAM education, and (3) dual RO-DfAM education. Furthermore, all students were given an overview of AM processes to ensure that all students had some knowledge of AM. The decision to give students an overview of AM processes (vs. a control group with no AM inputs) was made to ensure that students had some baseline information with AM processes before attempting the design task, which was contextualized specifically for AM. The content presented in each presentation component is summarized in Figure 2. We discuss the details of the implementation of the educational intervention in the Educational Content Presentation section. Our motivation to study the effects of O-DfAM education over and above R-DfAM education was grounded in prior work by researchers such as Blösch-Paidosh and Shea,[24] Yang *et al.*,[25] and Perez *et al.*,[26] who argue that introducing O-DfAM through design tools such as heuristics and design principles can encourage creative product design and redesign.

Table 1. Summary of Additive Manufacturing and Designing for Additive Manufacturing Education Research

	DfAM information presentation			*Design task*		*Assessment measures*			
Source	*Information content*	*Information order*	*Information modality*	*Task definition*	*Competitive structure*	*Self-efficacy*	*DfAM utilization*	*Design creativity*	*Manufacturability*
Williams *et al.*[70]		Informal competition			Competition				
Sinha *et al.*[71]		Informal makerspace							
Williams and Seepersad[53]			Semester course	Open-ended					
Yang[72]			Semester course		Competition				
Budinoff and McMains[73]			Semester course						
Budinoff[74]			Comparison						
Laverne *et al.*[48]			Comparison						
Laverne *et al.*[75]			Comparison						
Ferchow *et al.*[76]			Workshop+Expert feedback						
Leutenecker-Twelsiek *et al.*[77]			Workshop+Expert feedback						
Bracken *et al.*[78]			Presentation/workshop						
Diegel *et al.*[79]			Presentation/workshop						
Blösch-Paidosh and Shea[24]			Heuristics						
Blösch-Paidosh *et al.*[80]			Heuristics						
Fillingim *et al.*[81]			Heuristics						
Perez *et al.*[82]			Principles						
Hwang *et al.*[83]			Principles						
Yang *et al.*[25]			Principles						
Booth *et al.*[42]			Worksheet						
Barclift *et al.*[84]			Presentation						
Sinha *et al.*[85]			Presentation						
Prabhu *et al.*[86]			Presentation						
Prabhu *et al.*[87]			Presentation						
Prabhu *et al.*[88]			Presentation						
Prabhu *et al.*[89]			Presentation						
Prabhu *et al.*[90]			Presentation						
Prabhu *et al.*[91]			Presentation						
Prabhu *et al.*[92]			Presentation/workshop						
Prabhu *et al.*[93]			Presentation				Concept selection		

Variations studied or measures used highlighted in gray; bold indicates studies reviewed in this article.
DfAM, designing for additive manufacturing.

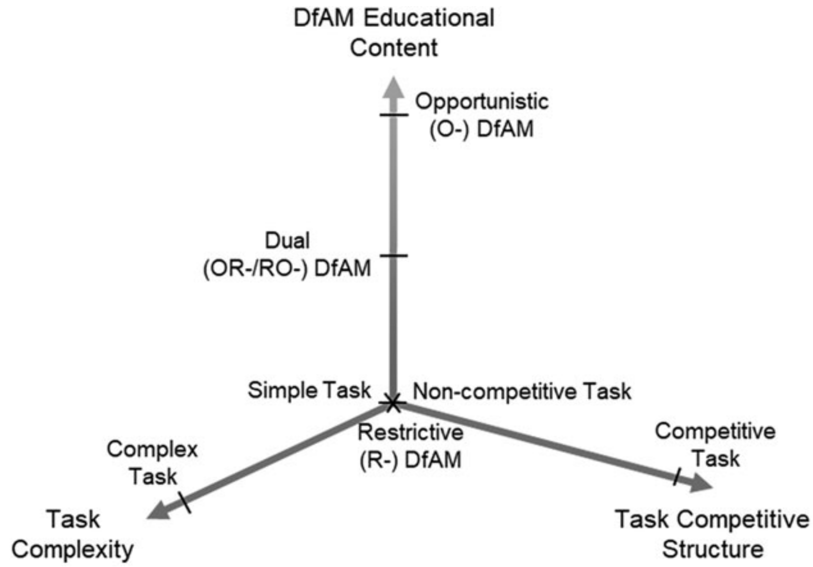

FIG. 1. Components and corresponding variations of the DfAM educational intervention considered in our research. DfAM, designing for additive manufacturing.

Order of presenting dual DfAM content

In the next experiment, we investigated the effects of the order of O-DfAM and R-DfAM content presentation on students' learning and creativity. Toward this aim, we manipulated the order of dual DfAM education where one group of participants were trained in R-DfAM first, followed by O-DfAM training (i.e., dual RO-DfAM), and the second group of participants were trained in O-DfAM first, followed by R-DfAM training (i.e., dual OR-DfAM). Furthermore, two control groups were included comprising students trained either in O-DfAM only or in R-DfAM only. Students from all four educational intervention groups were given the same design task. We present details of the presentation of the educational information in the Educational Content Presentation section.

Our motivation to study the effect of the order of DfAM content presentation was based on prior work highlighting the influence of prior knowledge and experiences on individuals' future learning and recall of information. Specifically, engineering design involves using knowledge from several domains to solve a problem. In the absence of external knowledge-based cues,[94] designers are expected to freely recall their domain knowledge. Prior research in learning and memory has demonstrated that the order of presenting information influences the free recall of said information through recall inhibition. Recall inhibition can either occur retroactively, that is, the inhibited recall of information presented first,[95] or proactively, that is., the inhibited recall of information presented later.[96] Furthermore, recall inhibition is also influenced by one's prior knowledge and familiarity with a partial set of information, as suggested in the Part Set Cue Theory.[97] Therefore, it is important to understand if the order of presenting O- and R-DfAM content influenced students' learning and recall of these concepts, and the subsequent effects of this recall on the creativity of their design outcomes.

