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FRESH IN MY MIND! INVESTIGATING THE EFFECTS OF THE ORDER OF PRESENTING OPPORTUNISTIC AND RESTRICTIVE DESIGN FOR ADDITIVE MANUFACTURING CONTENT ON CREATIVITY

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ABSTRACT

Additive manufacturing (AM) processes present designers with creative freedoms beyond the capabilities of traditional manufacturing processes. However, to successfully leverage AM, designers must balance their creativity against the limitations inherent in these processes to ensure the feasibility of their designs. This feasible adoption of AM can be achieved if designers learn about and apply opportunistic and restrictive design for AM (DfAM) techniques at appropriate stages of the design process. Researchers have demonstrated the effect of the order of presentation of information on the learning and retrieval of said information; however, there is a need to explore this effect within DfAM education. In this paper, we explore this gap through an experimental study involving 195 undergraduate engineering students. Specifically, we compare two variations in DfAM education: (1) opportunistic DfAM followed by restrictive DfAM, and (2) restrictive DfAM followed by opportunistic DfAM, against only opportunistic DFAM and only restrictive DfAM training. These variations are compared through (1) differences in participants' DfAM self-efficacy, (2) their self-reported DfAM use, and (3) the creativity of their design outcomes. From the results, we see that only students trained in opportunistic DfAM, with or without restrictive DfAM, present a significant increase in their opportunistic DfAM self-efficacy. However, all students trained in DfAM – opportunistic, restrictive, or both – demonstrated an increase in their restrictive DfAM self-efficacy. Further, we see that teaching restrictive DfAM first followed by opportunistic DfAM results in the generation of ideas with greater creativity – a novel research finding. These results highlight the need for educators to account for the effects of the order of presenting content to students, especially when educating students about DfAM.

Keywords: design education, design for additive manufacturing, creativity.

1. INTRODUCTION

Engineering design can be broadly described as the process of problem-solving by employing knowledge from different domains. Of the various domains of knowledge utilized in engineering design, the knowledge of manufacturing processes plays a crucial role as manufacturing processes govern the extent to which designers' solutions can be feasibly built. Designers are encouraged to integrate design for manufacturing and assembly (DfMA) [1] in engineering design to account for the characteristics of manufacturing processes early in the design process and prevent manufacturing losses in the later design and manufacturing stages.

However, a majority of traditional DfMA guidelines are restrictive, i.e., they primarily focus on the limitations of the associated manufacturing and assembly processes. For example, DfMA guidelines recommend the simplification of parts for ease of manufacturing and assembly [2,3]. Novel additive manufacturing (AM) processes – in addition to exhibiting several characteristic limitations – provide designers with unique manufacturing capabilities and these capabilities are artifacts of AM's layer-by-layer fabrication process [4]. The adoption of AM processes in several industries (see [5–7] for examples) has encouraged a transition from traditional limitation-based DfMA processes towards a dual design for AM (DfAM) process [8]. The ongoing COVID-19 pandemic has further demonstrated the

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potential of leveraging AM capabilities to facilitate the agile and distributed production of consumables such as valves for ventilators [9], and personal protective equipment such as face shields [10].

A dual DfAM approach helps designers leverage AM capabilities – through opportunistic DfAM – while accommodating AM's limitations – through restrictive DfAM [11]. Some examples of restrictive DfAM include: (1) the need for support structures [12–14], (2) warping of parts due to thermal stresses [15,16], (3) anisotropy and weakness in build direction [17–19], (4) surface roughness due to stair-stepping [20–23], and (5) limited feature size and accuracy [24–26]. These restrictive DfAM techniques help improve the producibility of AM designs and thereby minimize losses due to build failures [27].

In contrast, opportunistic DfAM techniques help designers leverage the unique capabilities of AM. These capabilities include the ability to: (1) mass customize parts [28–31], (2) consolidate parts and build assemblies to reduce assembly costs [32,33], (3) build complex geometries [34–37], (4) embed external components to improve design functionality [38–41], and (5) print with multiple materials [42–44]. These AM capabilities open up designers' solution space – both geometric and functional – beyond the capabilities of traditional manufacturing [45]. Therefore, opportunistic DfAM helps designers to capitalize on the capabilities of AM processes in addition to ensuring the feasibility of designs through the integration of restrictive DfAM [34,46].

By exposing designers to new design freedoms, opportunistic DfAM techniques enable designers to be creative in their designs; however, prior work has demonstrated that despite being trained in opportunistic DfAM, designers tend to simplify their designs [47] possibly under the assumption that simpler designs are easier to manufacture [2,3]. This presents the need for engineering design education to encourage designers to transition from a limitation-based DfMA mindset towards adopting a dual design mindset.

Furthermore, to successfully encourage the creative application of DfAM, design educators must not only encourage successful learning, but also the retrieval and application of DfAM knowledge – both opportunistic and restrictive – during appropriate stages of the design process. Several researchers (see Section 2.2) have demonstrated that the order of presentation of information as well as the nature of the content influences individuals' learning of information. Therefore, the order of presenting opportunistic and restrictive DfAM could influence designers' learning and retrieval of both these domains of DfAM. While several studies (reviewed in Section 2.3) have discussed effective techniques for integrating DfAM in engineering design education, few have explored how the order of presenting opportunistic and restrictive DfAM content affects students' learning and use of DfAM. Our aim in this research is to explore this gap in the literature through an experimental study.

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

2. RELATED WORK

The work presented in this paper was motivated and informed by prior work related to the role of domain knowledge in creativity, the effect of order in learning, and current strategies in DfAM education. We present a summary of a review of the literature in these areas in the next section.

2.1. Domain knowledge in creativity and problem solving

The capabilities of AM processes provide designers with design freedoms thus enabling them with the ability to creatively solve problems. To fully leverage these design freedoms, designers must not only be aware of the characteristics of AM processes but also integrate this domain knowledge into their design and problem-solving processes. Several researchers have proposed models that highlight the role of domain knowledge at various stages of problem solving and creativity.

Amabile's [48] componential model of creativity proposes one's creative process to comprise the cognitive components of (1) task motivation, (2) domain knowledge and skills, and (3) creativity processes. These cognitive processes drive the creative process through multiple iterations of problem identification, information gathering and preparation, response generation, and response evaluation until a successful or satisfying outcome is attained. Of these various stages of creative problem solving, domain skills inform two key stages: (1) information gathering to initiate response generation, and (2) response validation and evaluation.

