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TEACHING DESIGN FREEDOM: EXPLORING THE EFFECTS OF DESIGN FOR ADDITIVE MANUFACTURING EDUCATION ON THE COGNITIVE COMPONENTS OF STUDENTS' CREATIVITY

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ABSTRACT
Design for manufacturing provides engineers with a structure for accommodating the limitations of traditional manufacturing processes. However, little emphasis is typically given to the capabilities of processes that enable novel design geometries, which are often a point of focus when designing products to be made with additive manufacturing (AM) technologies. In addition, limited research has been conducted to understand how knowledge of both the capabilities (i.e., opportunistic) and limitations (i.e., restrictive aspects) of AM affects design outcomes. This study aims to address this gap by investigating the effect of no, restrictive, and both, opportunistic and restrictive (dual) design for additive manufacturing (DfAM) education on engineering students' creative process. Based on the componential model of creativity [1]*, these effects were measured through changes in (1) motivation and interest in AM, (2) DfAM self-efficacy, and (3) the emphasis given to DfAM in the design process. These metrics were chosen as they represent the cognitive components of 'task-motivation' and 'domain relevant skills', which in turn influence the learning and usage of domain knowledge in creative production. The results of the study show that while the short (45 minute) DfAM intervention did not significantly change student motivation and interest towards AM, students showed high levels of motivation and interest towards AM, before the intervention. Teaching students different aspects of DfAM also resulted in an increase in their self-efficacy in the respective topics. However, despite showing a greater increase in self-efficacy in their respective areas of training, the students did not show differences in the emphasis they gave to these DfAM concepts, in the design process. Further, students from all three education groups showed higher use of restrictive concepts, in comparison to opportunistic DfAM.*

Keywords: Design for Additive Manufacturing, Creativity, Education

INTRODUCTION
Additive manufacturing (AM) is one of the largest disruptors in engineering industry [2], as it has eliminated many of the constraints associated with traditional manufacturing processes [3]. AM processes, first conceived as a method for solid freeform fabrication using layer-based techniques, arose from the vision of being able to 'print' parts with the push of a button on a computer [4]. Built on this vision of being able to print any form designed using computer-aided drawing (CAD) techniques, AM processes have given designers the freedom and opportunity to push the limits of their design concepts, shapes, and structures. The increasing availability and access to AM processes has started to influence engineering design, with a growing need for awareness of the characteristics of the different AM processes [5]. These characteristics include both the capabilities as well as limitations of AM, which form the basis for opportunistic and restrictive design considerations, respectively [6]. Several industries (e.g., aerospace and medical) have even demonstrated the functional applications of AM [7].

Despite the accelerating progress of engineering research in AM, the current lack of education in AM is a potential barrier [8], especially the lack of teaching design methodologies for integrating AM [9]. While several efforts have been made to introduce design for additive manufacturing (DfAM) into the engineering design curriculum [10–12], limited research has been done to investigate its effect on the design process, specifically design creativity that leverages the design freedoms afforded by the different AM processes. This is of particular importance, given that knowledge of manufacturing processes is considered to be a crucial domain-relevant skill in engineering design [13]. The importance of manufacturing in design is also highlighted as industries often enforce the use of a concurrent design approach, integrating manufacturing considerations early in the design process [14]. While traditional design for manufacturing and assembly (DfMA) considerations increase the feasibility of manufacturing a given design [15,16], the limitations of traditional manufacturing processes often restrict one's design freedom. This is particularly seen in the case of AM, where one of the important capabilities of the process is that it provides complexity, "free of charge" [17]. A failure to emphasize on these capabilities could result in the under-utilization of AM processes, thus limiting the creativity of the design outcomes. This could possibly affect both, the *novelty*, as well as *usefulness* of the designs, both of which are strong determinants of design creativity [18].

Therefore, the aim of this study is to systematically investigate how exposing engineering students to different aspects of DfAM affects the cognitive components of their creative process. These effects were measured by investigating changes in motivation and interest towards AM, self-efficacy in DfAM, and self-evaluated emphasis on DfAM concepts during the design process. These metrics were selected as they represent the cognitive components of 'task motivation' and 'domain-relevant skills', both of which influence the learning and usage of domain knowledge in creative production [1]. The study compares three treatments: (1) teaching no DfAM, (2) teaching traditional limitation-based restrictive DfAM, and (3) teaching a combination of opportunistic and restrictive DfAM (dual DfAM).

RELATED WORK

To investigate the effects of DfAM on the design process of undergraduate engineering students, we surveyed the existing literature related to DfAM education, the importance of domain-relevant skills, and the role of motivation on design creativity.

Need for Design for Additive Manufacturing Education

The constantly accelerating research in modern manufacturing processes has resulted in the widespread use of DfMA [15]. Over time, engineering and product design processes have moved from an 'over-the-wall' sequential process [19] towards an integrated, concurrent design process [14]. The main aim of DfMA techniques is to account for manufacturing processes and their effects on the product early in the design process [15]. While an integrated manufacturing process has resulted in more feasible designs [16], these techniques predominantly emphasize the limitations of traditional manufacturing processes, such as using standardized components with simple geometries, for ease of manufacturing and assembly [15]. While these principles help in ensuring manufacturability, they also reduce the available design space.

AM processes are accompanied by manufacturing limitations, such as material anisotropy [20,21], surface roughness [22,23], feature size and accuracy [24,25], and the need for support structures [26]. Despite these limitations, AM also provides designers with several previously-unimaginable opportunities such as high levels of geometric complexity [27–29], the ability to print assemblies [30], part consolidation [31], and mass customization [32]. In order to fully utilize the design potential of AM processes, there needs to be a shift from the limitation-based DfMA approach to a more mixed emphasis on both a system's capabilities and limitations. For example, in the 2013 NSF workshop on AM, the understanding that "complexity is free" in AM was identified as one of the important qualities of an ideal AM engineer [33]. This change in design thinking for AM has resulted in the emergence of two spheres of DfAM: (1) opportunistic DfAM, which focuses on AM capabilities, and (2) restrictive DfAM, which focuses on AM limitations [6]. An overarching dual DfAM approach, employing both opportunistic and restrictive DfAM has also been suggested [34].

