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THE EARLIER THE BETTER? INVESTIGATING THE IMPORTANCE OF TIMING ON EFFECTIVENESS OF DESIGN FOR ADDITIVE MANUFACTURING EDUCATION

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ABSTRACT
Additive Manufacturing (AM) is a novel process that enables the manufacturing of complex geometries through layer-by-layer deposition of material. AM processes provide a stark contrast to traditional, subtractive manufacturing processes, which has resulted in the emergence of design for additive manufacturing (DfAM) to capitalize on AM's capabilities. In order to support the increasing use of AM in engineering, it is important to shift from the traditional design for manufacturing and assembly mindset, towards integrating DfAM. To facilitate this, DfAM must be included in the engineering design curriculum in a manner that has the highest impact. While previous research has systematically organized DfAM concepts into process capability-based (opportunistic) and limitation-based (restrictive) considerations, limited research has been conducted on the impact of teaching DfAM on the student's design process. This study investigates this interaction by comparing two DfAM educational interventions conducted at different points in the academic semester. The two versions are compared by evaluating the students' perceived utility, change in self-efficacy, and the use of DfAM concepts in design. The results show that introducing DfAM early in the semester when students have little previous experience in AM resulted in the largest gains in students perceiving utility in learning about DfAM concepts and DfAM self-efficacy gains. Further, we see that this increase relates to greater application of opportunistic DfAM concepts in student design ideas in a DfAM challenge. However, no difference was seen in the application of restrictive DfAM concepts between the two interventions. These results can be used to guide the design and implementation of DfAM education.

Keywords: Design for Additive Manufacturing, Engineering Education, Manufacturing.

INTRODUCTION
Additive manufacturing (AM) is the process of building a component layer by layer [1]. This process was developed as a method to be able to fabricate objects of any form, through a digital model, with the click of a button [2]. The development of this new 'freeform fabrication' process has provided designers with an opportunity to go beyond the limitations of conventional manufacturing processes. However, the characteristics of AM processes provide a stark contrast to conventional manufacturing processes, with the term 'Additive' established initially to distinguish from conventional 'Subtractive' processes [3]. For example, AM processes allow the designer to "print" complex geometries, whereas traditional manufacturing considerations suggest the use of simplified designs that are easier and more cost effective to manufacture. With Design for Manufacturing and Assembly [4–6] as the current standard for concurrent design, there is a strong movement towards integrating Design for Additive Manufacturing (DfAM) into our design process [7]. The main aim of this movement is to tap into the design freedom encouraged by AM processes while ensuring feasibility and manufacturability. This transformation has been facilitated by several industries demonstrating the ability of AM processes to produce functional components and not just prototypes [8].

AM is considered to be one of the largest disruptors in the manufacturing industry and is predicted to have an annual financial impact of up to $550 billion by the year 2025 [9,10]. As a result, there is a growing need for an AM skilled workforce, which was reported to have gone up by 1834% from 2010 to 2014, with an increase of 103% from August 2013 to August 2014 [11]. As described in the 'Roadmap for Additive Manufacturing', the lack of education in AM has been a potential barrier to the uptake of AM processes [12]. One of the key themes identified at the 2013 NSF AM Education and Training Workshop was the importance of "design practices and tools that leverage the freedom enabled by AM" [13,14]. This emphasizes the need for proven methods of educating engineering students in not just AM processes but also DfAM.

Several educational institutions have introduced AM/DfAM into the engineering curriculum through both formal and informal methods [14–16]. As 3D printers become more accessible, students receive greater exposure to the technology. This interaction with AM processes could result in the students having some experience and knowledge about them. However, due to the constructive nature of learning [17], it is important to account for students' prior knowledge in AM, when teaching DfAM. This is of particular importance since learning about AM through working with the printers could primarily expose students to the limitations of the process and how to overcome them, so as to prevent print failure [18,19]. For example, the university-wide printing service at UT Austin [19] provides guidelines to accommodate supports, bridging limits, and dimensional accuracy. A similarity can also be seen in the DfAM worksheet by Booth et al, which offers a list of considerations to evaluate the 3D printability of a part, by measuring the reduction in the number of iterations to reach a successful print [20]. In comparison, the students receive a relatively lower exposure to techniques that help them to fully utilize the capabilities of AM. For example, designers can now feasibly consolidate multiple components into a single, complex part [21]. These two paradigms of DfAM form the fundamentals of restrictive and opportunistic DfAM [22], respectively, with dual DfAM being a combination of the two [23].

Despite the increasing efforts at making 3D printing more accessible, limited research has been conducted on the effect this exposure has on student learning of DfAM concepts. This interaction is important, as it could potentially lead to a greater emphasis on restrictive DfAM over opportunistic, based on their prior knowledge of the concepts. This study aims at filling this gap by comparing two versions of a similar educational intervention to understand the effects of prior AM experience and DfAM educational interventions on student's learning.

RELATED WORK

The aim in this study is to understand the influence of timing of a DfAM intervention on its impact on students' learning in an engineering design course. This section provides the theoretical foundation upon which our study is conducted.

Current status of DfAM Education

The 2013 NSF workshop on AM education and training was one of the first attempts to systematically review current practices in AM education [13,14]. The key educational themes identified at the workshop were: a) process-material relationships, b) material sciences and manufacturing, c) problem-solving and critical thinking, d) design tools to leverage design freedom, and e) cross-functioning design techniques. While these themes highlight the importance of knowledge of AM process characteristics, they particularly stress the ability to apply this knowledge when designing components. This helps support the push towards the use of inductive learning in engineering education [24,25] to promote innovation. The two main forms of inductive learning, seen in manufacturing education, are problem-based (PmBL) and project-based (PjBL) learning. Problem-based learning utilizes the formulation of a solution to an open-ended problem statement, facilitated by the instructor, in order to develop the ability to utilize concepts and theories [26]. Similar to PmBL, project-based learning utilizes an open-ended project objective to encourage student groups to develop an artefact, over a longer period of time [27]. Further, hands-on rapid prototyping has also been shown to be successful in improving design and manufacturing proficiency [28].