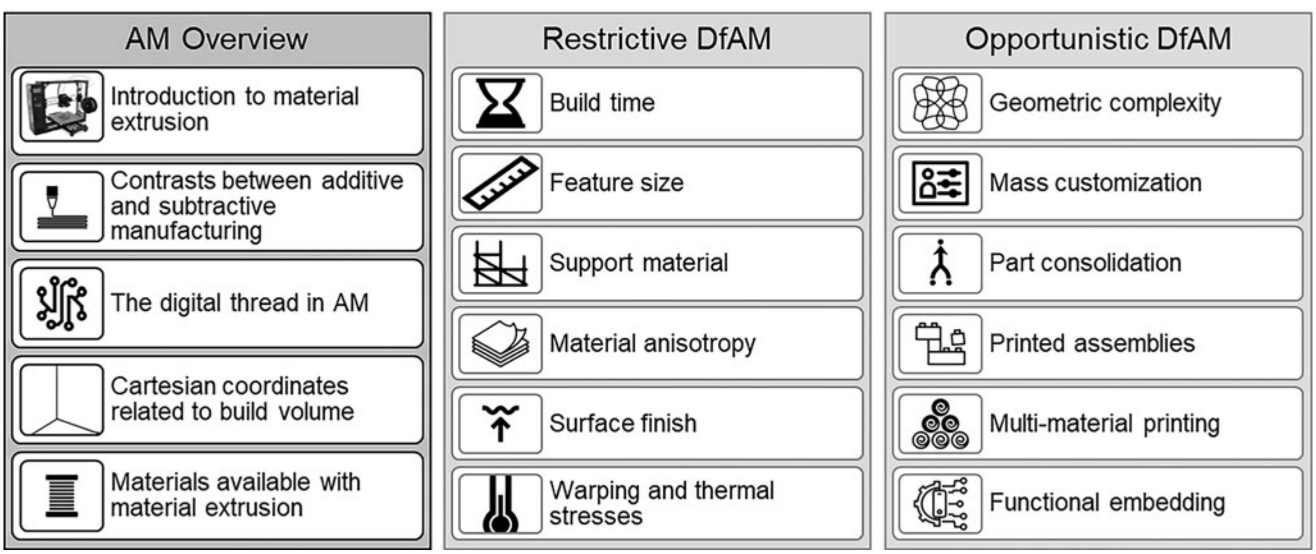

FIG. 2. Topics covered in the DfAM educational intervention.

Definition of AM design task

In our next experiment, we studied the effects of design task definition on students' learning and creativity. Specifically, we compared students' learning and design outcomes when given one of two design problems.[89] The first design problem was an open-ended task asking students to design a solution for hands-free viewing on a cell phone. In this design problem, designers were only given two objectives to achieve: minimizing build time and build material. In contrast, the second design problem was to design a tower to support a wind turbine-blade assembly. This design problem included explicit constraints such as the height of the tower and the load to be supported, in addition to the objectives of minimizing build time and build material. Both the design problems are available in Prabhu *et al.*[89] and in Ref.[98] These problems were chosen, given their reliance on minimum domain knowledge beyond basic mechanical engineering concepts such as the strength of materials. Furthermore, it should be noted that both design problems asked students to design solutions that could be fully manufactured with AM. The details of the implementation of the design task are presented in the Post-intervention Design Task and Survey section.

Our motivation to study the effects of design task definition was based on prior work in design and creative cognition highlighting the role of design task definition on designers' ideation. For example, in the componential model of creativity, Amabile[99] presents problem identification as the first step in creative production. The inclusion of constraints in a design problem has been widely studied in the creativity literature. For example, Jonassen[100] categorizes design problems into well-structured problems: problems that have specific constraints and a converging solution, and ill-structured problems: problems that are open-ended and have several directions for solution exploration. The authors further discussed how different educational strategies must be used when implementing these two types of problems.

Onarheim[101] characterizes constraints in problem-solving along six dimensions: (1) timing, (2) flexibility, (3) importance, (4) source, (5) domain, and (6) purpose. Through a case study, the author identifies various strategies used by designers to accommodate these constraints such as black-boxing and redefinition. Similarly, Biskjaer *et al.*[102] study designers' inspiration search strategies in problems with different levels of constraints. They observe that while open-ended problems do not give sufficient direction for exploring solutions, overconstrained problems could excessively limit creative ideation. Therefore, in the context of DfAM education, a design task must be defined such that it sufficiently encourages the application of the creative freedom enabled by O-DfAM to generate creative ideas.

Competitive structure of AM design task

In our final experiment, we investigated the effects of task competitive structure on the outcomes of DfAM education. Specifically, we compared the effects of R-DfAM and dual RO-DfAM education when introduced through either a competitive or noncompetitive design task.[91] The complex wind turbine problem was used in these experiments. The external motivation of the design task was manipulated by introducing a quality-based monetary reward. A subset of the students were informed that ''the best performing design would receive a $20 gift card,'' whereas the remaining students were informed that they would have to present their designs to the class in a later class period. The participants were also informed that their designs would be assessed for their performance with the objectives of the design problem, that is, minimizing build time and material. The details of the implementation of the design task are presented in the Post-intervention Design Task and Survey section.

This study was motivated by prior work highlighting the influence of task motivation on creative performance. For example, asper Amabile's Componential Model of Creativity,[99] individuals' task motivation influences their problem identification, solution generation, and learning of domain knowledge. Furthermore, Atkinson's Theory of Achievement Motivation[103] suggests that individuals' actions, especially in academic settings are governed by a combination of their motivation toward achieving success and toward avoiding failure, and these components are influenced by the presence of external rewards. A task-based DfAM educational intervention must encourage designers to both leverage O-DfAM to improve design functionality (i.e., achieve success) and utilize R-DfAM to minimize build failures (i.e., avoid failure).

Generalized Experimental Methods Used to Test the Variations in the Educational Intervention

We performed a series of experiments to test the effects of the different variations presented in the Overview of Factors Studied in Our DfAM Educational Research section. In this section, we present an overview of our experimental methods, including key characteristics of the participants recruited, the procedure followed, and the various metrics used to assess the effects of the DfAM educational intervention. An overview of the variations tested in our research and the studies in which we report the corresponding results is presented in Figure 3. The experimental procedure was reviewed and approved by the Institutional Review Board, before the experiments were performed.