As AM processes become more accessible and improve in quality, there is an increasing demand for practitioners with the relevant AM skills [35]. To address this demand, educational institutions are working to integrate AM in their curriculum through formal and informal education approaches [9,33]. Focusing on the importance of inductive learning in engineering [36,37], the University of Texas at Austin and Virginia Tech both offer a problem-based and project-based course which includes significant elements of DfAM [10]. Further employing project-based learning, Williams et al. [38] conducted a university-wide competition on designing a 3D printed vehicle and demonstrated the successful learning outcomes that can be derived from such an approach. On the other hand, to encourage informal and self-learning, initiatives have also been taken to make 3D printing facilities more easily accessible to the students. Some of these efforts include "3D printing vending machines" [39] and the establishment of 3D printing focused Maker Spaces [33,40,41]. These facilities attempt to tap into the use of rapid prototyping to build proficiency in DfAM, as suggested by Bøhn [11].

While integrating DfAM into the engineering curriculum is an important step towards the adoption of AM processes, these attempts can be successful if and only if a student is able to use relevant DfAM concepts during their design process. However, limited research has been conducted on the effect of variations in DfAM education on students' design processes, specifically their design outcomes. This study seeks to fill this research void.

Influence of Domain Relevant Skills on Creativity

Creativity is proving to be an important assessment metric for evaluating design educational techniques, as creativity and innovation go hand-in-hand [42], and for any company to be successful, it has to be innovative [43]. Creativity can be described as a combination of three cognitive components: (1) task motivation, (2) domain-relevant skills, and (3) creativity-relevant skills [1]. Domain-relevant skills include the learning, organization, and retention of domain-relevant knowledge [1], which in this study, is knowledge of AM and DfAM.

Amabile describes domain-relevant skills as the combination of two components: (1) the collection of possible solutions from which a new solution is generated, and (2) the pool of information used to assess the new solutions [1]. These skills are in effect in two stages. The first stage is the preparation stage when the designer is preparing a pool of possible outcomes before generating solutions. The second stage is the validation stage when the designer uses factual knowledge to validate the outcomes. As described by Wallas [44], prior knowledge has a strong influence on the preparation stage, where the thinker collects all the information that could be needed for solution generation. Further, Newell and Simon's concept of problem spaces specifically describes the organization of this information to be determined ease of access and the type of information [45]. Therefore, when studying the effects of education on student creativity, it is important to evaluate the learning and application of the concepts taught through the educational intervention.

Self-efficacy - a representation of the development of meta-cognition, has been demonstrated to correlate with learning [46]. Self-efficacy can be described as a measure of response initiation, the effort spent on the generation of the response, and the duration of the response [47]. In addition to the correlation of self-efficacy with learning in general, this concept has also been shown to correlate with one's ability in engineering design [48], computer science [49,50], and sports [51,52], thus reinforcing the use of self-efficacy as a substitute for measuring learning.

When designing parts for fabrication with AM, domain-specific skills include knowledge about the capabilities and limitations of the process. In the preparation phase of creative production, knowledge of opportunistic AM concepts could work towards increasing the available design space. Conversely, in the validation phase, knowledge about the constraints of the process could help prevent failure of the design [53]. Therefore, in order to identify a student's grasp of DfAM relevant skill, the current study employs a DfAM self-efficacy scale comprising both opportunistic and restrictive concepts (see the ***DfAM Self Efficacy*** subsection). This scale helps understand change in the students' learning of these concepts brought on by the intervention.

Role of Motivation and Interest on Design Creativity

While domain-relevant skills contribute towards preparation and validation of creative responses, the learning of these skills is governed by the motivation towards the task. In the componential model for creativity, Amabile [1] describes 'task motivation' to be a combination of two aspects: the trait – the person's attitude, and the state – the reasoning behind being involved in the task. The nature of creative task motivation is described to be predominantly intrinsic and not influenced by external factors (extrinsic). As Rogers describes in [54], the emergence of creativity is strongly driven by people's tendency to realize their potential. This hints towards the need for high intrinsic motivation to bring about creative production. Theorists have also emphasized that freedom from external evaluation is necessary for creativity so the creative process is task-driven, rather than towards an ulterior goal, which typically results in conformity [54,55]. Research has also shown that motivation influences a person's ability to control attention [56], which has, in turn, has shown a relation to creativity [57]. Thus, the main role of intrinsic motivation is to shift an individual's undivided attention towards the creative task and away from the environment.

As described by Bandura, development of self-efficacy and intrinsic interest are influenced by an individual's levels of self-motivation [58]. This research has also been extended towards creative processes, where an increase in self-perceptions of internal and external creative expectations have shown to increase creative self-efficacy [59]. This was further supported by the demonstrated use of creative self-efficacy, in predicting creative performance and success [60–62]. This research, therefore, shows that students' self-perceived motivation and interest can be a strong determinant of their creative outcomes.

Therefore, when investigating the impact of DfAM interventions on creativity, it is important to understand the effect it has on the students' motivation towards learning and using AM. This understanding will provide researchers with insight into the expected creative outcome from the task. At the same time, the students' motivation levels will also act as an indicator of the expected learning of DfAM knowledge.

RESEARCH QUESTIONS

Based on the current state of literature, this study aims to evaluate the effect of variations in DfAM education on the components of students' creativity. To do this, we seek to answer the following research questions:

RQ1: Do variations in DfAM education content impact students' motivation and interest towards future AM learning opportunities? Our hypothesis is that exposure to AM opportunities motivates students more than restrictive concepts, due to the design freedom provided by these concepts. This hypothesis is based on research, where a constraint-free environment has shown to promote constructivist learning and greater student motivation[63,64].

RQ2: Do variations in DfAM education content impact student comfort in integrating DfAM concepts in their design process? We hypothesize that exposure to opportunistic and restrictive DfAM results in an increase in the students' self-efficacy in integrating these concepts in the design process. This hypothesis is based on previous research where self-efficacy has been shown to correlate with student learning [65].