Similarly, researchers in entrepreneurship argue for the importance of information in the discovery of new ideas [49,50], with constrained, systematic idea searches demonstrating greater success [51]. Gielnick et al. [52] further suggest that the relationship between one's divergent thinking skills and one's ability to come up with new business ideas is influenced by the diversity of information possessed by the individual. Individuals with a more diverse set of information presented a strong positive correlation between divergent thinking and idea generation. In contrast to these findings, Wiley [53] argues that experts characterized by greater domain knowledge are often less accurate, demonstrate solution fixation, and are slower when compared to non-experts. These effects are further augmented when the higher domain knowledge leads the experts towards misleading information.

These studies highlight the influence of information and domain knowledge on creativity and idea generation. Moreover, these studies demonstrate that for domain knowledge to successfully influence creativity, designers must not only effectively learn the information, but also *retrieve* the appropriate information in the preparation and response validation stages. Therefore, for the successful application of

DfAM, designers must retrieve both opportunistic and restrictive DfAM during the various stages in the design process, especially concept generation. This retrieval of domain knowledge has been shown to be influenced by the order in which information is learned and individuals' familiarity with the information. To further understand the role of order of information presentation on learning and retrieval, prior research was explored as summarized next.

2.2. Role of order in learning (and forgetting)

For DfAM education to successfully encourage creativity, this domain knowledge must not just be effectively learned but also retrieved at appropriate stages during the design process. Successful retrieval is influenced by forgetting [54], which could be caused by both the lack of access to the information [55] and the unavailability of the information itself [56]. Forgetting of information can be attributed to several causes such as interference [57–60], decay with the passage of time [61], and context shifts [60,62], each of which interacts with each other to result in forgetting [58,63].

Of these factors, interference is strongly influenced by the order in which information is presented [64]. Interference induced forgetting occurs when the recall of certain information is impaired by the storage and recall of similar, competing information [59], and it is attributed to the stronger recall association of competitor information to certain cues [65]. Further, researchers argue that this inhibition is caused by an overload of information associated with the same retrieval cue [66] and this can occur along two paths: (1) retroactive inhibition and (2) proactive inhibition.

Retroactive inhibition occurs when the retrieval of old information is hindered due to memory inhibition caused by the learning of new, similar information [67]. This learning inhibition of new information is influenced by the similarity [68,69] and semantic-relatedness [70] between the old and new information. Robinson [71] and Harden [72] argue that a higher similarity between the original and new information results in better recall of the original information; however, Cheng [73] demonstrates that this effect varies based on the method of measurement. Additionally, retroactive interference is also influenced by the degree of learning of the new information, and this varies based on the method of learning [74]. For example, studies by Robinson and Heron [75] and Robinson and Darrow [76] demonstrate that a greater degree of learning of the original information – as assessed by the amount of material – corresponds to a lower retroactive inhibition. Britt and Bunch [77] further extend this effect to the age of the information and demonstrate that a higher degree of learning of older information results in lower retroactive inhibition. Retroactive learning inhibition is also influenced by ones' familiarity with the information as well as the amount of practice. For example, Brown [78] demonstrates that in free recall situations, a stronger familiarity with information results in an impaired recall of information with weaker association, and Karchmer and Winograd [79] further reinforce these findings.

In contrast to retroactive interference, proactive interference is the impaired retrieval of new information due to the stronger cue association of old information [80]. In a series of experiments studying the effect of time and degree of learning on proactive inhibition, Underwood [81] demonstrated that the recall of new information decreases, i.e., proactive inhibition increases, with a higher degree of learning of old information. A similar effect was also demonstrated by Underwood [82] where proactive inhibition increased with an increase in the quantity of information. However, this effect was transient and seen only in initial recalls, suggesting a stronger occurrence of proactive inhibition in short-term memory [83,84]. Melton and Lackum [85] further suggest that proactive inhibition operates by providing competitive responses at the time of recall of new information and does not necessarily influence the learning of new information. Additionally, Young [86] demonstrates that while retroactive inhibition is influenced by the similarity between the old and new information, this effect was not seen in case of proactive inhibition.

In light of these findings, it is important for DfAM education to take into account the order when presenting opportunistic and restrictive DfAM, especially in short-duration teaching interventions. Variations in the order could influence and potentially interfere with students' learning and use of certain concepts in their design process. This issue is further highlighted in the case of novice designers who are primarily exposed to restrictive DfAM, often in lower intensity, and this informal learning of restrictive DfAM could potentially interfere with their subsequent learning of opportunistic DfAM. However, there is a need to explore this effect of the order of content on DfAM learning and use and the creativity of the associated design outcomes. Before doing so, current practices in AM and DfAM education are reviewed and discussed.

2.3. Current strategies in AM and DfAM education

To address the need for a workforce skilled in AM, several researchers have presented educational interventions for DfAM education as reviewed in [87]. These interventions can broadly be classified into three types: (1) formal, in-class interventions, (2) informal, self-learning initiatives, and (3) design tools and frameworks. All three types of interventions demonstrate some reliance on inductive, problem-based learning.

Williams and Seepersad [88] discuss a formal AM educational intervention introduced at the University of Texas at Austin and Virginia Tech. As part of this AM course, students are introduced to the various AM processes, asked to choose appropriate processes for specific engineering applications, and apply their AM knowledge to solve a design problem. Their course uses three design activities: (1) designing a benchmarking part to identify AM limitations, (2) comparing various AM technologies and identifying appropriate processes for certain applications, and (3) a semester-long project where students design a product emphasizing unique AM characteristics. Yang [89] presents a more self-directed approach for AM education: students are asked to perform literature reviews to gather information about new developments in AM and apply these findings towards solving a design challenge. The discussed course structure provides students with experience in both applying AM and DfAM knowledge in design as well as identifying potential areas for research in the domain.