Participants

The sample studied in our experiments comprised undergraduate students in mechanical engineering. The participants were recruited from five consecutive cohorts—both fall and spring semesters—of a junior-level undergraduate course on mechanical design methodologies at a large public university in the northeastern United States. Although a cumulative total of $\sim$700 students were trained in our interventions, a sample size of 596 students was used in our studies after accounting for missing and incomplete data. The participants primarily comprised students in the junior year of study with a majority of participants pursuing their undergraduate degrees in mechanical engineering. Some participants were in their sophomore or senior year of study with a few participants pursuing dual majors in biomedical engineering or nuclear engineering. The participants were asked to report their prior experience in AM and DfAM (see the Pre-intervention Survey section) before the experiment and a majority of the participants reported having received ''some informal training'' in both AM and DfAM. Few participants had received ''significant formal training'' in AM/DfAM or had ''never heard of it.'' This distribution of prior AM and DfAM experience was observed among participants from all five samples. The total number of participants in each study is presented in Table 2.

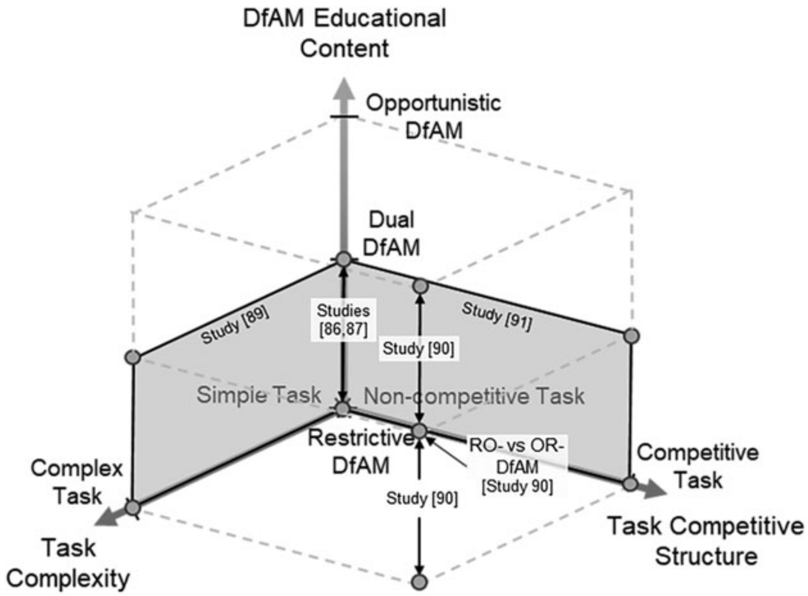

FIG. 3. Variations tested in our research and references to corresponding studies.

Procedure

The experiments comprised three stages: (1) a pre-intervention survey, (2) DfAM content presentation, and (3) a post-intervention design task and survey. Of these three stages, the DfAM educational content presentations and the post-intervention design task were varied as discussed next. An overview of the generalized procedure followed in the experiments is presented in Figure 4.

Pre-intervention survey. In the first stage of the experiment, participants were asked to complete a pre-intervention survey. As part of the survey, participants were asked to report their DfAM self-efficacy on the scale discussed in the DfAM Self-Efficacy section. In addition, participants were asked to report their prior AM, DfAM, and computer-aided design (CAD) experience on a scale of ''1 = Never heard of it'' to ''5 = Expert in it'' and this scale was adapted from the survey by Barclift *et al.*[84] Participants' responses to the pre-intervention survey served as a baseline for their prior experience and also helped compare differences from before to after participating in the educational intervention. The complete pre-intervention survey is accessible in Ref.[98]

Educational content presentation. Following the pre-intervention survey, participants were introduced to the DfAM educational content. The DfAM content was presented to the students in a large lecture hall and comprised three 20-min components: (1) an overview of AM processes, (2) R-DfAM, and (3) O-DfAM. The topics covered in each content presentation are summarized in Figure 2. All participants were given an overview of AM processes. Next, based on the semester of study, participants were introduced to one of five educational intervention groups: (1) no DfAM, (2) R-DfAM, (3) O-DfAM, (4) R-DfAM followed by O-DfAM (i.e., dual RO-DfAM), and (5) O-DfAM followed by R-DfAM (i.e., dual OR-DfAM). The number of participants in each group is presented in Table 2. The slides used in the presentations are accessible in Ref.[98]

Post-intervention design task and survey. Following the educational intervention content presentation, participants were asked to complete a post-intervention DfAM task. The design task comprised three stages: (1) individual brainstorming, (2) group concept selection, and (3) CAD. Of these three stages, participants' outcomes from only the first stage, that is, the individual brainstorming stage, were used in our

TABLE 2. SUMMARY OF THE VARIABLES INVESTIGATED AND THE NUMBER OF PARTICIPANTS IN EACH CONDITION

Design task definition (Definition of AM Design Task section)	Task competitive structure (Competitive Structure of AM Design Task section)	*Content of educational intervention (Content of DfAM Information Presented and Order of Presenting Dual DfAM Content sections)* No DfAM	R-DfAM	Dual RO-DfAM	O-DfAM	Dual OR-DfAM
Simple (cell phone holder)	Noncompetitive showcase	$N=49$ and 83	$N=42$ and 42	$N=49$ and 45	X	X
Complex (wind turbine)	Noncompetitive showcase	X	$N=46$	$N=44$	X	X
	Competitive design challenge	X	$N=64$	$N=41$	$N=45$	$N=46$

Multiple entries indicate multiple studies.
AM, additive manufacturing; O-DfAM, opportunistic DfAM; R-DfAM, restrictive DfAM; X, condition not tested.