As discussed in the reports from the NSF workshop, several institutions have introduced initiatives to encourage PmBL and PjBL of AM. For example, the University of Texas at Austin and Virginia Tech both offer a course that teaches students to understand different AM processes, choose the appropriate process for certain applications, as well as apply this knowledge to a design challenge. The course also enables students to identify research opportunities and challenges in the area of AM [15]. Leveraging the use of PjBL for teaching AM, Williams et al. [16] discussed the use of a university-wide vehicle design competition as a medium for effectively learning DfAM skills.

Similarly, several informal learning initiatives have also worked towards making 3D printing accessible to students. These initiatives rely on hands-on self-learning by encouraging students' interaction with the printers. For example, the DREAMS lab at Virginia Tech studied the use of a 3D printing vending machine [29]. Similarly, several institutions such as Georgia Tech and Penn State, have set up maker spaces to encourage the self-motivated use of 3D printing [14,18,19,30]. While these informal techniques improve familiarity with 3D printing, these interactions primarily introduce students to the limitations of AM processes and how they could overcome them. For example, the design guidelines by Penn State's 'Maker Commons' website [18] mainly consist of restrictive concepts such as supports and part orientation.

While these initiatives have attempted to integrate DfAM into the engineering curriculum, limited research has studied their learning effectiveness. Similarly, limited research has been conducted on the effect of external factors, such as students' previous experience, on their learning of DfAM concepts.

Prior knowledge, motivation, and interest in learning

AM knowledge consists of both, knowledge of the processes, as well as considerations for designing for them (DfAM). Current educational practices, both formal and informal, successfully present knowledge of AM processes; however, limited emphasis is given to DfAM. This is important because the learning process involves transferring knowledge from a student's previous experiences [31], and students' prior AM knowledge could potentially influence their learning of DfAM. Further, research has shown that previous experiences often result in the development of faulty concepts and mental models, and in order to make the learning process effective, it is important to build upon this initial information by understanding and challenging it [32]. Research has also demonstrated that procedural knowledge, as opposed to factual knowledge, results in more effective learning, especially knowledge built up from basic to advanced courses [17].

Similarly, students' motivation also influences the effectiveness of the learning process [31]. Motivation could either be extrinsic (e.g., grades) or intrinsic, where the person is self-driven [33]. Students of all ages have demonstrated higher levels of motivation when they see the usefulness and the context of the information [34]. Interest has also been demonstrated to influence the retention and processing of certain information in preference over others [35]. Schiefel, through studies using textual information [36], demonstrated that higher interest was correlated to a more meaningful and intense processing of the information compared to those with low interest.

When investigated in combination in a free-choice learning institution, participants with low and high prior knowledge, combined with moderate to high interest, showed the largest higher gains in knowledge [37]. This can also be an important aspect of creative processes, where task motivation influences the learning of domain-relevant skills, the organization, retention, and retrieval of which results in higher creative production [38]. These aspects, in combination, play a role in bringing about effective learning. Similarly, the students' prior experience with AM could possibly affect the learning of DfAM concepts, and the aim of this research is to further investigate the interaction between the two.

RESEARCH QUESTIONS

As discussed in the previous section, there has been limited research on how previous AM experience affects learning of DfAM concepts. The aim in this research is to fill this gap by addressing the following research questions (RQs):

RQ1: *Do students' previous experiences in AM change their perceived utility of learning DfAM?* We hypothesize that with lower previous knowledge of AM and higher interest levels, the students find greater use in learning about DfAM [37].

RQ2: *Do students' previous experiences result in a difference in their learning of DfAM concepts?* We hypothesize that the lack of previous experience and higher perceived utility would result in a greater increase in the students' *DfAM self-efficacy* after an educational intervention [34,37].

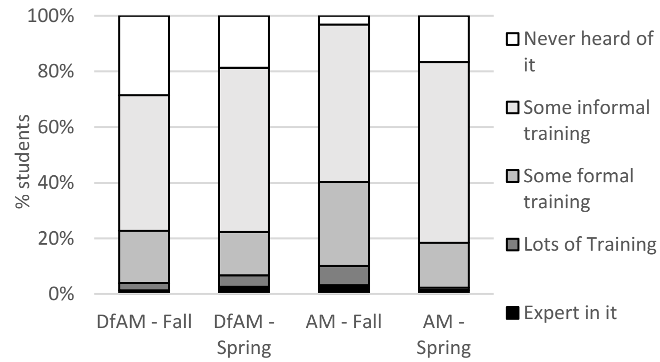

Figure 1 Comparison of participants' previous experience

RQ3: *Do students' previous experiences affect their emphasis on DfAM in the design process?* We hypothesize that better learning attitudes and an increase in DfAM self-efficacy would result in the students displaying a higher application of DfAM in the design process [39].

METHODOLOGY

In order to answer these research questions, an experiment was conducted by introducing an educational intervention consisting of lectures and short design challenges. The relevant details of the experiment, conducted as a part of a larger study, are discussed in this section.

Participants

The experiment was conducted with engineering students from a large Northeastern Public University. A total of 352 students were recruited from two semesters of a junior Mechanical Engineering Design Methodology course with 159 participants in the fall and 193 participants in the spring. Figure 1 summarizes the participants' previous experience in DfAM as collected at the beginning of the experiment.