Ferchow et al. [90] discuss the use of the experience transfer model of learning as a viable method for transferring DfAM skills from research to practicing designers. As discussed in [91], the educational model consists of three main steps. First, designers are given an input lecture presenting them with DfAM knowledge. Next, the designers are engaged in applying this knowledge through conceptual and detailed design of an AM part. Finally, the designers receive feedback on their designs from AM experts, and based on the outcomes, these three steps are performed iteratively. Diegel et al. [92] present a 4-day hands-on workshop for training industry professionals in DfAM. Each day of the discussed workshop introduces participants to some combination of opportunistic and restrictive DfAM concepts followed by design exercises. Richter et al. [93] extend the use of workshops to convey knowledge about AM capabilities and help designers eliminate possible barriers to the creative leveraging of these capabilities.

In addition to these formal classroom-based interventions, several educators have employed informal, extracurricular techniques for AM education. For example, Williams et al. [94] engage students in an extracurricular design competition where participants are tasked with designing remote-controlled vehicles. Students' designs were evaluated for their performance as well as their integration of DfAM and best-performing designs were rewarded monetarily. Several academic institutions have also set up maker-spaces both on and off-campus to provide students with access to AM and encourage learning by doing. Some examples include the 3D printing vending machines at UT Austin [95] and the maker spaces at Penn State [96], Georgia Tech [97], MIT [98], and Case Western [99]. These makerspaces provide students with the opportunity to interact with AM machines either directly or through online interfaces. Additionally, some of the makerspaces also provide students with design and build preparation guidelines; however, a majority of these instructional resources are focused on preventing build failure through restrictive DfAM. As AM technologies become accessible to students, the greater exposure to restrictive DfAM could reinforce their learning of these techniques. This reinforced learning of restrictive DfAM could, in turn, inhibit their learning and recall of opportunistic DfAM and the order of presentation of dual DfAM content could further influence this recall inhibition.

Several researchers have proposed design tools to further encourage DfAM integration, especially opportunistic DfAM, in engineering design. For example, Blösch-Paidosh and Shea [100] developed a set of design heuristics specifically aimed at the integration of opportunistic DfAM concepts such as part consolidation and material complexity in the early stages of conceptual design. They present the effectiveness of the DfAM heuristics towards increasing both DfAM integration [100] as well as the novelty and flexibility of design outcomes [101]. Additionally, they argue for a distributed introduction of the various DfAM heuristics – three sets of eight heuristics – to prevent cognitive overload. Perez et al. [102] crowdsourced a similar, principle-based DfAM tool. They demonstrate the successful use of the design principles towards increasing design novelty and quality in [103] and argue for the high perceived utility of the principles by designers in [104]. They also discuss the integration of the said design principles in a design innovation framework in [105]. In contrast to Blösch-Paidosh and Shea's strategy of a dispersed introduction of the various heuristics, Perez et al. collectively present all of the DfAM principles at once.

Another example is Valjak and Bojčetić's [106] design principles for AM that use a combination of CAD models, process manufacturability information, and sample applications of the design principle. Schumacher et al. [107] present a further modification of DfAM principle cards which provides designers with trade-offs between the positive and negative effects of incorporating the various DFAM techniques. Kumke et al. [108] combine workshop-style interventions with DfAM tools to demonstrate the effects of expertise and preferences on designers use of DfAM tools.

From these studies, we see that several researchers have discussed the effectiveness of formal and informal DfAM educational interventions. Researchers have also proposed frameworks for integrating DfAM in engineering design. However, there is a need to explore the effect of the order of presenting opportunistic and restrictive DfAM content on students' learning and creativity. This is important as research in learning and memory, reviewed in Section 2.2, has demonstrated the potential effect of the order of presentation of information on learning and recall. Therefore, our aim in the present research is to explore this gap in the literature through an experimental study. In the next section, we present the research questions we seek to answer to explore this gap in the literature.

3. RESEARCH QUESTIONS

Our goal in this study was to investigate the effect of variations in the order of presenting opportunistic and restrictive DfAM content on students' learning and use of DfAM and the creativity of their design outcomes. Specifically, we explored the following research questions (*RQs*).

- *RQ1: How does the order of presenting DfAM educational content affect the participants' self-efficacy with the various DfAM concepts?* Prior research has demonstrated that students find it easier to learn about restrictive DfAM compared to opportunistic DfAM [109]. Students also have been shown to demonstrate a greater familiarity and exposure to restrictive DfAM potentially due to their prior informal experiences with AM [110]. Therefore, based on Part-Set Cue Theory [111], we hypothesize that introducing opportunistic DfAM followed by restrictive DfAM could result in retroactive inhibition, therefore limiting the increase in students' opportunistic DfAM self-efficacy.

- *RQ2: How does the order of presenting DfAM educational content affect the participants' self-reported emphasis on the* *various DfAM concepts?* Similar to the hypothesis in RQ1, given students' familiarity and ease of learning restrictive DfAM, we hypothesize that introducing opportunistic DfAM followed by restrictive DfAM would result in a lower self-reported emphasis on opportunistic DfAM.

- *RQ3: How does the order of presenting DfAM educational content affect the creativity of participants' design outcomes?* Prior research has demonstrated the application of opportunistic DfAM to correlate with greater design creativity [101]. Building up on the hypotheses of the first two RQs, we hypothesize that teaching opportunistic DfAM followed by restrictive DfAM would inhibit students' recall of opportunistic DfAM, thus limiting the application of these concepts in design. This would result in the generation of ideas of lower creativity compared to teaching restrictive DfAM followed by opportunistic DfAM.

4. EXPERIMENTAL METHODS

To answer these research questions, we conducted an experiment comprised of a short-duration intervention lecture and an AM design challenge, and the details are discussed next.

4.1. Participants

The experiment was conducted at a large northeastern public university, where participants (N = 195) were recruited from a junior-level mechanical engineering course focused on product design and engineering design methods. The experiment was conducted in both the fall (N_f = 91 participants) and spring (N_s = 104) semesters with participants and Table 1 presents a breakdown of participants based on their year of study. The participants' self-reported previous experience in AM and DfAM was collected at the beginning of the study (see Figure 1), and the distribution of participants' previous AM and DfAM experiences were similar between the two semesters as seen in the figure.

