Exploring the Effects of Additive Manufacturing Education on Students' Engineering Design Process and its Outcomes

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ABSTRACT

Research in additive manufacturing (AM) has increased the use of AM in many industries, resulting in a commensurate need for a workforce skilled in AM. In order to meet this need, educational institutions have undertaken different initiatives to integrate design for additive manufacturing (DfAM) into the engineering curriculum. However, limited research has explored the impact of these educational interventions in bringing about changes in the technical goodness of students'

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design outcomes, particularly through the integration of DfAM concepts in an engineering classroom environment. This study explores this gap using an experimental study with 193 participants recruited from a junior-level course on mechanical engineering design. The participants were split into three educational intervention groups: (1) no DfAM, (2) restrictive DfAM, and (3) restrictive and opportunistic (dual) DfAM. The effects of the educational intervention on the participants' use of DfAM were measured through changes in (1) participants' DfAM self-efficacy, (2) technical goodness of their AM design outcomes, and (3) participants' use of DfAM-related concepts when describing and evaluating their AM designs. The results showed that while all three educational interventions result in similar changes in the participants' opportunistic DfAM self-efficacy, participants who receive only restrictive DfAM inputs show the greatest increase in their restrictive DfAM self-efficacy. Further, we see that despite these differences, all three groups show a similar decrease in the technical goodness of their AM designs, after attending the lectures. A content analysis of the participants' design descriptions and evaluations revealed a simplification of their design geometries, which provides a possible explanation for the decrease in their technical goodness, despite the encouragement to utilize the design freedom of AM to improve functionality or optimize the weight of the structure. These results emphasize the need for more in-depth DfAM education to encourage the use of both opportunistic and restrictive DfAM during student design challenges. The results also highlight the possible influence of how the design problem is stated on the use of DfAM in solving it.

1. INTRODUCTION

Additive manufacturing (AM) – the process of depositing material layer-by-layer to 'print' the desired object [1] – was developed with the aim of manufacturing parts of any shape and form [2]. This 'freeform' fabrication technique has enabled designers and engineers to go beyond the shortcomings of traditional manufacturing processes, such as the inability to manufacture complex, hollow structures and internal channels cost-effectively [3]. However, the layer-by-layer processing of material entails unique challenges that strongly contrast those of conventional subtractive processes [4]. This difference in process considerations has resulted in the emergence of design guidelines specific to AM, generally referred to as design for additive manufacturing (DfAM). Further, several frameworks have attempted to categorize DfAM concepts, of which [5] recommends the use of a 'dual DfAM' framework comprising of a combined application of opportunistic and restrictive DfAM. Specifically, while opportunistic DfAM employs techniques to leverage the capabilities of AM (e.g., shape complexity and part consolidation), restrictive DfAM techniques provide designers with guidelines to accommodate the limitations of AM processes.

Further, DfAM differs from traditional design for manufacturing and assembly (DFMA) [6–8] in many ways. For example, traditional DFMA considerations suggest the use of simplified designs as they demonstrate better manufacturability and cost-effectiveness [6]. In contrast, AM designers are encouraged to use more complex geometries to increase functionality and reduce weight, since researchers argue that 'complexity is free' when using AM [9].

In light of these differences in design methodologies, several industries are transitioning from traditional Design for Manufacturing and Assembly (DFMA), the current standard for concurrent engineering, towards using DfAM in the design process [10]. This movement, most prevalent in the aerospace and biomedical industries [11–13], aims at developing products that are not only feasible and easy to manufacture, but also leverage the design freedom enabled by AM. This is achieved through the use of a combination of opportunistic and restrictive considerations that emphasize the design freedom and process limitations of AM, respectively.

AM processes are predicted to have a significant impact not only on the manufacturing industry [14,15] but also on the employment landscape, with a constantly growing need for a skilled AM workforce [16]. However, the lack of systematic AM education [17,18], particularly in the area of DfAM methodologies [9,19], has been an impediment to the uptake of AM processes and the development of the AM workforce. This motivates the need for proven AM and DfAM courses and curriculum, and several educational institutions have introduced AM/DfAM into the engineering curriculum through both formal and informal instructional methods [9,20–22]. Furthermore, as 3D printers become more accessible through makerspaces and other shared facilities, students receive greater exposure to these AM processes and also a platform to develop their skills with AM technologies [23–25]. However, the experience gained by interacting with 3D printers primarily exposes students to the limitations of the process and methods of overcoming them to prevent print failure (i.e., restrictive DfAM) [26,27]. For example, the student-access 3D-printing service at UT Austin [27] provides students with design guidelines for support material, bridging overhangs, and dimensional integrity, but not lattice structures, topology optimization, biomimicry, and other opportunistic DfAM aspects. Similarly, the DfAM worksheet developed by Booth and co-authors offers a list of design metrics to evaluate the manufacturability of a part to reduce the number of failed prints [28], i.e., only restrictive DFAM. Opportunistic DfAM techniques such as multi-material printing [29,30] and shape optimization [31] have received even less emphasis in comparison. These design considerations are important as they encourage designers to fully leverage the capabilities of AM [32]. While the use of restrictive DfAM techniques is essential to ensure design feasibility, opportunistic DfAM techniques help designs capitalize on the freedoms provided by AM.