RQ3: Do variation in DfAM education content change how students use DfAM concepts in their design process? We hypothesize that the retention and application of the restrictive DfAM concepts is easier compared to opportunistic concepts due to their similarity with traditional DFMA concepts and their widespread use in informal AM experiences [3,66,67].

METHODOLOGY

To investigate the effects of variations in DfAM education on the students' creative process, an experiment was conducted employing a short-term intervention in the form of a lecture and a design challenges. The design challenges were conducted as a part of the larger study, and only the portions of the experiment relevant to the study are discussed in detail.

Participants

The experiment was conducted with a total of 159 engineering students from a large northeastern university. The participants were recruited from a junior-level Mechanical Engineering course focused on Mechanical Engineering Design Methodology. The experiment was conducted in the middle of the fall semester, in the 10th week of the academic calendar.

A majority of the participants were undergraduate students in the Mechanical Engineering major (N=158) with an exception being Nuclear Engineering (N=1). Among these, some participants were working towards double majors including Bio-medical Engineering (N=5), Nuclear Engineering (N=3), Mathematics, Economics, and German (N=1 each). The participants consisted of sophomores (N=1), juniors (N=74), seniors (N=73), as well as a few students in the fifth year of their study (N=3).

At the start of the study, participants were first asked to rate their previous experience in AM, and DfAM, on a scale of 1 = 'never heard of it', to 5 = 'expert in it'. A summary of their previous experience is shown in Figure 1. As seen in the figure, while a large group of participants had received some formal or informal training on Additive Manufacturing, a much smaller portion had received any formal training in Design for Additive Manufacturing. On average, the participants had 1.4 years of AM experience (±1.35), and 0.8 years of DfAM experience (±1.22).

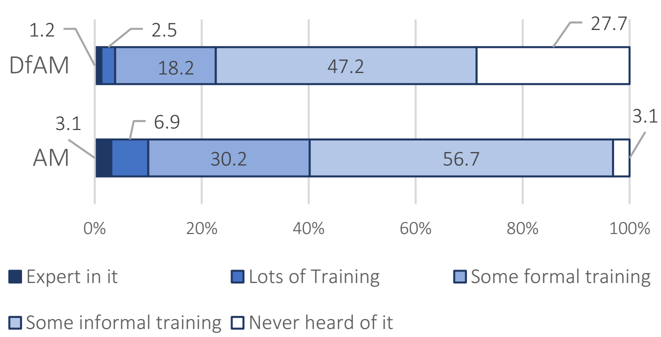

Figure 1 Distribution of participants' previous experience

Procedure

Since participants were students from a specific course, the experiment was structured around the available class hours, which consisted of two seventy-five (75) minute lectures on Monday (Day 1) and Wednesday (Day 2) of the same week. Before beginning the experiment implied consent was obtained from the students, following IRB protocol. The students were informed that while the use of their data was completely voluntary, student participation in the activity was counted towards their in-class participation points since the experimentation was conducted during the regular class periods and included content relevant to the course. The experiment was conducted in three parts: (1) a pre-survey and design challenge, (2) DfAM lectures (the educational intervention under investigation), and (3) a post-survey and design challenge.

As a part of the pre-survey, participants were asked to answer questions describing their previous experience in AM, and DfAM. The pre-survey also contained self-efficacy sections reporting their comfort with a set of DfAM techniques and a rating for their interest and motivation in learning about and using AM. The pre-survey was also used to randomly assign the participants into three groups. The prior experience and self-efficacy survey can be accessed at http://sites.psu.edu/madebydesign/design-cognition/.

Following the pre-survey, participants were asked to participate in a 10-minute design challenge. The design prompt was chosen such that minimal domain-knowledge, apart from AM knowledge, was needed to complete the challenge. The design challenge was conducted as part of a larger study and is not relevant to this paper.

Upon completing the design challenge, the educational intervention was introduced in the form of lectures on different aspects of AM and DfAM. First, all participants were given a 10-minute overview lecture about the overall concept of AM, with specific elements tailored to the material extrusion process type. The discussion included topics such as the distinction from subtractive manufacturing, the concept of the digital thread, Cartesian coordinates, and available printable materials.

Following this overview, the first group of students (N=52) was asked to leave the lecture hall. This group formed the control group, as they received no DfAM education. The remaining students were then given a 20-minute lecture on the *restrictive* aspects of DfAM. The topics of discussion were: build time, feature size, support material, anisotropy, surface finish, and warping. Following this, the second group of students (N=52) was asked to leave the lecture hall. Finally, the remaining students (N=55) were given a lecture on the *opportunistic* aspects of DfAM. This discussion included geometric complexity, mass customization, part consolidation, printed assemblies, multi-material printing, and functional embedding. In order to ensure that all three groups of students felt equally engaged, the students asked to leave early were led in a further discussion about 'making' and the various maker-spaces available on campus [68], with no additional inputs given on AM or DfAM. All three parts of the lecture were recorded and made available to all the students after the experiment was completed. The slides used in the lectures can be accessed at http://sites.psu.edu/madebydesign/design-cognition/.

On Day 2, students were asked to participate in a design challenge with a modified version of the problem statement from the pre-design activity so as to avoid design fixation while still being able to observe differences [1,69]. Following the concept generation and selection, they were asked to rate how much emphasis they gave to a list of DfAM techniques (both restrictive and opportunistic) in their design process, on a scale of 1= 'not important at all' to 5= 'absolutely essential.' At the end of the design challenge, students were asked to complete a post-survey with questions about their comfort with the different DfAM techniques covered during the educational intervention, similar to the pre-survey.

Metrics

The following metrics were used to evaluate the effect of the DfAM educational intervention on the components of creativity, specifically Motivation and Interest, DfAM self-efficacy, and the emphasis the students gave to the various DfAM concepts.

Motivation and Interest

In order to measure student interest and motivation before and after the intervention, the participants were asked to report their agreement to two statements on a 5-point Likert scale from 1= 'Strongly Disagree' and 5= 'Strongly Agree.' The two statements were:

1. I am interested in learning about and using Additive Manufacturing
2. I am motivated to learn about and use Additive Manufacturing.