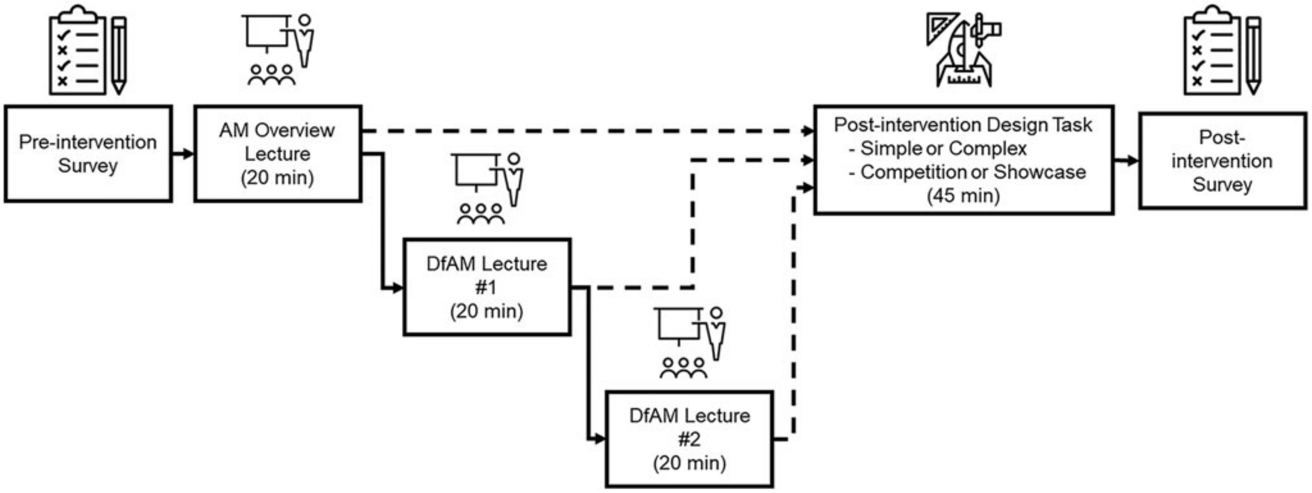

FIG. 4. Generalized procedure followed in the experiments.

analyses. Examples of ideas generated by the participants at this stage are presented in Figures 5 and 6. As part of the post-intervention design task, participants were given either the simple or complex design problem (see the Order of Presenting Dual DfAM Content section) and asked to individually brainstorm for ideas. Participants were given ~15 min and were given the freedom to generate as many ideas as they would like to. Furthermore, participants were asked to both sketch their ideas, use words to describe the ideas (e.g., different parts or functions), and also note down the strengths and weaknesses of each design. Following the initial brainstorming, participants were asked to individually come up with one final idea. They were given the freedom to brainstorm for a new idea, combine previous ideas, or select one of their initial ideas. This final idea generated by the participants was used in our analyses. Finally, upon completing the design task, participants were asked to complete a post-intervention survey collecting their DfAM self-efficacy using the same scale used in the pre-intervention survey (see the DfAM Self-Efficacy section).

Metrics

In this section, we discuss details of the metrics used to measure the effects of variations in the DfAM educational intervention. A summary of the metrics used to measure the effects of the DfAM educational intervention, their subcomponents, and method of testing reliability and validity is presented in Table 3.

DfAM self-efficacy. An effective DfAM educational intervention must result in positive changes in students' DfAM self-efficacy. Self-efficacy—one's beliefs in the performance abilities—has been identified as an important indicator of individuals' performance abilities.[107] The utility of self-efficacy as a measure of skill development and performance ability has been demonstrated in several domains such as engineering design,[108] computer science,[109,110] academics,[111] and sports.[112] Therefore, to measure participants' DfAM self-efficacy, a 10-item scale was developed and validated (see Prabhu *et al.*[113] for details on the development of the scale). Of the 10 items in the scale (Fig. 7), 5 items corresponded to the fundamental O-DfAM techniques, namely (i) mass customization, (ii) part consolidation and printed assemblies, (iii) geometric complexity, (iv) material complexity and multimaterial design, and (v) functional embedding, and the remaining 5 items corresponded to 5 R-DfAM techniques of (i) warping due to thermal stresses, (ii) material anisotropy, (iii) stair-stepping and surface roughness, (iv) support structures, and (v) feature size and build volume.

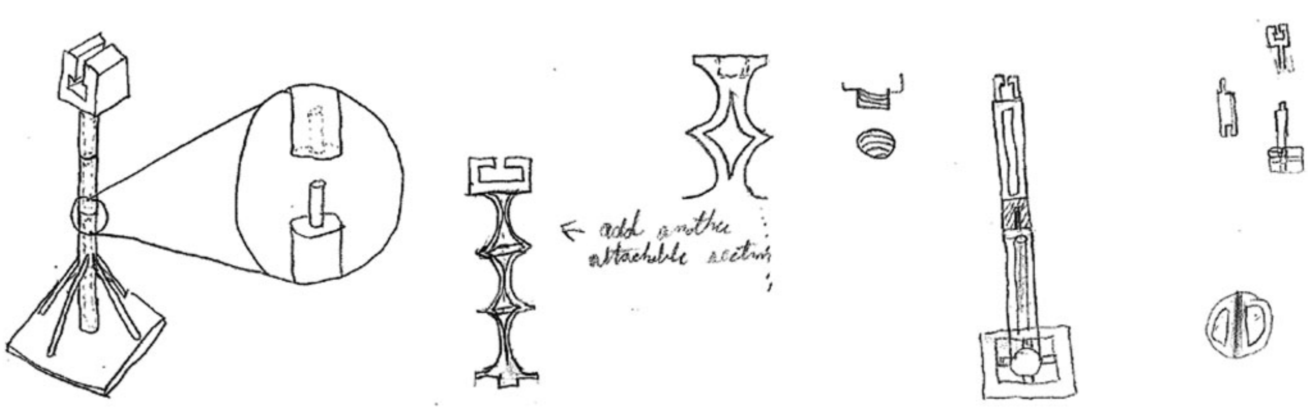

FIG. 5. Examples of ideas generated by participants who received the complex wind turbine tower design problem.

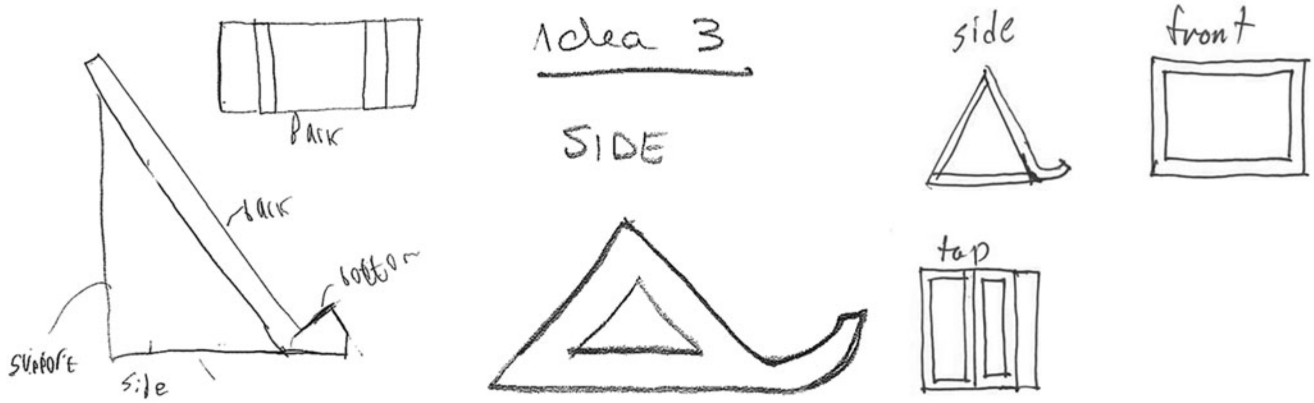

FIG. 6. Examples of ideas generated by participants who received the simple cell phone holder design problem.