Table 1 Distribution of participants based on their year of study

	Fall Semester	Spring Semester
Sophomores	0	3
Juniors	69	91
Seniors	22	10
Missing	0	3
Total	91	104

4.2. Procedure and Metrics

The experiment was conducted in the fall and spring semesters and consisted of three stages: (1) pre-intervention survey, (2) a series of DfAM education lectures, and (3) DfAM task followed by a post-intervention survey. The study was reviewed and approved by the Institutional Review Board, and implied consent was obtained from the participants prior to the experimentation in both semesters. Figure 2 summarizes the overall flow of events in both semesters.

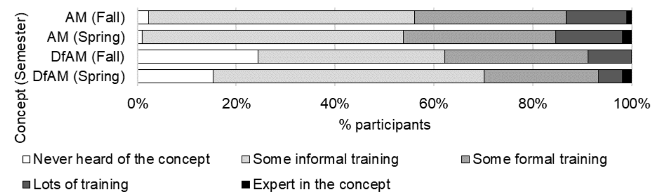


Figure 1 Distribution of participants' previous experience

4.2.1. Pre-intervention survey

For the first part of the experiment, the participants were asked to complete a pre-intervention survey. The survey collected their previous experience in AM and DfAM (see Figure 1) and their DfAM self-efficacy. Self-efficacy was used as a measure in this study as previous research has demonstrated the role of self-efficacy [112] and meta-cognition [113] in predicting effective learning. The self-efficacy survey from [110] was used to assess participants' learning of DfAM. The survey focuses on both the opportunistic and restrictive DfAM domains and uses a 5-point scale derived from Bloom's Taxonomy [114]. A difference between the participants' pre- and post-intervention self-efficacy scores was calculated to assess the change in their self-efficacy.

The internal consistency of the scale was assessed by performing a reliability analysis, and a high Cronbach's α [115] was observed (pre-intervention $\alpha = 0.91$, post-intervention $\alpha = 0.87$). Similarly, the individual opportunistic and restrictive sections of the scale also showed a high internal consistency, as determined by Cronbach's α (opportunistic: pre-intervention $\alpha = 0.86$, post-intervention $\alpha = 0.75$, and restrictive: pre-intervention $\alpha = 0.86$, post-intervention $\alpha = 0.81$).

4.2.2. DfAM educational intervention

Next, participants were introduced to the DfAM educational content through a series of lectures (see Figure 2). Participants in the spring semester were trained in either (1) restrictive DfAM ($N_R = 63$) or (2) restrictive followed by opportunistic (dual RO) DfAM ($N_{RO} = 41$). On the other hand, participants in the fall semester were trained in either (1) opportunistic DfAM ($N_O = 45$) or (2) opportunistic followed by restrictive (dual OR) DfAM ($N_{OR} = 46$).

In both semesters, all participants were first given a 20-minute lecture providing an overview of the AM process. In this lecture, the instructor discussed topics such as (1) introduction to the material extrusion process – the AM process available to the students in the AM design challenge, (2) contrasts between additive and subtractive manufacturing, (3) the digital thread, (4) the Cartesian coordinate system as it relates to the print volume, and (5) materials available in material extrusion. After the AM overview lecture, participants were introduced to the DfAM content. The 20-minute restrictive DfAM lecture covered: (1) build time, (2) feature size, (3) support material, (4) anisotropy, (5) surface finish, and (6) warping. On the other hand, the 20-minute opportunistic DfAM lecture comprised: (1) geometric complexity, (2) mass customization, (3) part consolidation, (4) printed assemblies, (5) multi-material printing, and (6)

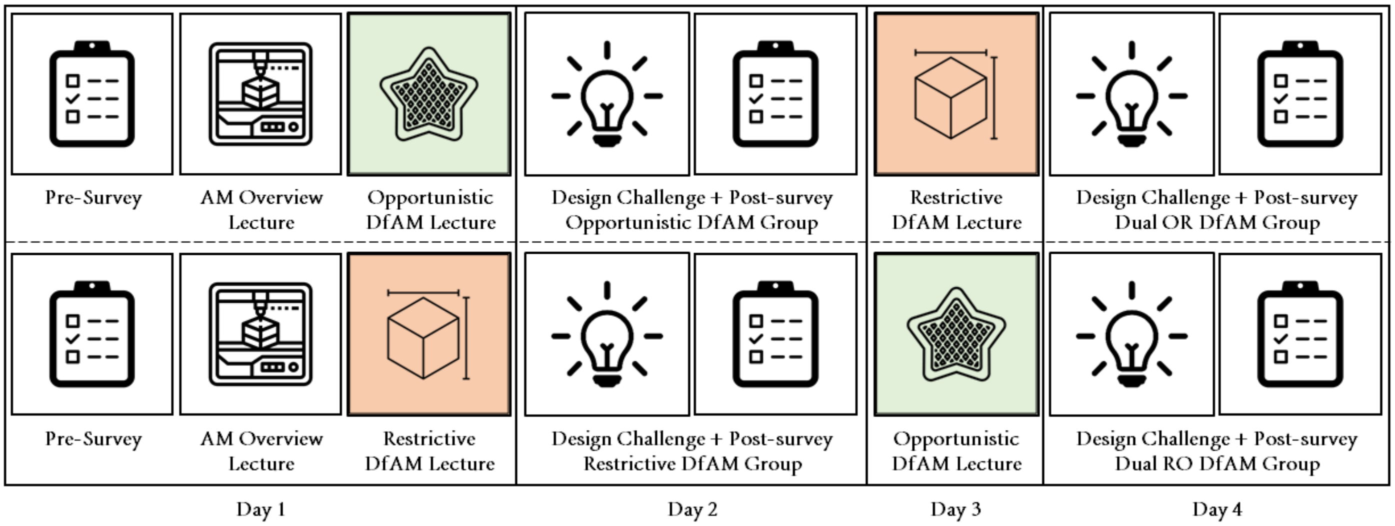


Figure 2 Summary of the various stages in the experiment

embedding. The lecture slides can be accessed at [116]. We used short-duration intervention lectures to ensure that we completed all parts of the experiment within the allotted class time. While researchers have argued for the effectiveness of such lecture-style DfAM interventions [90], we acknowledge the need to extend this experiment in future work to investigate effects of a longer intervention lecture where students are introduced to the various DfAM concepts in detail.