Responses to these statements were collected in the pre-survey, before the intervention, and then in the post-survey, after the design challenge was completed.

DfAM Self Efficacy

Previous research has determined the validity of self-efficacy as a tool for measuring academic outcomes [65]. Therefore, in order to measure the students' learning of DfAM knowledge, a self-efficacy scale was developed, combining design considerations from both, opportunistic and restrictive DfAM [6]. Restrictive principles included were: (1) support structures [26], (2) warping due to thermal stresses [25], (3) anisotropy [20,21], (4) surface roughness due to stair-stepping [23,70], and (5) feature size and accuracy [24]. Similarly, opportunistic DfAM principles chosen were (1) mass customization [32], (2) part consolidation [71] and printed assemblies [30], (3) free shape complexity [29,72,73], (4) multiple materials [74], and (5) embedding external components [75]. The items included in the self-efficacy survey are summarized in Table 1. The complete survey can be accessed at http://sites.psu.edu/madebydesign/design-cognition/.

These design principles were then grouped together based on two categories: opportunistic and restrictive. Items 1 to 5, which focus on utilizing AM capabilities, were grouped as opportunistic, and a mean opportunistic comfort score was obtained. Similarly, items 6-10, which focus on accounting for the limitations of AM processes, were grouped as restrictive, and a mean restrictive comfort score was calculated. Overall, the scale showed a high level of internal consistency to predict DfAM self-efficacy, as determined by a Cronbach's alpha [76] (pre-DfAM α = 0.897, post-DfAM α = 0.875). Further, the individual scales for both opportunistic and restrictive also had a high level of internal consistency as determined by a Cronbach's alpha (opportunistic: pre-DfAM α = 0.858, post-DfAM α = 0.801 and restrictive: pre-DfAM α = 0.820, post-DfAM α = 0.833).

The students' self-efficacy was evaluated on a 5-point scale (see Table 2). This scale helped us capture not just their understanding of the concept (ability to explain), but also their comfort in using it in the design process. The scale was developed based on levels in the cognitive domain of Bloom's Taxonomy, specifically, remembering, comprehending, and applying [77].

Table 1 DfAM principles used in self-efficacy survey

1	Making products that can be customized for each different user
2	Combining multiple parts into a single product or assembly
3	Designing parts with complex shapes and geometries
4	Embedding components such as circuits in parts
5	Designing products that use multiple materials in a single part or component
6	Using support structures for overhanging sections of a part
7	Designing parts to prevent them from warping and losing shape
8	Designing parts that have different material properties (e.g. strength) in different directions
9	Accommodating desired surface roughness in the parts
10	Accommodating for min and max feature size permitted by a process

Table 2 Scale 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

Emphasis on DfAM concepts.

A self-reported scale similar to the DfAM self-efficacy scale was developed to measure the emphasis given by the participants on the different DfAM concepts during their design challenge. The individual statements from the self-efficacy scale were modified to focus on the product, instead of the concept itself. For example, Statement #1 from Table 1 was modified to "the product can be customized for each different user". The participants were asked to rate the importance given to each technique on a 5-point Likert scale, with 1= 'Not important at all,' to 5= 'absolutely essential.' The scores for design concepts 1-5 were averaged to obtain a final opportunistic Emphasis Score. Similarly, concepts 6-10 were averaged to obtain a final restrictive Emphasis Score.

DATA ANALYSIS AND RESULTS

Before seeking results to the individual research questions, the descriptive statistics for each metric were obtained (Figure 2). First, an outlier analysis was performed, and outliers were treated by replacing them with the next closest values [78]. After accounting for missing values and outliers, a sample size of 140 was used for subsequent analysis. Out of a total of 140 participants, 49 participants received no DfAM intervention, 42

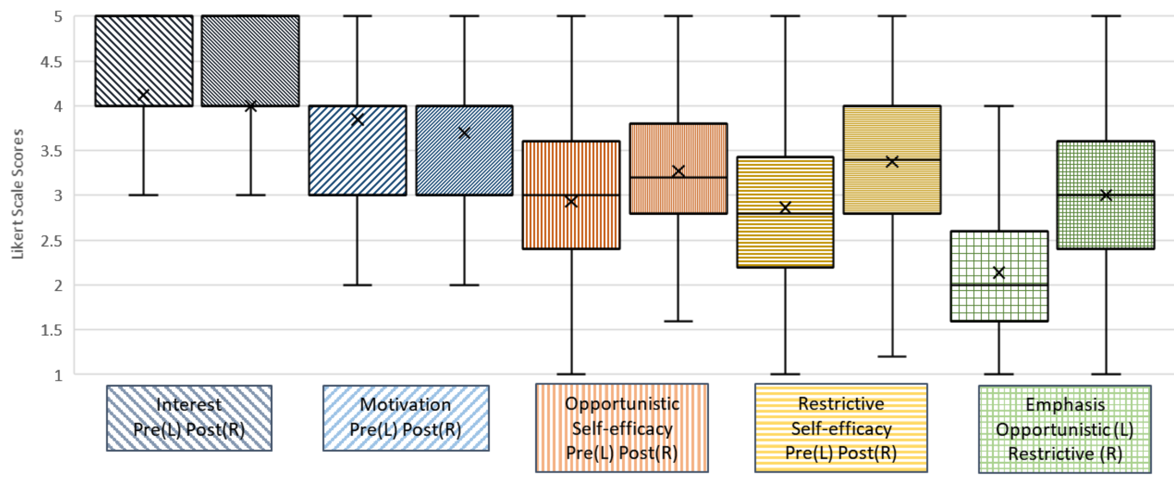

Figure 2 Descriptive Statistics of Metrics

participants received the restrictive DfAM intervention, and 49 participants received both the restrictive and opportunistic DfAM interventions. SPSS V. 25 software was used for all analysis, and a significance level of 0.05 was taken to be statistically significant. For all results, χ^2 = chi-square, p = statistical significance, and z = standardized test statistic, unless otherwise reported.