Several initiatives have attempted to integrate AM and DfAM into engineering education. However, limited research has studied the effect of these interventions on the students' use of DfAM in the engineering design process. Moreover, limited research has explored how variations in DfAM educational content could play a role in this usage. This is particularly important since the integration of DfAM into the students' design process could potentially affect the technical goodness of their designs. The present study aims at exploring this gap by investigating participants' learning and use of DfAM in their design process, and its influence on their AM design outcomes. Related work is reviewed next followed by a description of our experimental study.

2. RELATED WORK

To understand the effect of variations in DfAM education on the technical goodness of students' AM design outcomes, previous research was explored. Particularly, literature in the areas of current DfAM education and methods of assessing engineering education was looked into, as they would not only provide insights into current educational practices but also into the tools used for assessing the effectiveness of educational interventions. The key findings are discussed in the remainder of this section.

2.1. The need for and current status of DfAM education

In 2013, the National Science Foundation (NSF) supported a workshop on AM education and training, where leaders in AM research, both academic and industrial, were brought together to evaluate current practices in AM education [9,19]. One of the important outcomes of the workshop was the identification of the need for educational initiatives in the following areas: a) process-material relationships, b) material sciences and manufacturing, c) problem-solving and critical thinking, d) design tools to leverage design freedom, and e) inter-disciplinary design methods. These themes suggest the need for AM engineers to not only know about and understand the characteristics of AM processes but also be able to use these concepts to solve problems and improve existing solutions. This need for the development of a workforce capable of using AM to solve problems presents the need for inductive learning practices in AM education.

Several academic institutions have introduced educational initiatives based on inductive learning [33,34] that introduce AM in problem-based learning (PmBL) [35] and project-based learning (PjBL) settings [36]. For example, an AM-focused course offered in similar forms at both the University of Texas at Austin and Virginia Tech teaches students about the different AM processes, guides them in choosing an appropriate process based on an application, and encourages them to use this learning to solve a design challenge. As part of this course, students also work on identifying research gaps in the area of AM thus helping students develop the ability to analyze previous work and synthesize new research [20]. Similarly, Williams et al. [21] conducted a university-wide competition, where students demonstrated the learning of DfAM skills by designing a vehicle and competing against other student teams.

In addition to these curricular initiatives, several informal learning initiatives have been put in place, with the aim of providing students access to 3D printers and encouraging hands-on self-learning [37]. Some examples include the 3D printing vending machine by the DREAMS lab at Virginia Tech [38], the university-wide maker-commons at Penn State and Georgia Tech [26,27], and the mobile maker space developed at Penn State [39]. Similarly, the idea of setting up 3D printing services at libraries has also been explored by institutes such as Purdue [22,40]. A similar effort has been taken at MIT and Case Western, where students not only have the opportunity to interact with AM technologies but also combine their learning with traditional manufacturing processes such as CNC through a network of several makerspaces and machine shops [41,42]. Despite increasing familiarity with 3D printing among students, these informal exposures teach students about the limitations of AM processes, as the students primarily focus on reducing failed prints, print time, and material waste. This emphasis on restrictive DfAM can also be seen in the development process of Booth's AM worksheet [43], where importance is given to design considerations and workarounds that overcome AM limitations and ensure successful prints. An example can also be seen in the design guidelines provided on the Penn State 'Maker Commons' website [26] where a strong emphasis is given to restrictive concepts such as support material and part orientation.

Although these informal initiatives were developed to expose students to AM processes, they do not successfully inform students about the opportunities provided by AM, which could be important in encouraging innovation [44]. Given the constructive nature of learning [45], students' learning of DfAM could potentially be affected by their previous experience in AM [46]. These effects on learning could, in turn, affect their use of both opportunistic and restrictive DfAM in their design processes. Considering the strong emphasis on restrictive DfAM in informal education initiatives, as well as the similarity of restrictive DfAM to traditional DFMA, students could potentially learn to use the restrictive domain of DfAM more than the opportunistic aspects. To understand these differences in learning effectiveness of different DfAM concepts, it is important to use appropriate assessment techniques. Therefore, literature in the area of learning assessment, particularly in the engineering design domain was explored, as discussed next.