Fall semester (N=159): Participants were primarily composed of undergraduate students from the Mechanical Engineering Major (N=158) with one participant from Nuclear Engineering (N=1). A few participants were pursuing double majors such as Biomedical Engineering (N=5), Nuclear Engineering (N=3), Mathematics, Economics, and German (N=1, each). The year of study was distributed mainly among juniors (N=74) and seniors (N=73) with a sophomore (N=1), and a few students in their fifth year of study (N=3).

Spring semester (N=193): Participants from the spring were undergraduate students from the Mechanical Engineering Major (N=189) and Information Sciences and Technology (N=1), and some with unspecified majors (N=3). Some of the participants were pursuing double majors such as Biomedical Engineering (N=1), Nuclear Engineering (N=6), and Spanish (N=1). The year of study was mainly juniors (N=160) with some seniors (N=17), a sophomore (N=1), and several unspecified (N=15).

Procedure

As the aim of the experiment was to understand the effects of timing and previous experience, the educational intervention was held constant to avoid confounding effects. Common elements between the fall and spring sessions include the pre-design challenge, DfAM lectures, and post-design challenge. The differentiating elements between the two sessions were (a) timing in the semester and (b) the timeline of events. Before the experiment in each semester, implied consent was obtained, as per IRB protocol. The participants were informed that while the usage of their data was subject to their consent, their participation in the activities would count towards their in-class participation points.

a. Common experimental elements: The experiment in both semesters was broken down into three sections: (1) pre-survey and baseline design challenge, (2) DfAM education lectures, and (3) post-survey and DfAM design challenge.

Pre-survey and baseline design challenge: At the beginning of the experiment, participants were asked to fill out a pre-survey. The pre-survey asked the students to report previous experience in AM and DfAM, as well as the number of years and source of training in each area. The pre-survey also contained a section evaluating the students' self-efficacy with respect to a set of DfAM techniques (including both opportunistic and restrictive elements) and a rating for their own interest and motivation in learning about AM. After the pre-survey, a 10-minute design challenge was conducted to understand the students' baseline creativity. The pre-design challenge was included as a part of a larger study and is not relevant to this paper. The prior experience and DfAM self-efficacy survey can be accessed at http://sites.psu.edu/madebydesign/design-cognition/.

DfAM lectures: Once the challenge was completed, the students were introduced to different AM processes and DfAM concepts through lectures. First, all participants were given an overview lecture on AM which contained an overview of the material extrusion AM process, distinction from subtractive manufacturing, the digital thread, Cartesian coordinates, and printable materials. The group that attended only the first part of the lecture was our control group, as they received no DfAM education during the intervention. Following this overview, a portion the students attended a lecture on the *restrictive* aspects of DfAM, with a discussion on build time, feature size, support material, anisotropy, surface finish, and warping. Following this, a fraction of this group of students was given a lecture on the *opportunistic* aspects of DfAM. The lecture included a discussion of geometric complexity, mass customization, part consolidation, printed assemblies, multi-material, and functional embedding. The distribution of the number of students is summarized in Figure 2. The DfAM slides can be accessed at http://sites.psu.edu/madebydesign/design-cognition/.

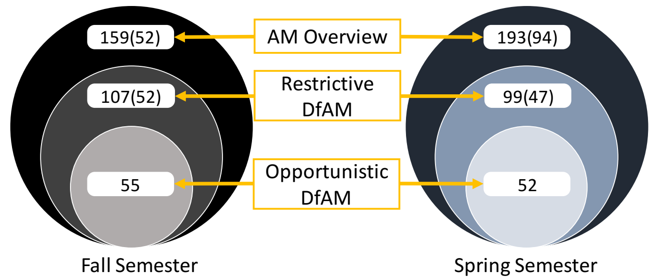

Figure 2 Distribution of participants - fall (L), spring (R)

Post-survey and design challenge: For the third section of the experiment, the students were asked to participate in a design challenge with a modified version of the problem statement from the baseline design challenge. The problem statements were chosen such that differences could be observed while avoiding fixation effects [38,40]. The design challenge was conducted as part of a larger study and the details are not relevant to this paper. Upon completing the concept generation and selection, they were asked to rate how much emphasis they gave to different DfAM techniques (opportunistic and restrictive) on a scale from 1= 'not important at all' to 5= 'absolutely essential.' Once the design challenge was completed, they were asked to complete a post-survey with questions about their self-efficacy with the different DfAM techniques; the post-survey also asked students to evaluate the usefulness of the lecture, the design challenge, and the overall experience.

b. Differentiating Elements: Based on the outcome and feedback received from the participants in the fall, certain changes were made in the intervention to account for students' previous experience. The key differences are described in this section.

Timing in the semester: In order to investigate the effect of prior AM experience and timing of the DfAM intervention on students' learning, the intervention was conducted at two points of time in the semester. In the fall session, the experiment was conducted mid-way through the semester, in the 10th week of the academic calendar. As a result, students had already experienced some formal AM training in the course through previous class laboratory assignments. The experiment was also introduced as a 'guest lecture', and not as an integrated part of the course curriculum itself (though the connection to the course content was still emphasized). In contrast, the spring version was conducted in the 2nd week of class and was introduced as an integral part of their course plan. As a result, the students had less prior AM/DfAM experience in the class, mostly derived from their personal projects. This can be seen in the distribution of the participants' previous experience in Figure 1. In the fall, 40% of the participants reported having some formal training (or more) in AM, whereas, in the spring, only 21% fell into these categories. It was also observed that, among the students who reported the source of their previous AM experience, a majority of the students in the fall mentioned the current course (ME340) as being one of them, therefore confirming the absence of any seasonal effects. It should also be noted that, while there were differences in previous AM experience, the distribution of previous DfAM experience was similar between the two groups, with approximately 22% of students having some formal DfAM training (or more), in both semesters.