RQ1: Do variations in DfAM education content impact students' motivation and interest towards future AM learning opportunities?

This section describes the results that quantify the change in interest and motivation from before and after the DfAM educational intervention. A Generalized Estimation Equation was used to understand whether or not the content of DfAM education received by the students could predict the students' change in interest and motivation before and after the intervention. A Wilcoxon Signed Rank Sum test [79] was used to check for the difference from before and after the intervention.

Change in interest in using AM:

A Generalized Estimation Equation was generated with DfAM education group as the predictor, interest as the test field, and time as the within-subjects variable. The test reported no significant effect of the education group ($\chi^2(2) = 0.614$, $p = 0.736$). This result shows that teaching different aspects of DfAM does not appear to have a different effect on the students' interest levels. This refutes our initial hypothesis that teaching students about opportunistic DfAM would lead to an increase in their interest in learning about and using DfAM. A Wilcoxon Signed Rank Sum test was performed to check the difference in interest before and after participating in the intervention. The results are shown in Figure 3 with no DfAM: $z = -2.665$, $p = 0.008$, restrictive DfAM: $z = -0.688$, $p = 0.491$, and dual DfAM: $z = 0.296$, $p = 0.767$.

This lack of change in interest could be attributed to the higher interest levels reported by the students before the intervention was conducted. To validate this, a Wilcoxon Signed Rank test was performed for initial interest level for each group, against a hypothesized median of 3. All three groups showed a significantly higher median interest of 4: no DfAM ($z = 5.720$, $p < 0.001$), restrictive DfAM ($z = 4.731$, $p < 0.001$), and dual DfAM ($z = 5.570$, $p < 0.001$).

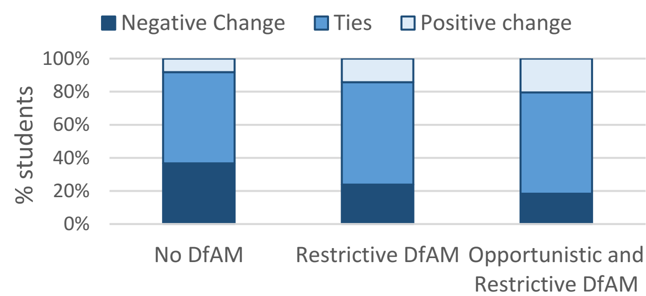

Figure 3 Change in Interest

However, the number of students who showed a decrease in interest was almost twice as high in the control group in comparison to the groups that received DfAM education. This goes to show that teaching DfAM, succeeds in maintaining the students' interest in AM, if not increase it. Another possible explanation for the decrease in interest in the control group could be the general frustration due to the experiment setup. Since the control group was asked to leave early on in the lecture, the students possibly felt that the lecture did not teach anything new compared to what they already knew.

Change in motivation in using AM:

A Generalized Estimation Equation was generated to understand the influence of variations in DfAM education on the change in motivation before and after the intervention. Motivation was used as the test field, time as the within-subjects variable, and DfAM education group as the predictor. The test reported no significant effect of the DfAM education group ($\chi^2(2) = 0.327$, $p = 0.849$) on their motivation levels. This result shows that teaching different aspects of DfAM fails to predict any changes in the students' motivation levels. This result also refutes our hypothesis that exposure to opportunistic DfAM would result in an increase in the students' motivation towards using AM. Further, as summarized in Figure 4, a Wilcoxon Signed Rank Sum test showed no significant change in motivation for any group before and after the intervention, no DfAM: $z = -1.826$, $p = 0.068$, restrictive DfAM: $z = -1.091$, $p = 0.275$, and dual DfAM: $z = -0.544$, $p = 0.586$.

A possible explanation for this result is that the students had a relatively high level of motivation before participating in the intervention. To verify this, a Wilcoxon Signed Rank test was performed for each group, in comparison to a hypothesized median of 3. All three groups showed a significantly higher median of 4 compared to the hypothesized median: no DfAM ($z = 4.838$, $p < 0.001$), restrictive DfAM ($z = 4.847$, $p < 0.001$), and dual DfAM ($z = 4.015$, $p < 0.001$).

Although the results were not significant, an important observation seen in Figure 4 was that introducing more DfAM concepts results in more students reporting an increase in motivation, and fewer students reporting a decrease. In addition, the number of students reporting no change is nearly the same in all groups. At the same time, it should also be noted that teaching opportunistic DfAM results in a relatively higher number of students to reporting increase.

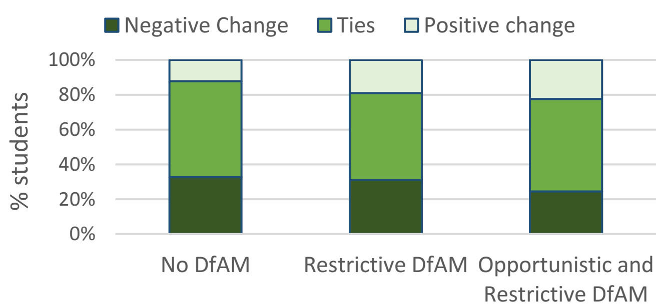

Figure 4 Change in Motivation

Overall, we can see that the participants show a high level of motivation and interest in AM before participating in the intervention. As a result, the intervention fails to bring about any significant change in their attitudes. However, it is worth noting from the summary charts in Figure 3 and Figure 4, that introduction of restrictive and opportunistic DfAM has a relatively lower percentage of students showing a negative change, and a relatively higher number of students showing a positive change, in both interest and motivation.

RQ2: Do variations in DfAM education content impact student use of concepts in their design process?

The second research question investigates the student-perceived acquisition of domain-relevant skills as it relates to DfAM. In order to achieve this, a Wilcoxon signed-rank sum test [79] was used to understand the change in comfort for each group (G1: No DfAM, G2: restrictive, G3: opportunistic and restrictive). A Generalized Estimation Equation was then used to understand if these differences were related to the different DfAM concepts introduced. Since DfAM self-efficacy could be influenced by the participants' previous experience, previous AM (*AMexp*) and DfAM experience *(DfAMexp)* were also included as factors in the model.