4.2.3. DfAM task and post-intervention survey:

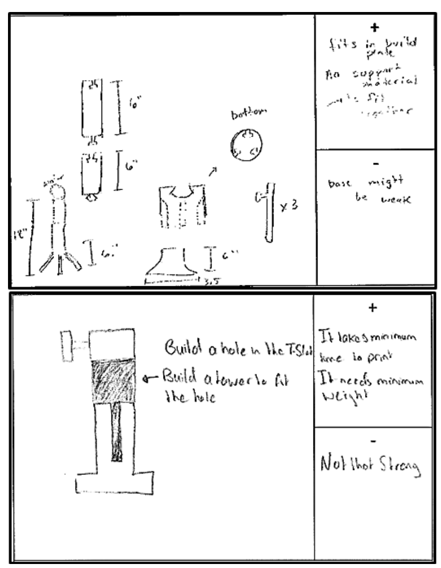
For the final part of the experiment, the participants were asked to individually participate in a DfAM task. The wind-turbine design prompt from [117] was used in the experiment as it requires minimal domain-specific knowledge beyond AM (as suggested by [48]). Furthermore, the design problem was chosen given its complexity and the functional and manufacturing constraints that could be placed on the solution space – both of which have shown to encourage creativity in DfAM [117]. Participants from both semesters were informed that the best performing design (in terms of build material and time) from each section would receive a $20 gift card. This competition structure was chosen based on preliminary findings – currently in review [118] – demonstrating the greater effectiveness of competitions in encouraging creativity in DfAM tasks.

During the design challenge, participants were first asked to individually brainstorm for ideas using both sketches and words to describe their ideas. Participants were also asked to evaluate each idea by noting down its strengths and weaknesses. Next, the participants were asked to individually develop a final design with the freedom to redesign or combine previous ideas or brainstorm again. These individual final designs were assessed for their creativity as part of this experiment.

The participants' final individual designs were assessed for their creativity using the Consensual Assessment Technique (CAT) [119,120]. Two quasi-experts with a background in AM and DfAM (as suggested by [121,122]) independently rated the designs on a scale of 1 = least creative to 6 = most creative using the following metrics (as suggested by the three-factor model [123,124]):

– *Uniqueness*: Measures the originality of each design idea compared to other ideas generated in the sample [48].
– *Usefulness*: Measures the idea's ability to solve the given design problem along with its value and appropriateness.
– *Technical Goodness*: Measures the suitability of a design idea with respect to the AM processes, both in terms of capabilities and limitations [47,109].
– *Overall Creativity*: Provides a subjective evaluation of the overall creativity of a design idea.

A moderate to high inter-rater reliability was observed between the two raters, as verified by an Intraclass Correlation



Participant ID	TEER11
Uniqueness	4.25
Usefulness	4.25
Technical Goodness	5.25
Overall Creativity	5

Participant ID	DAAH12
Uniqueness	2
Usefulness	2
Technical Goodness	1.75
Overall Creativity	1.5

Figure 3 Example of participants' ideas from the design challenge and their assigned CAT scores (1 = least creative and 6 = most creative)

Coefficient of 0.77 [115]. An average score for each metric was then calculated by taking a mean of the scores from the two raters for each design. Examples of ideas generated by the participants and their assigned creativity scores are presented in Figure 3.

Upon completing the final individual designs, participants were asked to self-report the emphasis they gave to the different DfAM techniques during the AM design challenge. The scale developed in [110] was used to measure the self-reported emphasis and participants were asked to report the importance they gave to each DfAM technique on a 5-point Likert-type scale, with 1 = 'Not important at all' to 5 = 'Absolutely essential'.

Students were then split into groups, asked to pick an idea to represent the group, and generate CAD models for this idea. The group and CAD portions of the experiments were part of a larger study and are not relevant to the work presented in this paper. Finally, participants were asked to complete a post-intervention survey with the same DfAM self-efficacy questions as in the pre-intervention survey.

5. DATA ANALYSIS AND RESULTS

To answer the three research questions, a statistical analysis of participant data was performed using a statistical significance level of $\alpha = 0.05$ and a 95% confidence interval. A sample size of 195 was used for the analyses, of which, (1) $N_R = 63$ received restrictive DfAM only, (2) $N_{RO} = 41$ received restrictive followed by opportunistic (dual RO) DfAM, (3) $N_O = 45$ received only opportunistic DfAM, and (4) $N_{OR} = 46$ received opportunistic followed by restrictive (dual OR) DfAM. However, it should be noted that participants with significant missing values were list-wise deleted for analysis of the individual research questions. All reported results are either mean (M) ± standard deviation or median (Mdn) unless otherwise specified.

5.1. RQ1: How does the order of presenting DfAM educational content affect the participants' self-efficacy with the various DfAM concepts?

To answer the first research question, a series of repeated measures Wilcoxon Signed Rank tests [125] were performed. The pre- and post-intervention self-efficacy scores were taken as the within-subjects' factors, and an independent analysis was conducted for each educational intervention group. The results of the analysis are summarized in Figure 4. As seen in the figure, participants from all four educational intervention groups demonstrate an increasing trend in their restrictive DfAM self-efficacy. However only groups that received opportunistic DfAM training (i.e., the opportunistic only and the two dual DfAM groups) demonstrated an increase in their opportunistic DfAM self-efficacy.

Next, to investigate the effect of the order of lectures on the participants' DfAM self-efficacy, a series of Mann-Whitney U tests [126] were performed comparing the change scores (i.e., the difference between pre- and post-intervention scores) between the two dual DfAM groups. The results showed a significant effect of the order of lectures on the change in self-efficacy with mass customization, $z = 2.57$, $U = 1230.00$, $p = 0.01$, with the dual OR group demonstrating a greater increase in self-efficacy ($Mdn = 1.00$) compared to the dual RO group ($Mdn = 0.00$). No differences were seen in the changes in self-efficacies with the other DfAM concepts – both opportunistic and restrictive. The implications of these results are discussed in Section 6.

5.2. RQ2: How does the order of presenting DfAM educational content affect the participants' self-reported emphasis on the various DfAM concepts?