As seen in Figure 3, the participants in the spring also showed higher levels of motivation and interest than in the fall. In the fall, approximately 70% participants reported above moderate levels of motivation, as opposed to 88% in the spring. Similarly, in the fall, 89% reported above moderate interest levels compared to 95% in the spring. While this could be attributed to the fall students already having received significant exposure to AM, it could also be due to the timing in the semester, when students generally have several deliverables due.

Timeline of events: As summarized in Figure 4, another key difference in the procedure was the timeline of events. The changes in the timeline were mainly introduced to tap into the available lab sessions, while keeping constant the duration and quantity of the delivered content. In the fall, the experiment was carried out over two lecture periods of 75 minutes each. The first lecture period was used to conduct the pre-DfAM survey and design challenge, along with the DfAM lectures. The first 10 minutes were used for the pre-design challenge, after which all students received the 15-minute AM overview lecture. Then, a third of the students (N=52) were asked to leave the room, and the remaining students (N=107) were given a 20-minute lecture on restrictive DfAM. Following this, half of the remaining students (N=52) were asked to leave the room, and the remaining students (N=55) were given a 20-minute lecture on opportunistic DfAM. The second lecture period was used to conduct the post-DfAM design challenge and survey.

In the spring version, the experiment was spread out over four days comprising two 55-minute lecture sessions and two 180-minute lab sessions. The lectures were conducted on successive Wednesdays, with one lab session between them, and one after. The students were divided into eight lab sections, with Sections 1-4 as our control group (no DfAM), Sections 5-6 as our restrictive only DfAM group, and Sections 7-8 as the opportunistic and restrictive DfAM group. The number of participants in each group is summarized in Figure 2.

Day 1 (Wed, Lecture): The first lecture period was used to conduct the pre-DfAM survey and baseline design challenge, followed by all students receiving the AM overview lecture. No DfAM concepts were discussed in this lecture.

Day 2 (Tues, Lab): This lab session was used to conduct the post-DfAM challenge for Sections 1-4 (control group). Followed by the design challenge and post-survey (~45 min), the rest of the lab was spent developing CAD models and preparing prints.

Day 3 (Wed, Lecture): On the second lecture period, all students were given a 20-minute lecture on restrictive DfAM. Then, students from Sections 5 and 6 were asked to leave the room, and the remaining students were given a lecture on opportunistic DfAM. This was possible since the control group had already completed their post-design challenge and survey.

Day 4 (Thurs, Lab): This lab session was used to conduct the post-DfAM design challenge and survey for Sections 5-8 (~45 min), with the remaining time given for CAD modelling and print preparation.

CAD modelling and print preparation: At the end of the post-design challenge in the fall, the students were given an optional take-home printing assignment. The assignment provided instructions for developing CAD models for their designs and printing them using the university-provided printing services. In comparison, in the spring session, the post-DfAM design challenge was conducted as a mandatory part of the students' labs. Upon completion of the challenge and the post-survey, the students were broken into teams and asked to choose one design, model it using CAD, and send a prepared print file to the university printing service. Since the data relevant to the experiment was conducted before the CAD modelling stage, we anticipate that this change did not affect their learning; however, future studies should investigate the effect of including CAD in the students' learning related to AM and DfAM concepts.

Metrics

In order to measure the effectiveness of each educational intervention, three metrics were used: (1) perceived utility of the lectures and design challenge, (2) DfAM concept self-efficacy, and (3) use of DfAM concepts in the student's design challenge solutions. This section describes each metric in detail.

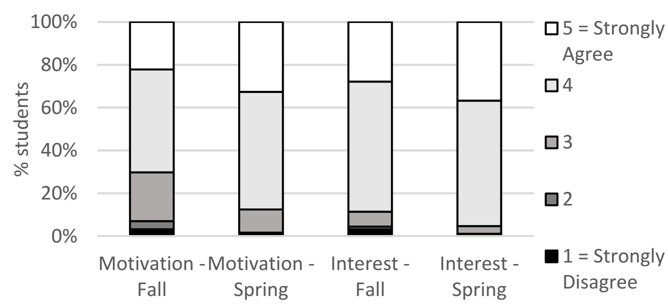

Figure 3 Summary of motivation and interest

Perceived utility of the intervention

In order to assess the perceived utility of the DfAM lectures and the design challenges, the participants were asked to evaluate their experience on a 5-point Likert scale from 'Strongly Disagree' to 'Strongly Agree' using the criteria in Table 1. These criteria were designed based on the recommendations from the NSF workshop on AM education. For example, "understands that 'complexity is free' in AM" was one of the recommended traits of an 'ideal AM engineer' [14]. These evaluations were aggregated and averaged to obtain a final evaluation score for the lectures (L1-L6) and the design challenge (C1-C4).