Comfort in integrating Opportunistic DfAM:

A Wilcoxon Signed Rank Sum test showed that all three groups showed a significant increase in their comfort in opportunistic DfAM concepts, with no DfAM: z=2.352, p=0.019, restrictive DfAM: z=1.842, p=0.066, and dual DfAM: z=0.3769, $p < 0.001$. However, the group that received training in opportunistic DfAM showed the highest median increase of 0.400, compared to the other two groups with 0.200. The results also showed that the percentage of students showing an increase was highest in the group that received opportunistic training, as summarized in Figure 5. The increase in comfort among students from no DfAM and restrictive DfAM groups could be attributed to the use of lattice structures and complex geometries as examples in the AM overview lecture. The slides contained examples such as Cortex casts [80] and the Renishaw cranial implant [81] to demonstrate the use of AM to manufacture both prototypes as well as functional parts.

In order to further investigate the influence of exposure to different DfAM concepts on the change in opportunistic comfort, a Generalized Estimating Equation was set up. DfAM education group, previous AM experience, and previous DfAM experience were used as predictors. The test reported significant main effects of the DfAM education group ($\chi^2(2) = 10.240$, $p = 0.006$) and previous AM experience ($\chi^2(4) = 163.495$, $p < 0.001$). The results also showed a significant interaction effect of group and AM experience ($\chi^2(7) = 111.111$, $p < 0.001$). After reducing the model to include only significant components, the individual parameter estimates were obtained, and significant parameter estimates are summarized in Table 3. The parameter estimates from the results show the dependence of the students' opportunistic self-efficacy, at each level of the independent variables.

Table 3 Parameter estimates for Opportunistic self-efficacy

Parameter	*β*	*Std. Error*	χ^2	*Sig.*
Intercept	4.100	0.2121	373.556	<0.001
Group = 1	-0.600	0.2121	8.000	0.005
Group = 2	0.500	0.2121	5.556	0.018
Group = 3	0	-	-	-
AM exp = 1	-1.100	0.2121	26.889	<0.001
AM exp = 2	-1.107	0.2437	20.632	<0.001
AM exp = 3	-1.036	0.2592	15.984	<0.001
AM exp = 4	0.117	0.3483	0.112	0.738
AM exp = 5	0	-	-	-
*G=2*AMexp=2*	-0.653	0.2733	5.708	0.017
*G=1*AMexp=3*	0.757	0.2810	7.264	0.007
*G=2*AMexp=4*	0.3554	-1.513	5.279	0.022
(Only statistically significant estimates reported)				

As seen from the parameter estimates, while previous AM experience is a significant predictor of constant change in opportunistic comfort ($\beta \approx -1.1$), this is only true for students with low levels of previous experience (*AMexp* < *4*). A deviation is seen in students with high AM experience, where β = 0.117 for *AMexp* = 4. This suggests that while teaching DfAM, it is important for educators to account for the students' previous AM experience. By having an understanding of the students' prior experience in AM, DfAM educators can try to mould the students' preconceived ideas about AM, and particularly emphasize the application of opportunistic DfAM. It also shows that students with lower previous AM experience have a greater potential for learning DfAM concepts.

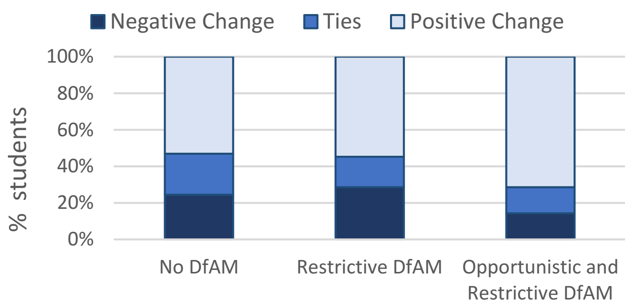

Figure 5 Change in Opportunistic Self-efficacy

Comfort in integrating Restrictive DfAM:

A similar result was observed in the change in restrictive comfort, before and after the intervention. A Wilcoxon Signed Rank Sum test showed a significant difference in *distribution* for all three groups, with no DfAM: z = 2.113, p = 0.035, restrictive DfAM: z = 4.058, p < 0.001, and dual DfAM: z = 4.282, p < 0.001. However, only groups that received restrictive DfAM education showed a median increase in their restrictive self-efficacy (restrictive DfAM: 0.800 and dual DfAM: 0.400), with the control group showing no median increase (*Mdn*: 0.000). Also, as seen in Figure 6, groups that received education in restrictive DfAM, have a higher percentage of students reporting a positive change. Therefore, results suggest that teaching restrictive DfAM causes an increase in the self-efficacy among the students who receive this concept during DFAM training.

To further understand the influence of teaching different DfAM concepts on this increase in comfort, a Generalized Estimation Equation was generated. Intervention Group, Previous AM experience, and Previous DfAM experience were used as predictors. The test reported significant main effects of the DfAM education group ($\chi^2(2)$ = 32.872, p < 0.001), Previous AM experience ($\chi^2(4)$ = 57.575, p < 0.001), and Previous DfAM experience ($\chi^2(4)$ = 24.092, p < 0.001). The results also showed a significant interaction effect of education group and AM experience ($\chi^2(7)$ = 29.629, p < 0.001). The significant parameter estimates are summarized in Table 4. These estimates represent the level of dependence of the students' restrictive self-efficacy on the different independent variable.

As seen from the parameter estimates, previous AM experience predicts a constant change in restrictive self-efficacy ($\beta \approx$ -1.5) for students with low levels of previous experience *(AMexp < 4)* and a deviation is seen in students with high AM experience. Further, a significant interaction effect of previous AM experience is seen in all three education groups for students with high previous experience *(AMexp ≥ 4)*, and the interaction is not significant for students with low AM experience. This result suggests that the students' previous AM experience interferes with their potential for learning restrictive DfAM concepts. Particularly, we see that teaching restrictive DfAM to students with high levels of previous AM experience fails to bring about a significant increase in their self-efficacy with these concepts. This also further suggests that the students' prior experience in AM could have mainly resulted in the acquisition of restrictive knowledge.