To answer the second research question, a series of independent samples median tests were performed. A median test

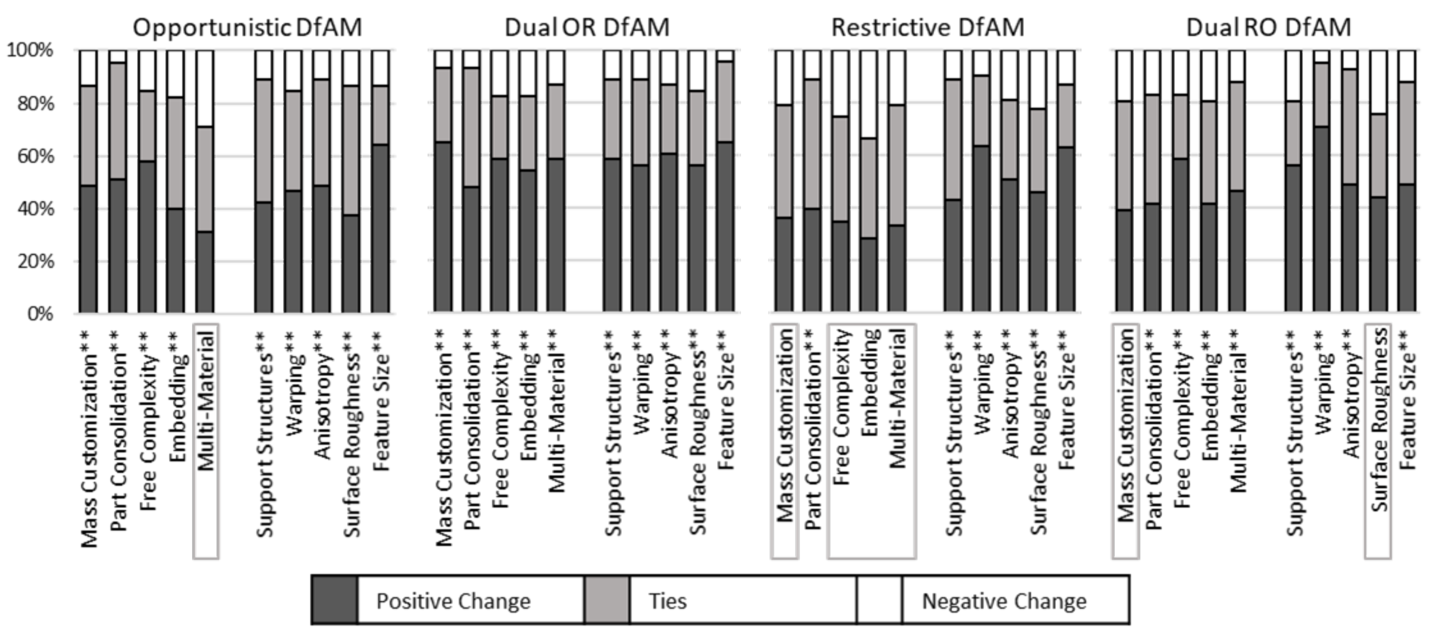


Figure 4 Changes in participants' DfAM self-efficacy - first five columns in each group comprise of opportunistic DfAM and last five columns comprise of restrictive DfAM ($p < 0.05$ and non-significant changes are highlighted)**

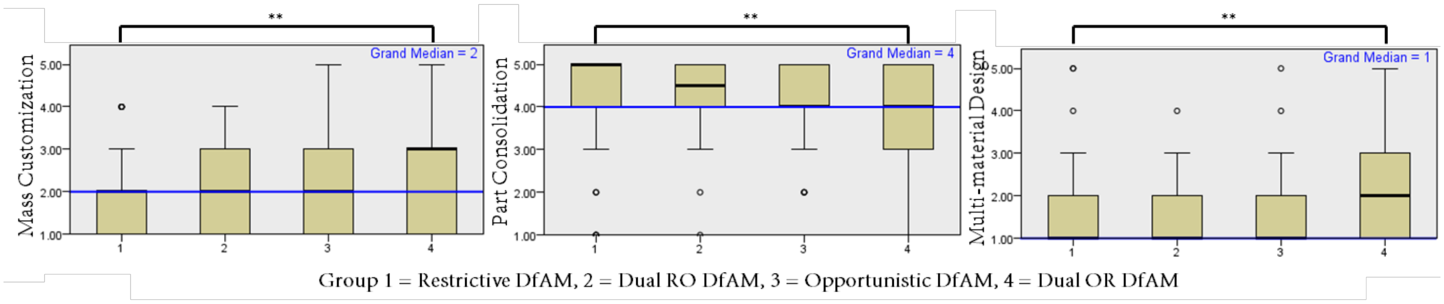


Figure 5 Pairwise comparisons for significant effects of educational intervention group on participants' self-reported DfAM emphasis ($p < 0.05$)**

was chosen (as opposed to an ANOVA) given the ordinal and non-normal nature of the data. The participants' self-reported emphasis on each DfAM concept was compared against the pooled median for the DfAM concept and the DfAM educational group was taken as the independent variable. A sample size of 175 (as opposed to 195 in RQ1) was used for this analysis due to list-wise missing values and data from participants with significant missing responses were entirely deleted. The results showed a significant effect of the educational intervention group on the participants' self-reported emphasis on mass customization (χ^2 (3) = 12.16, p = 0.01), part consolidation (χ^2 (3) = 8.91, p = 0.03), functional embedding (χ^2 (3) = 8.99, p = 0.03), and multi-material printing (χ^2 (3) = 8.00, p = 0.046). No significant effects were seen in case of the restrictive DfAM concepts.

Further, pairwise comparisons within the independent samples median test showed that participants from the dual OR DfAM group gave a significantly higher emphasis on mass customization (*Mdn* = 3) and multi-material design (*Mdn* = 2) compared to the restrictive DfAM group (*Mdn* = 2 and 1 respectively), $p_{adj} < 0.05$. On the other hand, participants from the restrictive DfAM group gave a significantly higher emphasis on part consolidation (*Mdn* = 5) compared to the dual OR DfAM group (*Mdn* = 4), $p_{adj} < 0.05$. No significant differences were seen between the two dual DfAM groups. The pair-wise comparisons for significant results are summarized in Figure 5, and the implications of these results are discussed in Section 6.

5.3. RQ3: How does the order of presenting DfAM educational content affect the creativity of the participants' design outcomes?