2.2. Assessing Learning in Engineering Design

Research in education has resulted in the development of several methods for assessing effective learning. Effective learning has been characterized by the development of metacognition – the ability to assess our own learning [47]. This was extended towards the concept of self-efficacy, which, as demonstrated by Bandura [48,49], strongly correlates to one's performance ability and motivation. Particularly, self-efficacy has been shown to strongly correlate to the level of response initiation, the effort spent on generating the response, and the duration of the response. The use of self-efficacy has also been validated in relation to one's ability in engineering design [50], computer science [51,52], and sports [53,54]. Therefore, to understand the effect of the DfAM intervention on students' comfort with the concepts, a DfAM self-efficacy scale was used.

In order to support the growing need for integrating DfAM in engineering design, DfAM education must not only increase students' self-efficacy with the DfAM concepts but also bring about meaningful learning through the ability to use the concepts in practice. Mayer [55], distinguishes *meaningful* learning – building knowledge for successfully solving problems [56] – from *rote* learning – learning to remember and reproduce information [57]. A similar perspective of learning has also been presented in the cognitive, knowledge-based domain of Bloom's Taxonomy of learning [58], where effective learning is characterized by six levels of objectives: (1) remember, (2) understand, (3) apply, (4) analyze, (5) evaluate, and (6) create. The higher levels of learning are described as the process of 'transferring knowledge' to either solve, find, or learn new problems [59], using an understanding of previous learning [47,60–63].

Assessment of the effectiveness of an educational intervention must, therefore, not only measure the conceptual understanding induced by the intervention, but also evaluate the development of the ability to use these concepts towards problem-solving [62]. This idea has resulted in the increased use of inductive learning and assessment techniques in engineering education [33,34], which focus primarily on the development of the ability to solve problems. Research has also explored the use of design practica as a successful tool for assessing learning in engineering design [64]. Therefore, to understand the effects of the studied intervention on students' problem-solving processes, a DfAM design challenge was conducted in addition to exploring changes in the participants' DfAM self-efficacy. Assessing the outcomes from the design challenge would help understand the effects of the DfAM educational intervention on the technical goodness of the students' AM designs and explore the role of DfAM use in causing these effects.

3. RESEARCH OBJECTIVES

Based on our review of prior work, the current study was developed to explore the effect of variations in DfAM education on the technical goodness of participants' AM design outcomes, and the role of DfAM use in bringing about these effects. Specifically, the following research questions were explored:

RQ1: What effects do variations in DfAM educational content have on the participants' DfAM self-efficacy? We hypothesize that exposing participants to either restrictive or dual DfAM would result in an increase in the participants' self-efficacy with the respective concepts because prior work has demonstrated effective learning to be correlated with an increase in self-efficacy [65].

RQ2: What effects do variations in DfAM educational content have on the technical goodness of the participants' ideas during a design challenge? We hypothesize that teaching participants about opportunistic and restrictive DfAM would result in the generation of designs that are not only feasible but also leverage the capabilities of AM since effective learning is shown to correlate with the ability to use knowledge to synthesize new ideas [58].

RQ3: What effects do variations in DfAM educational content have on the participants' use of DfAM concepts in describing and evaluating their ideas? We hypothesize that teaching participants about opportunistic and restrictive DfAM would result in an increased use of the respective DfAM concepts in their design self-evaluations, as previous research has shown effective learning to correlate with the ability to use the new information to evaluate concepts [58].

4. METHODOLOGY

To answer these research questions, an experiment was conducted that comprised of both DfAM educational lectures as well as design challenges with undergraduate engineering students. While the experiment was conducted as a part of a larger study (see [46,66]), only the experimental details relevant to the current paper are discussed in the remainder of this section.

4.1. Participants

The participants in the experiment (N = 193) were recruited from the spring semester of a junior-level course focused on Mechanical Engineering Design Methodology at a large northeastern university. The participants primarily comprised of juniors (N = 160), and seniors (N = 17), with some sophomores (N = 3), and some participants with an unspecified year of study (N = 13). Before participating in the experiment, the participants were asked to report their prior experience in AM and DfAM, which is summarized in Figure 1. As seen in the figure, a small portion of the students had received any formal training in AM or DfAM, with a majority of the participants having received some informal exposure. Further, a greater portion of participants had never heard of DfAM compared to those who had never heard of AM.