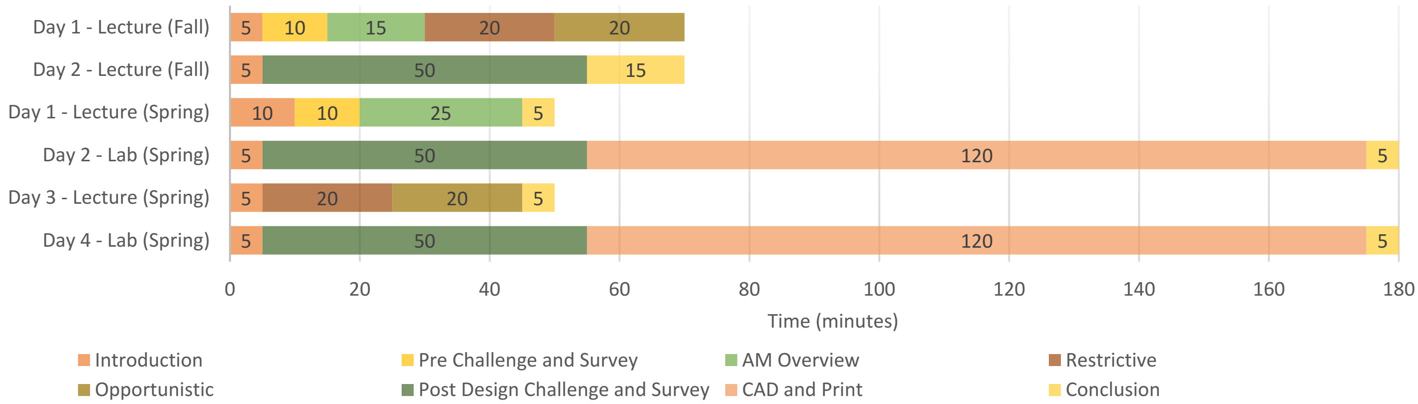

Figure 4 Comparison of timelines between the two semesters

Table 1 Criteria used for evaluating perceived utility

L1	Helped me understand about the AM process
L2	Helped me understand about the different AM processes
L3	Helped me understand the steps involved in making a part using AM
L4	Helped me understand the design freedom provided by AM
L5	Showed me how I can be creative with my designs
L6	Showed me how I can ensure my designs are feasible to manufacture
C1	Helped me utilize the capabilities of AM
C2	Helped me utilize the limitations of AM
C3	The design challenge fit well with the lectures
C4	Was useful in better understanding the concepts discussed in the lectures

DfAM self-efficacy

Effective instruction and learning are also characterized by the development of metacognition – a student's ability to assess their own learning [31]. Bandura [42] demonstrated the use of self-efficacy as a determinant of response initiation, the effort spent on the response, and the duration of the response. The concept of self-efficacy has also been proven to be a measure of performance ability in engineering design [43], computer science [44,45], and sports [46,47].

Based on the usefulness of self-efficacy as an assessment for learning, a DfAM self-efficacy survey was developed. The survey consisted of concepts from the two paradigms of design, namely, opportunistic and restrictive DfAM [22]. Opportunistic DfAM concepts focus on utilizing the capabilities of AM through design concepts such as (1) mass customization [48], (2) part consolidation [21] and printed assemblies [49], (3) free shape complexity [50–52], (4) embedding external components [53], and (5) printing with multiple materials [54]. On the other hand, restrictive DfAM principles, which are important in reducing the failure of prints, include constraints such as (1) support structures [55], (2) warping due to thermal stresses [56], (3) anisotropy [57,58], (4) surface roughness due to stair-stepping [59,60], and (5) feature size and accuracy [61]. Table 2 shows the items from the developed DfAM self-efficacy survey.

The participants were asked to rate their comfort with each concept on a 5-point Likert scale as seen in Table 3. This scale was developed based on the cognitive domain of Bloom's Taxonomy, particularly, the concepts of remembering, comprehending, and applying [39]. Concepts O1-5 and R6-10 were then aggregated to obtain a mean opportunistic and a mean restrictive score, respectively. A difference between students' pre- and post-intervention self-efficacy scores was calculated for both, opportunistic and restrictive DfAM.

Table 2 DfAM self-efficacy items

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

Table 3 Scale used for DfAM self-efficacy

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

A high Cronbach's alpha [62] determined the internal consistency of the scale as a whole to predict DfAM self-efficacy (pre-DfAM α = 0.897, post-DfAM α = 0.875). The individual opportunistic and restrictive sections of the scale also showed a high internal consistency, as determined by 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).

Use of DfAM in the design process

To understand the students' use of DfAM in their design challenge solutions, the students were asked to report the importance they gave to a list of DfAM concepts. The items from the DfAM self-efficacy scale were modified to shift the focus to the product instead of general DfAM concepts. For example, Statement #1 from Table 3 was modified to "the product can be customized for each different user". The participants were asked to reflect on their design process and report the importance given to each concept on a 5-point Likert scale, with 1= 'not important at all,' to 5= 'absolutely essential.' Opportunistic and restrictive DfAM emphasis scores were obtained by taking the means of concepts O1-5, and R6-10, respectively.

DATA ANALYSIS AND RESULTS

Before investigating the results of each research question, descriptive statistics were obtained for each metric (Figure 5). Before conducting the analysis, an outlier analysis was conducted, and unusually low values were replaced with the next extreme value [63]. A sample size of 313 (vs. 352) was used for the analysis, after addressing any missing values. Out of the total 313 participants, 140 were from the fall session and 173 from the spring. Of the 140 participants in the fall, 49 participants received no DfAM intervention, 42 participants received only the restrictive DfAM intervention, and 49 participants received both the restrictive and opportunistic DfAM interventions. Similarly, among the 173 participants in the fall, 84 participants received no DfAM intervention, 43 participants received only the restrictive DfAM intervention, and 46 participants received both the restrictive and opportunistic DfAM interventions. SPSS V. 25 was used for all analysis, and a significance level of 0.05 was used for statistical significance. The results for each research question are discussed in the following sections.

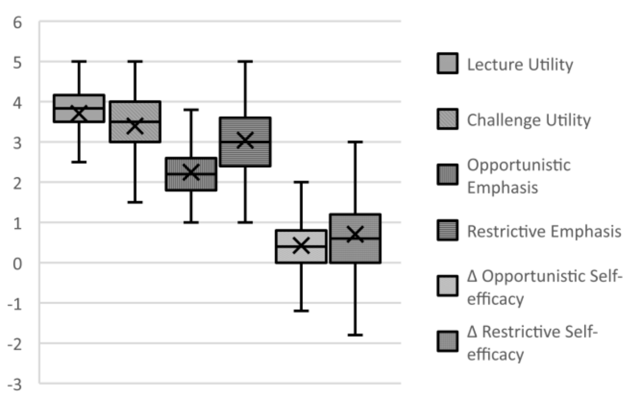

Figure 5 Descriptive statistics for metrics

RQ1: Do students' previous experiences in AM change their perceived utility of learning DfAM?