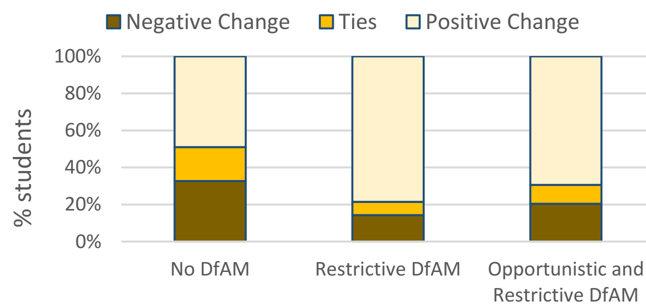

Figure 6 Change in Restrictive Self-efficacy

Table 4 Parameter Estimates for Restrictive Self-efficacy

Parameter	β	*Std. Error*	χ^2	*Sig.*
Intercept	3.400	1.2402E-07	7.5E+14	<0.001
Group = 1	-0.700	2.1035E-07	1.1E+13	<0.001
Group = 2	0.586	0.2460	5.675	0.017
Group = 3	0	-	-	-
AMexp = 1	-1.573	0.5164	9.275	0.002
AMexp = 2	-1.711	0.5051	11.468	0.001
AMexp = 3	-1.474	0.5143	8.218	0.004
AMexp = 4	-0.367	0.1905	3.704	0.054
AMexp = 5	0	-	-	-
DfAMexp = 1	1.173	0.5164	5.157	0.023
DfAMexp = 2	1.310	0.5164	6.437	0.011
DfAMexp = 3	1.514	0.4630	10.689	0.001
DfAMexp = 4	1.400	2.7984E-07	2.5E+14	<0.001
DfAMexp = 5	0	-	-	-
*G=1*AMexp=4*	-1.033	0.1905	29.418	<0.001
*G=2*AMexp=4*	-0.515	0.2526	4.160	0.041
*G=3*AMexp=4*	0	-	-	-

(Only statistically significant estimates reported)

Results show that the intervention succeeds in bringing about a greater increase in opportunistic and restrictive self-efficacy, in the groups that receive the respective training. At the same time, the results highlight the need for DfAM educators to understand students' previous AM experience, as this can influence their potential learning of DfAM concepts. This is particularly important among students with high levels of previous AM experience, who show a relatively lower potential for learning DfAM concepts. Further, an understanding of the students' AM experiences will enable educators to build upon and, if necessary, challenge their existing knowledge of AM. This need is further reinforced by the constant interaction between the *high levels of students' previous experience with the DfAM education group in the case of restrictive self-efficacy.*

RQ3: Do variation in DfAM education content change how students use concepts in their design process?

The third research question was developed to understand if self-efficacy increases reported by the participants in Research Question 2 are translated into a greater ability to apply the design concepts in their design process. A Kruskal-Wallis H test [82] was performed to understand the differences in distributions of opportunistic and restrictive Emphasis between the three groups.

Emphasis on Opportunistic DfAM:

A Kruskal-Wallis H test was run to determine if there were differences in self-reported Emphasis on *opportunistic DfAM* concepts between the three groups of participants with no controlled exposure to DfAM, restrictive DfAM, and dual DfAM. Distributions of opportunistic emphasis scores were similar for all groups, as assessed by visual inspection of a boxplot, shown in Figure 7. Median emphasis scores for participants with no DfAM (2.20), and both restrictive and opportunistic (2.20) was higher than those with only restrictive exposure (2.00). However, the differences were not statistically significant between groups, $\chi^2(139) = 0.033, p = 0.984$. This shows that despite showing an increase in their comfort with opportunistic DfAM, the group that received opportunistic and restrictive DfAM training did not emphasize these concepts more than the other groups. The short duration of the design challenge could possibly have resulted in the students not having enough time to think about and incorporating the DfAM considerations into their designs.

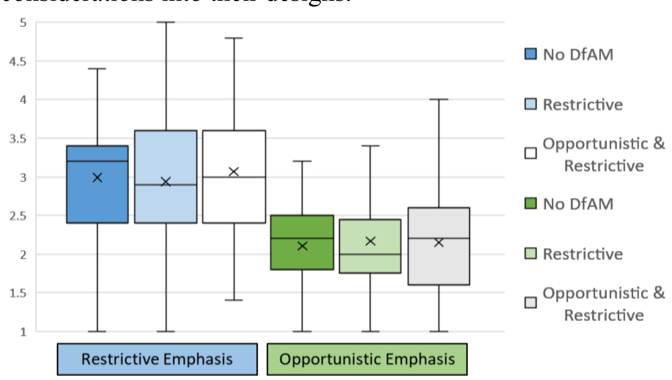

Figure 7 Summary of DfAM emphasis in design process

Emphasis on Restrictive DfAM:

A Kruskal-Wallis H test was also run to determine if there were differences in self-reported Emphasis on *restrictive DfAM* concepts between the three groups of participants with exposure to no DfAM, restrictive DfAM, and both, opportunistic and restrictive DfAM. Distributions of restrictive emphasis scores were similar for all groups, as assessed by visual inspection of a boxplot, shown in Figure 7. Median emphasis scores were higher for participants with no DfAM (3.20), and both, opportunistic and restrictive DfAM (3.00), compared to those with only restrictive DfAM exposure (2.80) However, the differences were not statistically significantly different between groups, $\chi^2(139) = 0.642$, $p = 0.725$. This result shows that students from all three groups give similar and moderate emphasis on restrictive DfAM concepts, and teaching different DfAM concepts does not have an effect on their use of these concepts. This result further reinforces the hypothesis that the time given to the students to design their solutions was not enough to emphasize either opportunistic or restrictive DFAM.