The scale was tested for its criterion and construct validity using participants' responses. First, we observed that the participants' responses to all 10 items in the self-efficacy scale positively and significantly correlated with their prior AM and DfAM experience with participants having more prior experience reporting higher levels of DfAM self-efficacy. This observation established the criterion-related validity of the scale responses. Furthermore, exploratory and confirmatory factor analyses[104] revealed that participants' responses to items corresponding to (i) mass customization, (ii) part consolidation, (iii) geometric complexity, and (iv) multimaterial design loaded significantly on the same component and this component was labeled as ''opportunistic DfAM self-efficacy.'' On the contrary, participants' responses to their self-efficacies in (i) warping, (ii) material anisotropy, and (iii) surface roughness loaded significantly on a second component and this component was labeled as ''restrictive DfAM self-efficacy.'' Since similar categorizations of DfAM concepts have been proposed in the literature,[49] the results of the factor analyses provided construct-related validity to the scale. Further details on the validation and specific inferences made from the factor analyses are available in Prabhu *et al.*[113]

Creativity of students' designs. AM processes present designers with newfound design freedoms and to tap into the potential of AM, designers must be encouraged to creatively leverage these design freedoms. Therefore, a successful DfAM educational intervention must encourage students to be creative in their utilization of DfAM, both opportunistic and restrictive. Our main objective in this research was to identify variations in task-based DfAM educational interventions that encourage creativity among students. Therefore, to measure the effects of variations in the DfAM educational intervention on creativity, the participants' designs from the DfAM task were assessed using the Consensual Assessment Technique.[99,114] Specifically, the students' designs were evaluated for creativity by two or more raters on the following four components:

TABLE 3. SUMMARY OF METRICS USED IN THIS RESEARCH, THE CORRESPONDING CONSTRUCTS, AND METHOD OF ESTABLISHING VALIDITY

Construct	*Metric*	*Subcomponent (level 1)*	*Subcomponent (level 2)*	*Establishing validity*
Learning	DfAM self-efficacy	O-DfAM self-efficacy	Mass customization Part consolidation and printed assemblies Geometric complexity Functional embedding Multimaterial printing	1. Construct validity through exploratory and confirmatory factor analyses[104] 2. Internal consistency via Cronbach's α[105]
		R-DfAM self-efficacy	Support structures Warping due to thermal stresses Material anisotropy Surface roughness and stair stepping Feature size and build volume	
Design creativity	Consensual assessment technique	Uniqueness Usefulness Overall creativity		Inter-rater reliability through the intraclass correlation coefficient[106]
DfAM integration in designs	Consensual assessment technique	AM technical goodness		

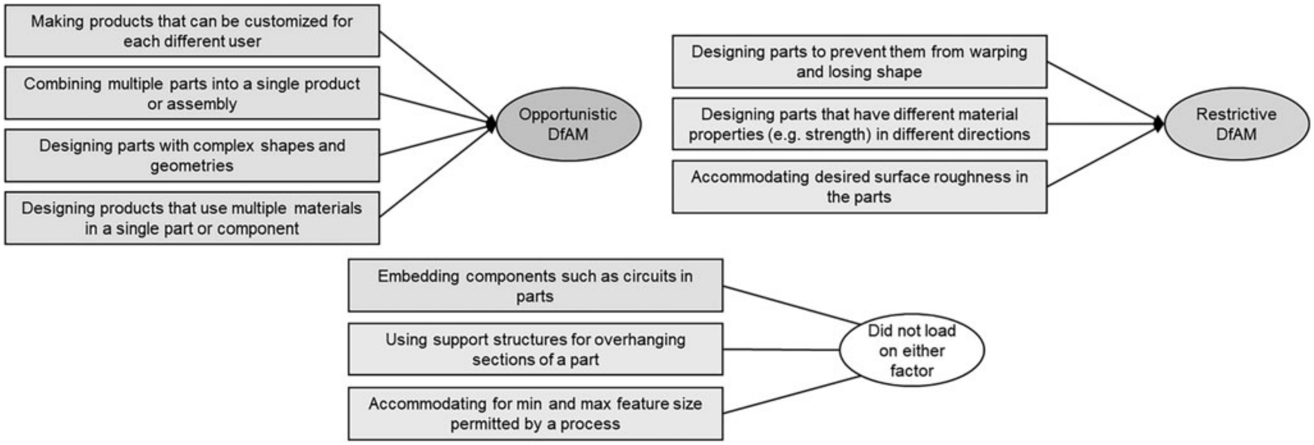

FIG. 7. The DfAM self-efficacy scale and its underlying factor structure.