To answer this research question, a Mann-Whitney U test [64] was performed to check for differences in perceived utility of the intervention, between the fall and spring. Then, a Generalized Estimating Equation was generated to determine whether teaching different DfAM concepts had an influence on these differences.

Change in perceived utility of Lectures:

A Mann-Whitney U test was run to determine if there were differences in the perceived utility of the lectures between the fall and spring interventions. The distributions of mean perceived utility were similar, as assessed by inspecting the frequency distribution. The median of the perceived utility was significantly higher in spring (Mdn = 4.00) compared to fall (Mdn = 3.67), U = 16,236.00, z = 5.207, $p < 0.001$. A Generalized Estimating Equation was set up to check if these differences were affected by the different DfAM education groups. There was no significant interaction effect between the input group and the semester (χ^2 (2) = 2.705, p = 0.259). This result suggests that irrespective of the DfAM concepts taught to the students, the students in the spring, where DfAM was introduced earlier in the semester, found the lectures to be more useful than those in the fall, where it was introduced later. Therefore, a DfAM educational intervention is likely to be more effective if introduced at an early stage, when students have less previous experience in AM.

Change in perceived utility of the Design Challenge:

Similarly, a Mann-Whitney U test showed that the median of the perceived utility of the design challenge was significantly higher in the spring (Mdn = 3.75) than in the fall (Mdn = 3.25), U = 15,123.50, z = 3.812, $p < 0.001$. A Generalized Estimating Equation showed that teaching different DfAM concepts did not have an interaction effect with the intervention semester (χ^2 (2) = 0.250, p = 0.882). Therefore, we see that the use of a design challenge as a PmBL tool to teach DfAM is likely to result in greater learning effectiveness if it is conducted at a stage where the students have less prior experience with AM.

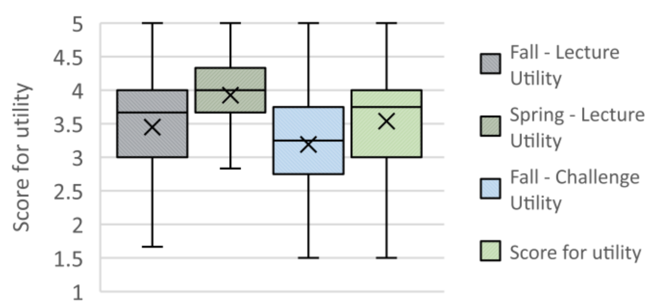

Figure 6 Summary of perceived utility

Overall, we can see that the students' prior knowledge of AM influences their perceived utility of the DfAM intervention. Students from the spring, who had limited formal exposure to AM, find the intervention to be more useful, in comparison to the participants in the fall. As demonstrated in previous research [34]*, students show greater learning if they find usefulness in the presented content. This emphasizes the importance of introducing DfAM education early in the students' AM journey.*

In order to further investigate this effect on the students' learning, we next discuss the results of analyzing the change in students' self-efficacy.

RQ2: Do students' previous experiences result in a difference in their learning of DfAM concepts?

In order to answer the second research question, a Mann Whitney U test was performed to check for differences in the pre- to post-survey in DfAM self-efficacy for both fall and spring. Then a Generalized Estimating Equation was used to check if this result varied based on different DfAM concepts.

Change in Opportunistic DfAM Self-efficacy:

The results of the Mann Whitney U test, summarized in Figure 7, showed that the participants in the spring reported a greater median increase in opportunistic self-efficacy, compared to the fall. While the distributions of the scores were similar, the median of the change in opportunistic self-efficacy was significantly higher in the spring (Mdn = 0.600) than in the fall (Mdn = 0.200), U = 13,976.00, z = 2.354, p = 0.019. This result was not affected by teaching different DfAM concepts, as verified by a Generalized Estimating Equation which showed no significant interaction effects (χ^2 (2) = 1.447, p = 0.485). This result suggests that students with lower prior experience show a relatively higher potential for learning opportunistic DfAM.

Change in Restrictive DfAM Self-efficacy:

A similar result was seen in restrictive DfAM; a Mann Whitney U test showed that the participants in spring showed a greater increase in self-efficacy compared to those in the fall. The distributions of the change were similar, with the median increase in spring (Mdn = 0.800) being significantly higher than in the fall (Mdn = 0.400), U = 14,948.00, z = 3.574, p < 0.001. A Generalized Estimation Equation was used to determine if these differences were affected by teaching different DfAM concepts.

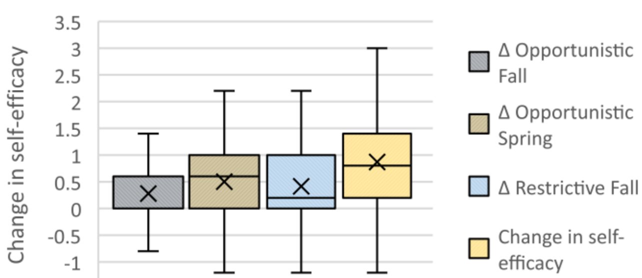

Figure 7 Summary of change in DfAM self-efficacy

The model showed no significant interaction effects (χ^2 (2) = 2.805, p = 0.246). These results further support our hypothesis that students with low previous AM experience, show a greater potential for learning of DfAM concepts, in this case, restrictive DfAM.