These results show that the groups show no difference in their usage of DfAM concepts in the design process. While the participants, in general, gave a moderate importance to restrictive DfAM, they gave less emphasis to opportunistic DfAM. A possible explanation for this difference could be due to the commonly evident emphasis given to restrictive concepts, through informal use of AM technology, so as to prevent failure of prints. The results also point out that despite reporting an increase in comfort in using DfAM, this comfort did not translate into being used in the design process. A possible explanation for this is the low fidelity of the designs, where the focus was mainly given to functions, rather than the form of the product.

DISCUSSION

The goal of this study was to understand the effects of teaching different aspects of DfAM on the cognitive components of students' creativity. The key findings and their significance in engineering design education are discussed in this section.

Engineering students inherently have high levels of interest and motivation towards AM

Literature has shown the importance of intrinsic motivation and interest in both creative production [1,54] as well as learning [83]. Therefore, to encourage the learning and use of DfAM concepts in creative production, it is necessary to generate an intrinsic motivation towards it. Although the intervention did not result in a significant increase in the interest or motivation towards AM, the students reported having a high level of motivation at the beginning of the intervention. This high initial motivation and interest could be attributed to two factors: (1) the presence of 3D printing services on campus and (2) the limited hands-on access to the 3D printers themselves. The presence of 3D printing services makes students aware of the existence of such technologies, thus motivating them to learn about them. However, not being able to interact with them directly develops a curiosity in using the 3D printers for AM.

While this result does not demonstrate the effect of the intervention on the interest or motivation among the students, students' high level of motivation and interest should result in the effective learning of DfAM concepts, as shown in previous research [83]. Further, this result shows that the students possess a high level of intrinsic motivation in using AM, which is conducive to generating creative outputs. However, we must also be careful in making these inferences, because while a five-point scale captures the high levels of motivation and interest, it fails to fully capture the degree to which this is higher. High levels of motivation and interest could also be characteristic of the studied sample and may not be seen in all engineering students.

The current intervention successfully increases the students' self-efficacy in DfAM

The second main finding showed that exposing engineering students to opportunistic and restrictive DfAM concepts results in an increase in self-efficacy in each of the respective areas. An interesting observation was the influence of the students' prior AM experience on this change. While students with low levels of AM experience demonstrated a potential for learning of DfAM concepts, this was not seen in the case of students with high levels of experience. Further, higher AM experience also showed a significant interaction with all three DfAM education groups, in predicting an increase in restrictive self-efficacy.

This observation suggests two points. First, it shows that students with a high level of formal AM training show lower potential for increased DfAM self-efficacy. This could be a result of the significant amount of DfAM knowledge already possessed by students with high levels of AM experience. Second, it shows that this interaction effect of high level of previous AM experience is particularly strong in the case of restrictive DfAM. From this result, we can infer that their previous AM training and hands-on printing experience could have exposed students primarily to the limitations of the AM process. This could be attributed to the constant emphasis given to the considerations needed to prevent failure of prints, in both formal and informal education [66,67]. In comparison, students receive limited exposure to the methods to fully utilize AM capabilities, such as freely using complex geometries, unless it is well folded in with their AM education. Also, while restrictive DfAM considerations are necessary to ensure successful printing, opportunistic DfAM only assist in the optimal use of AM. This further goes to point out the importance of including DfAM training, particularly opportunistic DfAM, in the students' AM learning process. This observation is in line with the recommendations from the NSF AM education and training workshop [9,33].

Self-efficacy does not necessarily translate into the application of DfAM concepts

Finally, the third research question looked at understanding whether a change in self-efficacy is reflected in the emphasis given to the DfAM concepts during the design challenge. Results showed two important observations. The first observation was that, despite exposing the students to different DfAM concepts, they did not show any measurable differences in their reported use of the respective concepts. This is of particular importance because the three groups showed a difference in their comfort in the DfAM concepts, particularly in their comfort in integrating it with their design process. A possible explanation for this outcome could be the low fidelity of their designs, where the students mainly focused on the functions of the product, not the form and structure. Since the design challenge only included sketching of concepts, the scope for incorporating manufacturing considerations was low, since these considerations, especially those related to restrictive DfAM, are typically implemented in the CAD modelling stage, or later.

The second observation was the higher emphasis given to restrictive DfAM concepts by all three groups. This result implies that while a higher emphasis on restrictive DfAM may result in greater manufacturability of the parts, a lower emphasis on opportunistic DfAM may result in the participants not fully utilizing AM capabilities. This can further be related to findings from RQ2, where we see a constant interaction of high previous AM experience on the learning of restrictive concepts. This strengthens our inference that students' prior experience in AM primarily results in an increased familiarity with restrictive concepts. This, in effect, results in them giving greater emphasis to restrictive DfAM in comparison to opportunistic DfAM. While this could result in fewer failed prints, in order to be successful AM designers, it is equally important to focus on the opportunities enabled by AM processes [9,33]. Therefore, this result goes to reinforce the need for AM educators to emphasize on opportunistic DfAM, in order to ensure the successful adoption of AM processes.

CONCLUSION AND FUTURE WORK

As the influence of AM processes increases, it is important to generate a workforce capable of using this disruptive technology toward the design of innovative products. Motivated by this, the purpose of this study was to understand how teaching different aspects of DfAM, specifically opportunistic and restrictive, could have different effects on design creativity. Results show that, while these two aspects do not differently affect students' interest and motivation towards learning and using AM, the students inherently possess relatively high levels of motivation and interest before the educational intervention. While this high level of motivation encourages learning and results in an increase in DfAM self-efficacy, this comfort fails to translate into being used in the design process. These results provide an initial insight into how teaching DfAM could work towards making students more creative in using AM.

The study has several limitations that could possibly be addressed through further research. First, while short interventions have demonstrated an increase in creative self-efficacy in other domains, the time provided to the students might not have been sufficient to recollect and apply a large number of design considerations together. Second, the students' prior background was not given particular importance, which is evident in that a major portion of students had received some AM training before the intervention, which could have resulted in a lower motivation in attending the lectures. Finally, due to the exploratory nature of the study, the learning and use of DfAM in the design process were measured through students' self-evaluations. The design outcomes from the challenge could be used in the future to compare and understand if students can appropriately evaluate their own use of DfAM in their designs when compared to the assessment of DfAM experts.

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