1. Usefulness: In this component, the raters were asked to evaluate the quality of the design in its ability to solve the given design problem. This component was derived from the ''appropriateness'' subcomponent under the ''resolution'' factor by Besemer[115] and is analogous to the quality assessments used by Refs.[116,117]

2. Uniqueness: In this component, the raters were asked to evaluate the originality[118] and novelty[117] of each solution and this component was derived from the ''novelty'' factor by Besemer.[115] It should also be noted that the raters were asked to evaluate the uniqueness of designs in comparison to the pool of solutions generated in the sample as suggested by Amabile.[99]

Table 4. Summary of Findings from the Various Studies

	DfAM self-efficacy	*Design technical goodness*	*Design creativity*
Content of DfAM education (no DfAM, R-DfAM, and dual RO-DfAM)	Participants trained in R-DfAM reported a greater increase in their R-DfAM self-efficacy compared with those trained in no DfAM and dual RO-DfAM. No differences were observed in the changes in O-DfAM self-efficacy.	Participants who were trained in dual RO-DfAM generated ideas of higher technical goodness compared with those trained in no DfAM and R-DfAM.	No differences were observed in the creativity of the designs generated by the participants from the three educational intervention groups.
Order of DfAM education (R-DfAM, O-DfAM, dual RO-DfAM, and dual OR-DfAM)	Order of dual DfAM training did not influence changes in participants' DfAM self-efficacy. However, only participants explicitly trained in O-DfAM, with or without R-DfAM, reported an increase in O-DfAM self-efficacy.	Participants trained in dual RO-DfAM generated ideas of higher technical goodness compared to those trained in dual OR-DfAM.	Participants trained in dual RO-DfAM generated ideas of higher uniqueness and overall creativity compared to those trained in dual OR-DfAM.
Design task definition (simple and complex)	Participants who received the simple design task reported a greater increase in their self-efficacy with mass customization, warping, material anisotropy, and surface roughness. The effect sizes were small, especially with warping.	Participants who received the simple design task generated ideas of higher AM technical goodness compared with those who received the complex design task. However, the observed effect sizes were small.	Participants who received the complex design task generated ideas of higher uniqueness and overall creativity compared with those who received the simple design task. While the effect size for uniqueness was moderate, it was relatively small for overall creativity.
Design task competitive structure (competition and showcase)	Participants who received the competitive design task reported a greater increase in their self-efficacy with material anisotropy compared with those who received the noncompetitive design task.	Participants trained in dual RO-DfAM generated ideas of higher technical goodness compared with those trained in R-DfAM, but only when given a competitive design task.	Participants trained in dual RO-DfAM generated ideas of higher creativity compared with those trained in R-DfAM, but only when given a competitive design task.

3. Technical goodness: In this component, the raters were asked to assess the level of DfAM integration, both O-DfAM, and R-DfAM, in the designs. This component was derived from the ''well-craftedness'' subcomponent under the ''elaboration and synthesis'' factor[115] and was adapted for assessment in the AM domain.
4. Overall creativity: In this component, the raters were asked to evaluate the designs using their subjective definition of overall creativity. This component was used to capture design creativity as a composite of usefulness, uniqueness, and technical goodness, and besides, any additional components that might not have been included in these three components. Furthermore, overall creativity has been used in previous studies such as by Kaufman *et al.*[119]

The participants' designs were evaluated by a combination of graduate and undergraduate student raters with at least 2 years of experience in DfAM and creativity-related studies. Furthermore, the raters developed their mental model for assessing design creativity through interactions with experts in the DfAM domain.[120] Sufficient inter-rater reliability—evaluated using intraclass correlation coefficients[106] >0.7—was observed in all studies, thereby lending validity to the assessments.[114] In the next section, we present key findings from our experiments as assessed using these metrics.

Summary of Results and Implications for DfAM Educational Practice

Our aim in this research was to study the effects of variations in a DfAM educational intervention—comprising content presentations and DfAM tasks—on students' learning and the creativity of their designs. As summarized in Table 2, we have studied close to 600 participants in our experiments and the results of the individual comparisons are available in the references listed in the table. In this section, we present key findings from our experiments. An overview of the key findings is presented in Table 4. Based on these findings, we provide recommendations to translate these findings into educational practice. These recommendations are categorized based on the objective of the educational intervention (see Fig. 8 for a summary).