In summary, we can make two important inferences from these second results. First, we see that students in the spring, with a relatively lower exposure to AM, show a greater potential for learning DfAM concepts. This is seen in case of both opportunistic and restrictive concepts. This goes to further reinforce the findings of RQ1, where we deduced the importance of integrating DfAM education, early in the students' AM learning process. This observation also fits with previous research, where higher perceived usefulness was shown to result in effective learning [34]. *A second observation is that the change in restrictive self-efficacy was higher in both semesters, compared to opportunistic self-efficacy. This observation is particularly important because, while this could indicate that restrictive concepts are easier to comprehend and retain, we could also infer that these concepts tend to be applied more than opportunistic concepts. This outcome is not favourable, as it would result in fewer print failures but at the expense of underutilization of AM capabilities.* An investigation into the application of these concepts is discussed next.

RQ3: Do students' previous experiences affect their emphasis on DfAM in the design process?

To answer the final research question, a Mann Whitney U test was performed to check for differences in the usage of DfAM concepts between the fall and spring. A Generalized Estimating Equation was then generated to understand if there were any interaction effects of teaching different DfAM concepts. The results obtained are as discussed in this section.

Change in Emphasis on Opportunistic DfAM:

A Mann-Whitney U test was run to determine if there were differences in the emphasis given to Opportunistic DfAM concepts, between the fall and spring sessions. The distributions of the scores were similar, and the median opportunistic emphasis score was significantly higher in the spring (Mdn = 2.20) than in fall (Mdn = 2.00), U = 14,637.50, z = 2.988, p = 0.003. A Generalized Estimating Equation showed no significant interaction effects between the two predictors, χ^2 (2) = 1.785, p = 0.410. This result suggests that introducing DfAM at a stage when students have low previous AM experience succeeds in increasing their use of opportunistic DfAM concepts in the design process. This is particularly important because the higher emphasis on opportunistic DfAM will result in better utilization of AM capabilities and thus more innovative end products.

Change in Emphasis on Restrictive DfAM:

Similarly, a Mann-Whitney U test was performed to determine if there were differences in the emphasis given to Restrictive DfAM in the design process between the fall and spring sessions. Results showed no significant median difference between the scores in the spring (Mdn = 3.00) and fall (Mdn = 3.00), U = 12,744.00, z = 0.617, p = 0.537. A Generalized Estimating Equation showed that this result was not affected by any interaction effects due to teaching different DfAM concepts, χ^2 (2) = 2.441, p = 0.295. These results suggest that the students report a similar usage of restrictive DfAM, irrespective of their level of prior experience in AM. Further, educating the students about different DfAM concepts does not interact with these results. However, we also see that this emphasis is relatively higher than opportunistic DfAM concepts, thus reducing the potential for seeing the hypothesized increase.

These results point us towards two important inferences. First, we see that teaching DfAM at an early stage results in the students reporting a greater usage of opportunistic DfAM. This is favourable, as it would result in the students using the capabilities of AM to a greater extent in their designs. However, this increase is not seen in the case of restrictive DfAM. The second observation is that while the emphasis on restrictive DfAM is the same in both semesters, it is higher than the usage of opportunistic DfAM. This goes to further support the findings of RQ2 that along with easier comprehension and retention of restrictive DfAM concepts, these concepts are also applied more than opportunistic DfAM. This second observation points out that teaching opportunistic DfAM early on is not sufficient to encourage an increase in the use of these concepts. A change in mindset from restrictive to dual (opportunistic plus restrictive) DfAM must be brought about by teaching the students how to tie in opportunistic DfAM concepts into their design process.

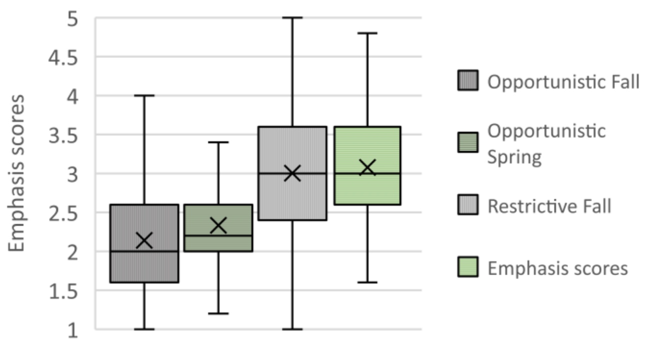

Figure 8 Summary of emphasis on DfAM

DISCUSSION

The goal in this research is to understand the effect of prior AM experience on the learning and application of DfAM concepts. Specifically, perceived utility, self-efficacy, and use of DfAM in the design process were used as measures of effectiveness. The three main findings of the research are:

1. Students with minimal previous AM experience found the DfAM lectures and design challenge to be more useful.
2. Students with minimal previous AM experience also showed greater learning of both opportunistic and restrictive DfAM concepts.
3. While the students with lesser prior experience reported a greater application of opportunistic AM, there were no differences in the application of restrictive DfAM. Also, the use of restrictive DfAM was generally higher than opportunistic DfAM.

Overall, we see that a DfAM education intervention has a greater impact as hypothesized, if introduced at an early stage in the students' AM learning journey. The significance of these results is discussed further in this section.

Students with lower levels of prior AM experience perceive the DfAM intervention to be more useful.

Prior research in education has shown that students who see the utility of a concept, tend to show higher motivation and effective learning [34]. Therefore, in order for the DfAM intervention to be effective, it is crucial that the students perceive the intervention to be useful. The results of the first research question suggest that introducing DfAM when students have limited prior experience in AM results in the students perceiving the intervention to be of greater utility. As AM processes become more accessible, this interaction with the process acts as a source for learning about the process [28]. This exposure could in effect result in the students not seeing the usefulness of learning about DfAM at a later stage, therefore reducing the effectiveness of a DfAM intervention. Further, as seen in Figure 1, while the participants showed differences in their previous AM experience, their previous DfAM experience was approximately the same. This further highlights the lack of DfAM in their learning process, and the importance of integrating the same, early on. Therefore, it is important for DfAM educators to have an understanding of the students' prior AM experience, in order to effectively teach DfAM. This goes for both lecture-based as well as problem-based teaching techniques. This knowledge will enable educators to not only build up on the students' experiences but also introduce DfAM at a point when they perceive it to be most useful.