To answer the third research question, one-way ANOVAs were performed with each component of creativity – uniqueness, usefulness, technical goodness, and overall creativity – as the dependent variables and the DfAM educational group as the independent variable. Before performing the analysis, the assumptions of the test were verified. There were no outliers exceeding three standard deviations, and while there was homogeneity of variances for usefulness, uniqueness, and technical goodness ($p > 0.05$), this assumption was violated for overall creativity ($p < 0.05$). Further, although the assumption of normality – as assessed by the Shapiro-Wilk test [127] – was violated for some variables, the analysis was performed given the robustness of the test to deviations from normality. Two data-points were removed due to missing/illegible designs leading to a total sample size of 193.

The results of the ANOVA showed a statistically significant effect of educational intervention group on idea uniqueness (F(3,190) = 4.01, p = 0.01, η_p^2 = 0.06), technical goodness (F(3,190) = 4.28, p = 0.01, η_p^2 = 0.06), and overall creativity (F(3,190) = 3.29, p = 0.02, η_p^2 = 0.05). However, the results showed no significant effect of educational intervention group – opportunistic, restrictive, or dual – on the usefulness of the ideas (F(3,190) = 2.63, p = 0.05, η_p^2 = 0.04). Tukey's post-hoc tests [128] were performed on the significant effects, see Figure 6. The results showed that the dual RO DfAM group generated ideas of significantly higher uniqueness, technical goodness, and overall creativity, compared to the dual OR DfAM group ($p < 0.05$). No other significant pair-wise differences were observed. The implications of these results and the findings for the other RQs are discussed in the next section.

6. IMPLICATIONS ON DESIGN EDUCATION

Our goal in this research is to understand the effect of the order of presenting DfAM educational content on students' learning and use of DfAM and its resulting effects on students' creativity. The key findings from the research are:

1. Only students trained in opportunistic DfAM – with or without restrictive DfAM – demonstrated an increase in their opportunistic DfAM self-efficacy. However, all

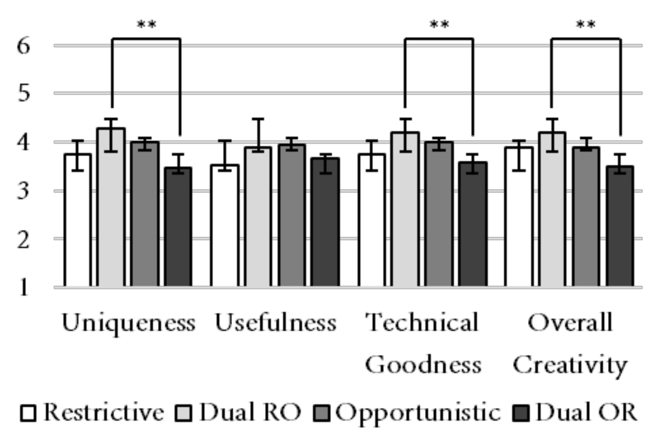


Figure 6 Summary of creativity scores ($M \pm SD$) of the different educational groups ($p < 0.05$)**

students trained in DfAM – opportunistic, restrictive, or both – demonstrated an increase in their restrictive DfAM self-efficacy.
2. Dual DfAM training results in a greater self-reported emphasis on some opportunistic DfAM concepts compared to restrictive DfAM training but only when opportunistic DfAM is introduced first.
3. Teaching restrictive DfAM first followed by opportunistic DfAM results in the generation of design ideas with higher creativity

The implications of these findings on DfAM education are discussed next.

6.1. Students must explicitly be trained in opportunistic DfAM to result in an increase in their opportunistic self-efficacy

The first key finding from the results was that for DfAM education to positively influence students' opportunistic DfAM self-efficacy, students must explicitly be trained in these concepts. Specifically, the results show that only students trained in opportunistic DfAM, either with or without restrictive DfAM, present a positive change in their self-efficacy with these concepts while those trained only in restrictive DfAM do not. In contrast, no such effect was seen in case of restrictive DfAM – all four groups including those trained only in opportunistic DfAM demonstrated an increase in their restrictive DfAM self-efficacy. This finding suggests that despite not being explicitly trained in restrictive DfAM, students demonstrate some knowledge about these topics, possibly gained through their prior formal and informal learning experiences (see Figure 1). Introducing students to DfAM – either opportunistic, restrictive, or both – potentially results in the retrieval of this restrictive DfAM knowledge, thus reinforcing their perceived efficacy in these techniques. This finding corroborates with prior findings (e.g., [47]) that students show a greater increase in restrictive DfAM self-efficacy compared to opportunistic DfAM.

However, this effect was not seen in the case of students' opportunistic DfAM self-efficacy; only those trained in opportunistic DfAM – with or without restrictive DfAM – showed an increase in their self-efficacy with these DfAM concepts. This result, therefore, suggests that students have limited exposure to opportunistic DfAM through their prior AM and DfAM experience and must explicitly be trained in these opportunistic aspects of DfAM. This training would inform students about the various capabilities of AM, and this awareness has been identified as a key characteristic of successful AM engineers [34].

The second key finding was that the order of the lectures did not have a significant effect on students' self-efficacy with the various DfAM concepts. This finding suggests that students' DfAM self-efficacy is not affected by either retroactive or proactive interference caused by the order of presentation of content. However, we must be careful in making this inference since the self-efficacy scale used in this study captures students' comfort and familiarity with the various DfAM concepts and not necessarily their ability to *recall* these concepts, whether with or without cues. This distinction is crucial as prior research has demonstrated that individuals demonstrate superior performance in familiarity and recognition tasks compared to recall tasks [129]. Therefore, future research must investigate whether or not the absence of memory interference can be extended to recall tasks such as knowledge tests.

6.2. Order of Dual DfAM training influences participants' self-reported emphasis on DfAM when compared against restrictive DfAM training

The second key finding from the study was that the order of the dual DfAM education influenced students' emphasis on opportunistic DfAM concepts, but only when compared against participants who received only restrictive DfAM education. Specifically, we see that participants trained in dual OR DfAM gave a significantly higher emphasis on the opportunistic DfAM concepts of mass customization and multi-material design. This finding suggests that introducing opportunistic DfAM first followed by restrictive DfAM is more successful in encouraging an application of certain opportunistic DfAM concepts. This finding extends the findings of the first research question which suggested the need for explicit dual DfAM training to result in an increase in opportunistic DfAM self-efficacy.