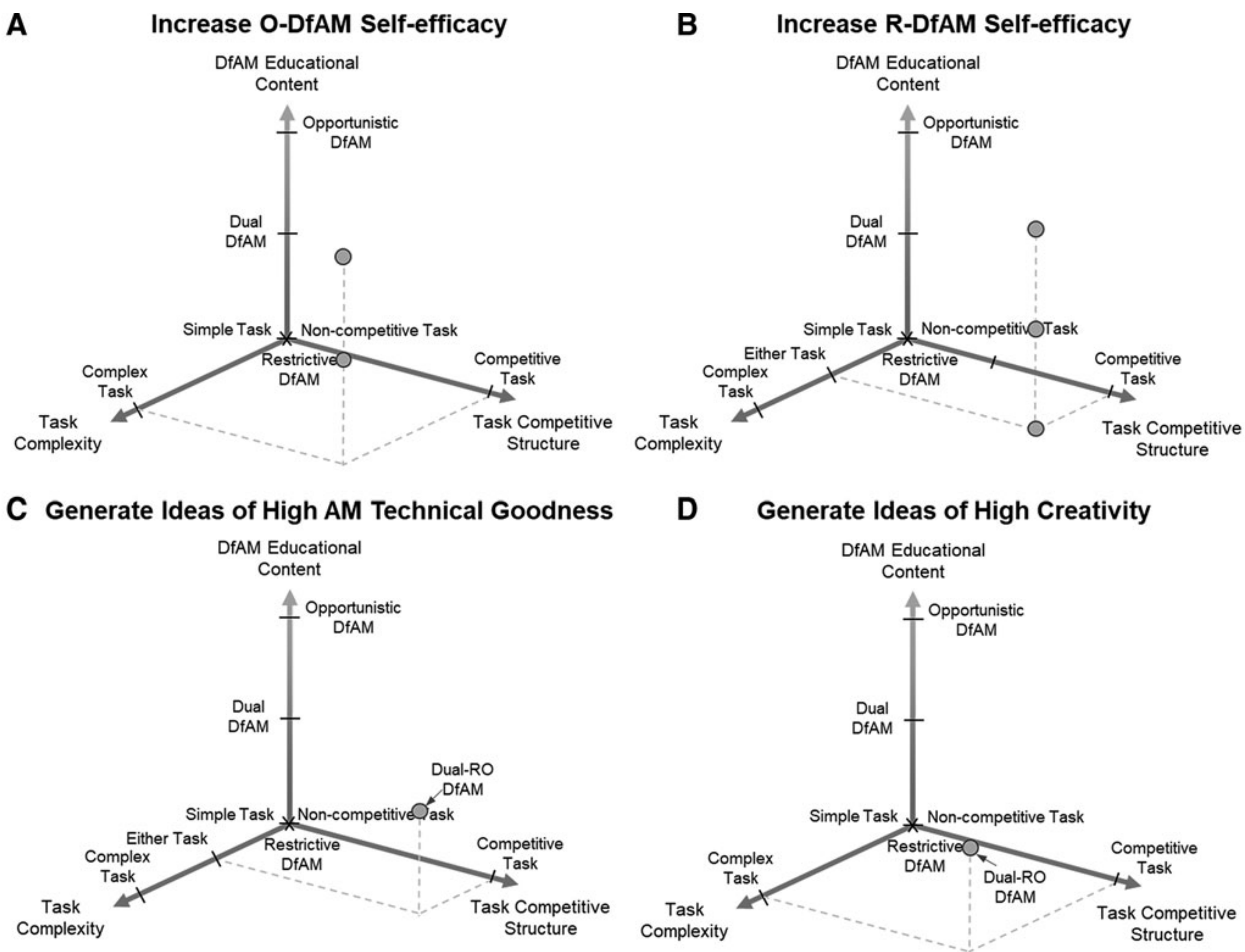

FIG. 8. Recommendations for formulating DfAM educational interventions based on the desired educational outcome. **(A)** Increase O-DfAM self-efficacy. **(B)** Increase R-DfAM self-efficacy. **(C)** Generate ideas of high AM technical goodness. **(D)** Generate ideas of high creativity. AM, additive manufacturing; O-DfAM, opportunistic DfAM; R-DfAM, restrictive DfAM.

Effects on students' O-DfAM self-efficacy

Prior research has demonstrated the relationship between self-efficacy and one's performance ability[121]; therefore, an effective DfAM educational intervention must increase students' self-efficacy, both with O-DfAM and R-DfAM. From the results (see Fig. 8A), we observe that the DfAM educational content presented to the participants did not have a significant impact on their O-DfAM self-efficacy when given a simple, noncompetitive design task (i.e., the cell phone holder design task). Participants trained in no DfAM, R-DfAM, and dual RO-DfAM reported a similar increase in their O-DfAM self-efficacy. However, among participants who received the complex design task in a competitive structure, we observed a significant effect of the content of DfAM education. Specifically, we observe that *only* students trained in O-DfAM, with or without R-DfAM, reported an increase in their O-DfAM self-efficacy. Moreover, the order of dual DfAM education did not influence the increase in students' O-DfAM self-efficacy. Based on these findings, if the objective of the DfAM educational intervention is to increase students' O-DfAM self-efficacy, we recommend that educators give an explicit emphasis on O-DfAM concepts in the educational intervention. Furthermore, we recommend using a complex design task that comprises specific objectives and constraints and introducing the design task in a competitive structure.

Effects on students' R-DfAM self-efficacy

In addition to increasing students' O-DfAM self-efficacy, a successful educational intervention must also increase students' R-DfAM self-efficacy. From the results (see Fig. 8B) of our experiments, we observed that the content of DfAM education had a significant effect on participants' R-DfAM self-efficacy when students were given the simple design task in a noncompetitive structure. Participants who were introduced to only R-DfAM showed the highest increase in R-DfAM self-efficacy compared with those who received no DfAM inputs or received dual RO-DfAM inputs. This finding suggests that introducing O-DfAM over and above R-DfAM could potentially hamper students' learning of R-DfAM content.

We also observed that participants who were given the simple design problem reported a greater increase in their self-efficacy with the R-DfAM concepts of warping, anisotropy, surface roughness, and feature size and accuracy. On the contrary, participants who were given the complex design task in a competitive structure reported a greater increase in their self-efficacy with material anisotropy compared with those who were given the noncompetitive design task. Moreover, this difference was observed in participants trained in both R-DfAM and dual RO-DfAM, with no interaction effects observed between the content of DfAM education and task competitive structure. This finding suggests that quality-based rewards potentially trigger students' motivation to avoid (build) failure[103] and encourage them to ensure that their design is strong enough to support the desired loads—a constraint in the complex design problem, thereby resulting in a higher increase in their self-efficacy in material anisotropy.

Finally, we observed that all participants—including those trained *only* in O-DfAM—reported an increase in their R-DfAM self-efficacy when given the complex design task in a competitive structure. This increase could potentially be attributed to participants' familiarity with R-DfAM through their prior experiences outside the intervention. Therefore, if the objective of the DfAM educational intervention is to increase R-DfAM self-efficacy, engaging students in a DfAM design task with minimal educational inputs would suffice. In addition, if using a complex design task, introducing it in a competitive task structure is recommended. However, this recommendation goes with the assumption that students have some prior experience in DfAM.

Effects on technical goodness of students' designs

An effective DfAM educational intervention must successfully encourage students to utilize DfAM—both, opportunistic and restrictive—in their design process and generate designs of high AM technical goodness. From our results (see Fig. 8C), we observed that among participants who received the simple design task in a noncompetitive structure, those trained in dual RO-DfAM generated ideas of highest AM technical goodness compared with no DfAM education and R-DfAM education. Furthermore, the design task definition did not have a significant impact on the technical goodness of participants' designs; however, the task competitive structure did influence design technical goodness. Specifically, we observed that among the participants who received the complex design task in a competitive structure, those trained in dual RO-DfAM generated ideas of higher technical goodness compared with O-, R-, and dual OR-DfAM education. Therefore, to encourage students to generate designs of high AM technical goodness, they must be introduced to both O- and R-DfAM, that is, dual DfAM. In addition, when introducing dual DfAM, students must be introduced to R-DfAM first, followed by O-DfAM. Furthermore, we suggest using either a simple or a complex design task and presenting the design task in a competitive structure.

Effects on the creativity of students' designs

Finally, AM processes provide designers with new creative freedoms, previously limited by traditional manufacturing. Therefore, to leverage the potential of AM, designers must be encouraged to harness the creative freedom offered by AM. From our results (see Fig. 8D), we observe that among participants who received the simple design task in a noncompetitive structure, the content of DfAM education did not significantly influence the design creativity. This finding highlights that educators must do more than simply introduce dual DfAM content in their DfAM educational intervention to encourage creative idea generation. Moreover, this finding reinforces the recommendation made in the Effects on Students' O-DfAM Self-Efficacy section, calling for educators to give a special emphasis on O-DfAM in their educational intervention.