Changes in the intervention result in a greater increase in DfAM self-efficacy

In order to further understand the effect of prior knowledge on the learning and comprehension of DfAM concepts, the change in students' self-efficacy was compared. The results suggest that students with lower prior experience in AM, show a greater increase in their self-efficacy in both opportunistic and restrictive DfAM. This result is in agreement with previous results demonstrating the importance of perceived usefulness in encouraging learning [34]. Moreover, these results further strengthen the conclusion from RQ1, namely, introducing the intervention at an early stage results in better learning of DfAM concepts.

Another important finding from the result was that the increase in the students' self-efficacy is greater in the case of restrictive DfAM concepts in comparison to opportunistic DfAM. This is seen in both semesters, which suggests that restrictive DfAM concepts are easier to learn and comprehend, relative to opportunistic DfAM. While this would favourably lead to students developing parts that are more feasible to manufacture, it would also lead to students not using AM processes to their full design potential. Such an outcome would not be in line with the excitement surrounding AM and recommendations from the NSF workshop, where understanding the free complexity provided by AM was identified as necessary for the success of an AM engineer [13,14]. This result further suggests that educators must take special efforts to emphasize and teach opportunistic DfAM concepts to ensure effective DfAM learning.

While students with low AM experience report a greater use of opportunistic DfAM, no change is seen in the use of restrictive DfAM

The third research question looked at the difference in the use of DfAM concepts among students who have low and high levels of previous AM experience. From the results, we see that students with low levels of previous AM experience result in reporting a greater use of opportunistic DfAM concepts. However, no difference is seen in the use of restrictive DfAM. Two important observations can be made from the results. First, we see that in the case of opportunistic DfAM, the results support our hypothesis that the intervention succeeds in bringing about a greater application of opportunistic DfAM if introduced early in the students' AM learning. Since the students have limited experience in AM, they possibly demonstrate greater flexibility in integrating opportunistic DfAM in their design process. This is a favourable outcome as it would possibly result in better utilization of the capabilities of AM processes. This result further reinforces the observations from previous results, that teaching DfAM, particularly opportunistic, early on, is favourable in encouraging the use of these concepts in the design process.

The second observation was that students from both levels of previous experience showed a relatively higher use of restrictive DfAM in comparison to opportunistic DfAM. This higher emphasis could be a possible explanation for the refutation of the hypothesis that students with less previous experience would show a greater use of DfAM in the design process. This could also further support the conclusion from RQ2, that in addition to restrictive concepts being easier to learn and comprehend, these concepts are also easier to apply in the design process. This could be attributed to the widespread use of DFMA concepts, where manufacturing considerations mainly focus on the limitations of the manufacturing process. This result further stresses the need for educators to not only teach opportunistic DfAM early on but also emphasize integrating these concepts into the design process as students learn.

CONCLUSION AND FUTURE WORK

Literature has shown the influence of prior experiences on learning [31], along with the importance of building upon and challenging preconceived mental concepts [32]. In order to meet the growing need for an AM skilled workforce, various formal and informal educational initiatives are being undertaken to teach AM to engineering students. While a similar effort is not seen in the case of DfAM, students' previous AM experience could, in turn, influence their learning of DfAM concepts.

The aim in this research was to investigate this interaction between the students' previous AM experience and their learning of DfAM. This was achieved by introducing a DfAM intervention at two different points in the semester during an engineering design class. The interventions were evaluated using the students' perceived utility of the intervention, change in their self-efficacy with these DfAM concepts, and the emphasis given to these concepts in the design process. Results suggest that students with lower previous experience in AM, find greater utility in the intervention. A similar result was also seen in the students' DfAM self-efficacy, where students with low previous experience showed a greater increase in both opportunistic and restrictive self-efficacy. However, it was also seen that the increase in restrictive self-efficacy was greater than the increase in opportunistic self-efficacy. The results further supported our hypothesis where students with low previous AM experience reported a greater use of opportunistic DfAM in the design process. While this difference was not seen in the case of restrictive DfAM, the use of restrictive DfAM was relatively higher in both semesters compared to opportunistic DfAM. This suggests that restrictive DfAM concepts, in addition to being easier to comprehend and learn, are also easier to apply in the design process.

These results emphasize two points. First, the results demonstrate the influence of students' previous AM experience in learning of DfAM concepts. This further emphasizes on the need for teaching DfAM, early in the students' AM learning journey, so as to bring about effective learning. Second, the results demonstrate the need to not just teach but make special efforts to encourage the integration of opportunistic DfAM concepts into the students' design process. This is crucial for the successful uptake of AM processes in engineering design.

Although the research demonstrates the importance of timing of a DfAM intervention on its effectiveness, future research could investigate a deeper understanding of the nature of these results. First, the study primarily relies on self-reported data from the participants to evaluate the effectiveness of the intervention. A study of the design process and the outcomes of the design challenge could provide further insights into whether this data accurately represents the actual designs. Second, further research could be focused on understanding the use of DfAM at different stages of the design process, such as concept generation and evaluation, instead of the design process as a whole. This is particularly important as the design concepts could have been used differently at different stages of the process, and a single evaluation might not be able to capture these differences. This would also reach out to different cognitive aspects of learning such as analysis, synthesis, and evaluation [39]. Third, the short duration of the intervention could have limited the students' ability to apply the various DfAM concepts together. Therefore, this research could also be extended towards using a more elaborate design challenge, to understand its effects.

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