However, we also see from the results that compared to other forms of DfAM education, participants trained only in restrictive DfAM gave the highest emphasis on part consolidation – an important DfAM concept considering the constraints and objectives of the design challenge. The design challenge tasked students with developing a tower at least 18" tall that could be built in a single 11.6" x 7.6" x 6.5" build volume. The constraint-based nature of restrictive DfAM training could have shifted participants' focus on the constraints of the design problem, which in turn could have resulted in a greater emphasis on part consolidation – an opportunistic DfAM concept – to satisfy the design constraints. This is an interesting finding as it suggests that restrictive DfAM training encourages students to give a greater emphasis on design constraints and potentially employ part consolidation techniques to overcome them. However, the participants self-reported their emphasis on the various DfAM concepts and given the relatively low reliability of self-report scores, we must be careful in making these inferences.

6.3. Teaching restrictive DfAM first followed by opportunistic DfAM results in the generation of ideas with higher creativity

The final key finding from the study was that the order of presenting dual DfAM content affected the uniqueness, technical goodness, and overall creativity of the participants' designs. Specifically, we see that participants presented with dual RO DfAM generated ideas of higher creativity compared to those presented with dual OR DfAM. This is a critical and novel finding as it evaluates the effect of the order of presenting DfAM content on students' recall and DfAM use without relying on familiarity-driven self-reported scores.

Prior research has demonstrated that the integration of opportunistic DfAM positively correlates with the uniqueness and creativity of designs [101]. Therefore, the higher creativity of the ideas generated by the dual RO group suggests that the order of the lectures influences participants' retrieval and integration of opportunistic DfAM in their designs. This could be attributed to the retroactive inhibition [67] – students' learning of restrictive DfAM following opportunistic DfAM could have interfered with their recall of opportunistic DfAM. This could further have been aggravated by participants' familiarity with restrictive DfAM, as suggested by Part-Set Cue Theory [111]. Students' familiarity with restrictive DfAM – as seen in the first RQ – potentially due to their prior experiences with AM could further interfere with their learning and recall of opportunistic DfAM. This finding could also be attributed to the recency effect [130] – since opportunistic DfAM was taught temporally closer to the design challenge, it could have been freshly consolidated in memory and therefore easily recalled.

However, this finding conflicts the findings from RQ2 where participants from the dual OR DfAM group reported a greater emphasis on the opportunistic DfAM concepts of mass customization and multi-material design. This difference suggests a potential disparity between students' self-reported use of DfAM – particularly opportunistic DfAM – and their actual integration of these techniques in designs. Therefore, future research should compare how students' self-reported DfAM use corresponds to an external and objective assessment of their designs.

These findings suggest that students' prior AM experience – particularly with restrictive DfAM could interfere with their opportunistic DfAM integration in design, thereby influencing the creativity of their designs. Prior research has demonstrated the effectiveness of repeated rehearsal [131] and deep encoding in enhancing retrieval. Therefore, educators must ensure that students are encouraged to repeatedly rehearse the various opportunistic DfAM concepts. Additionally, educators are also encouraged to ensure that students deeply encode the various opportunistic DfAM concepts. This could be achieved through targeted elaboration and synthesis [132] where students are encouraged to actively apply the various DfAM concepts. These strategies could help prevent students' knowledge of and familiarity with restrictive DfAM from interfering with their recall and integration of opportunistic DfAM.

7. CONCLUSION, LIMITATIONS, AND FUTURE WORK

Our aim in this research was to investigate the effect of the order of presenting dual DfAM content on students' DfAM self-efficacy, their self-reported emphasis on DfAM, and creativity of their design outcomes. The results showed that in order to increase students' self-efficacy in opportunistic DfAM concepts through a task-based educational intervention, they must explicitly be introduced to the various opportunistic DfAM concepts. However, this is not true in case of restrictive DfAM concepts. This finding suggests that engineering design students demonstrate greater ease in developing restrictive DfAM self-efficacy – a finding observed in previous research [47]. Further, the results show that while dual DfAM education results in a greater self-reported emphasis on mass customization and multi-material design compared to restrictive DfAM, this was true only for those trained in dual OR DfAM. Finally, we see that students who were introduced to dual RO DfAM generated ideas of higher creativity and technical goodness compared to those who received dual OR DfAM training. Given the potential role of opportunistic DfAM in encouraging creativity [101], this could be attributed to a hindered recall of opportunistic DfAM caused by retroactive interference due to restrictive DfAM knowledge. Therefore, educators are recommended to encourage deeper learning and recall of opportunistic DfAM aspects to minimize interference due to restrictive DfAM, and this could potentially be achieved through repeated rehearsal and targeted application of opportunistic DfAM.

Despite providing important insights on the potential effects of the order of presenting DfAM content on students' design outcomes, this research has several limitations. First, the study used a lecture-style delivery of content where students are introduced to the various DfAM concepts through 20-minute lectures on opportunistic and restrictive DfAM. This rapid and condensed introduction of content could have limited students' learning of the various DfAM concepts as prior research has demonstrated the higher effectiveness of temporally-spaced learning [133–135]. Therefore, future research must extend this study towards an intervention spaced over several input sessions. Second, the study uses a single design challenge as a hands-on learning experience for several DfAM concepts together. Therefore, in addition to expanding the input lectures, future research must also employ multiple design challenges, therefore, resulting in a targeted application and rehearsal of the various DfAM concepts. Such a study could also explore the use of different design tasks for the various DfAM concepts as suggested in [117]. Third, the study primarily assesses students' learning and application of DfAM in the concept generation stage. However, different DfAM processes could play a different role in the various stages of engineering design such as concept evaluation and selection. Therefore, future research must explore whether or not variations in students' use of DfAM are based on the various stages of design and the consequent effect on the designs. Finally, the study uses AM technical goodness – a subjective measure – to assess students' integration of DfAM in their designs. While this measure provides a useful overall assessment of DfAM integration, future research must employ specific objective measures for capturing students' DfAM integration. The use of objective measures could highlight variations in students' learning of the various DfAM concepts, as well as variations in the influence of DfAM on design creativity.

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