We also observed that the design task definition influenced the uniqueness of participants' designs. Specifically, participants presented with the complex design task generated designs of higher uniqueness compared with those who received the simple design task. One inference from this result is that the lack of functional requirements in the simple design problem does not sufficiently motivate students to use O-DfAM, and students, therefore, direct their efforts toward improving design feasibility through

R-DfAM. This inference is informed by findings from our previous studies[86] and work by Pradel *et al.*,[122] who observe that designers give a greater emphasis to the feasibility of designs compared with design creativity. On the contrary, the explicit functional requirements of the complex design task engage students in utilizing O-DfAM in their designs, which in turn increases design uniqueness. This inference is informed by findings by Blösch-Paidosh and Shea[24] and Yang *et al.*[25] who demonstrate that designers who are introduced to AM capabilities through external design cues such as heuristics generate more creative designs. The findings of our study therefore highlight the need to carefully choose and define the design problem in task-based DfAM interventions to encourage designers to use both O- and R-DfAM techniques. This use of DfAM will, in turn, result in better learning and use of these concepts, especially toward creative ideation.

Furthermore, we observed that the competitive structure of the design task influenced the participants' design creativity, and this effect varied based on the content of DfAM education. Specifically, we observed that participants trained in dual DfAM, that is, both O- and R-DfAM, generated ideas of higher uniqueness, usefulness, and overall creativity compared with those trained in R-DfAM only. However, this difference was only observed among participants who were given the competitive design task; no differences were observed among those who received the noncompetitive design task. We also observed that participants trained in dual RO-DfAM generated ideas of higher uniqueness and overall creativity compared with those trained in dual OR-DfAM.

These findings further support our inference that students must be sufficiently motivated to leverage the potential of AM processes toward creative concept generation. Moreover, these findings suggest that external motivation manipulated through quality-based monetary rewards can be used as a potential mechanism to encourage the creative utilization of O-DfAM. Our findings also suggest that students' recall of O-DfAM is potentially inhibited by the introduction of R-DfAM and this inhibited recall of O-DfAM could result in the generation of ideas with lower creativity. Moreover, our results suggest that this recall inhibition occurs retroactively, that is, the recall of information presented first—in our case, O-DfAM—is inhibited by the learning and recall of information presented later, that is, R-DfAM. Students' previous knowledge of R-DfAM could also have interfered with their learning of O-DfAM, as suggested by the Part Set Cue Theory.[97] This finding further reinforces the previous inference suggesting the need for specific emphasis on O-DfAM when teaching dual DfAM. Therefore, if the objective of the educational intervention is to encourage the generation of creative ideas, we recommend teaching R-DfAM first, followed by O-DfAM. Furthermore, we recommend using a complex design task in the intervention and presenting the design task in a competitive structure.

Directions for Future Work

The research discussed in this article provides several key insights toward the development of task-based DfAM educational interventions; however, several directions for future work still exist. Specifically, we identified three key areas for future research as follows:

- Investigating the influence of DfAM educational interventions at different stages of the engineering design process.
- Studying the influence of other skills such as CAD expertise and engineering experience on designers' learning and DfAM use.
- Investigating the effects of a spaced intervention distributed over multiple design and information presentation sessions compared with the massed intervention used in our studies.
- Using a full factorial design of experiments to test interactions between the four factors studied in this research.

First, the studies presented in this article primarily investigate the conceptual designs generated by the student participants. While concept generation is an important part of the product design process, the final outcomes of the design process are also governed by the decisions made in later stages of design such as concept selection, embodiment design, and detail design. From the preliminary results of a study of designers' concept selection decisions,[123] we see that the content of DfAM education influences designers' propensity for selecting creative ideas. Several researchers have proposed decision-making tools for DfAM[42,43,124]; however, there is a need to investigate how the use of these tools influences designers' learning and future use of DfAM, especially in their decision-making. Therefore, future research must investigate the use of DfAM knowledge beyond concept generation. Such an investigation will facilitate the development of educational tools as well as design tools that could assist designers to select more AM appropriate designs. Furthermore, since designers' concept selection decisions are influenced by their risk-taking tendencies, future research must explore this effect in DfAM tasks. Such an investigation could assist in the development of design and educational tools that ''derisk'' AM processes by informing designers about the capabilities of these processes.

Second, the implementation of conceptual ideas into final solutions depends on designers' ability to successfully use CAD, and this need for CAD expertise is particularly highlighted in the ''digital thread'' of design and manufacturing used in AM.[125] In the studies discussed in this article, we only focused on junior mechanical engineering students who have more engineering and CAD expertise compared with freshmen, but have much lesser experience compared with experienced designers and industry practitioners. Although we attempt to extend our findings to industry practitioners,[92] future research must further investigate the effect of prior engineering and CAD experience on both designers' performance in the task-based intervention and their future efforts toward learning and using DfAM. Such an investigation will also help identify the appropriate timing of DfAM educational interventions, such that students can appropriately apply the DfAM concepts into designing and executing solutions.

Third, we used a short DfAM presentation to introduce the various DfAM concepts to the students. Although such lecture-based interventions have been demonstrated to be effective for DfAM education,[76] these short-duration interventions rely on students' ability to successfully memorize and recall the various DfAM concepts at appropriate stages in the design process. As observed in the Generalized Experimental Methods Used to Test the Variations in the Educational Intervention section, students' recall of O-DfAM could be influenced by their prior knowledge and exposure to a partial set of information, for example, R-DfAM. Therefore, future research must work toward extending our findings toward the development of longer educational interventions comprising multiple presentation sessions and design tasks. Such interventions should also incorporate multiple design tasks specifically developed to engage students in applying the various DfAM concepts. Furthermore, future research must investigate the integration of design tools such as design heuristics[24] and design principle cards[25,26] as a medium to provide external cues to students and identify the appropriate stages at which these cues must be introduced.

Finally, the studies conducted as part of this work tested the effects of the four factors in isolation. Although the interaction between the contents of DfAM education was tested with the task complexity and competitive structure, future work must extend this work toward a full-factorial design of experiments. Such work must test the interactions between the various factors to provide more granular recommendations for the formulation of DfAM educational interventions. Specifically, such an investigation would require a $4 \times 2 \times 2$ design with the first factor being the DfAM content presented (R, O, dual-OR, and dual-RO), the second factor being the design task definition (simple and complex), and the third factor being the task competitive structure (competitive and noncompetitive).

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