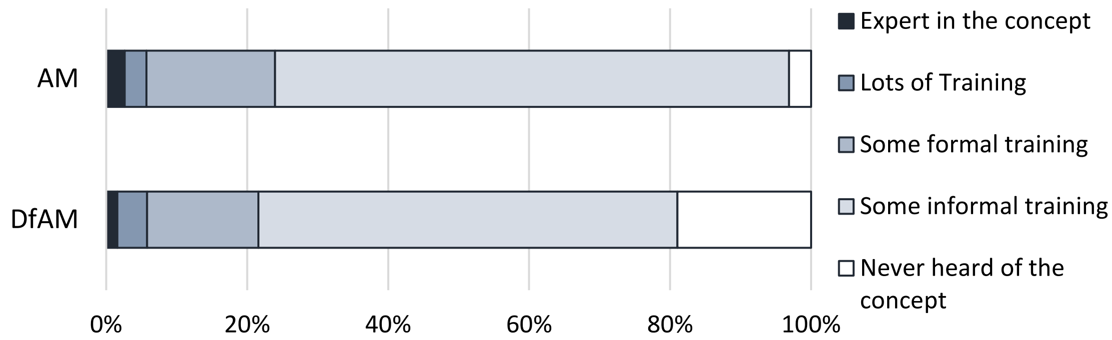


Figure 1 Distribution of participants' previous experience

4.2. Procedure

Before starting the experiment, the participants were informed that the usage of their data was voluntary, and implied consent was obtained as per the Institutional Review Board protocol. Next, the experiment proceeded in three main stages: (1) a pre-intervention survey and design challenge, (2) DfAM educational lectures, and (3) a post-intervention design challenge and survey. The experiment was conducted in the second week of the semester and was distributed over four days. The timeline of events is discussed in Section 4.2.4. All three stages of the experiment asked the participants to engage individually and not in groups.

4.2.1. Pre-intervention Survey and Design Challenge:

After obtaining implied consent, the participants were asked to complete a pre-intervention survey which collected their previous experience in AM and DfAM, as well as their DfAM self-efficacy (see Section 4.3.1). Next, a 10-minute design challenge was conducted; participants were asked to *individually* "Design a fully 3D-printable solution to protect a smartphone in the event of a fall". This prompt was chosen as it minimizes the domain-specific knowledge required to generate solutions while giving participants the opportunity to innovate [67]. The participants were asked to sketch their ideas, describe them in words, as well as list the strengths and weaknesses of each idea in the context of both functional usefulness and manufacturability. See Figure 2 for examples of the ideas generated by the participants.

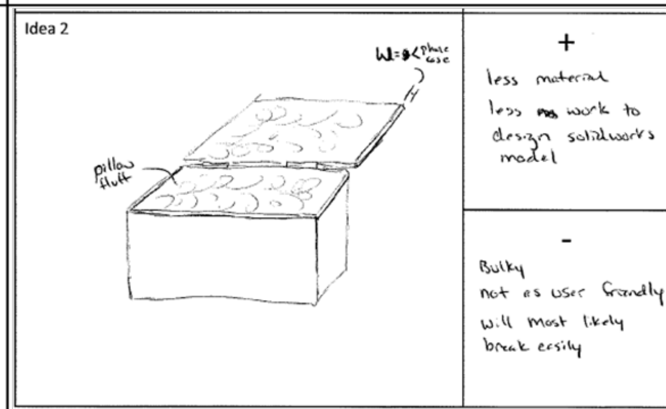
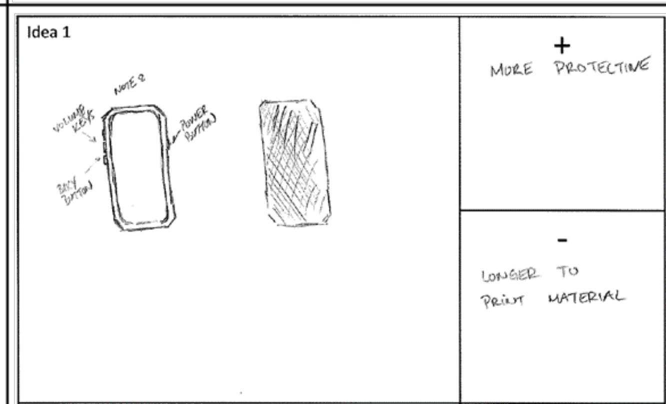
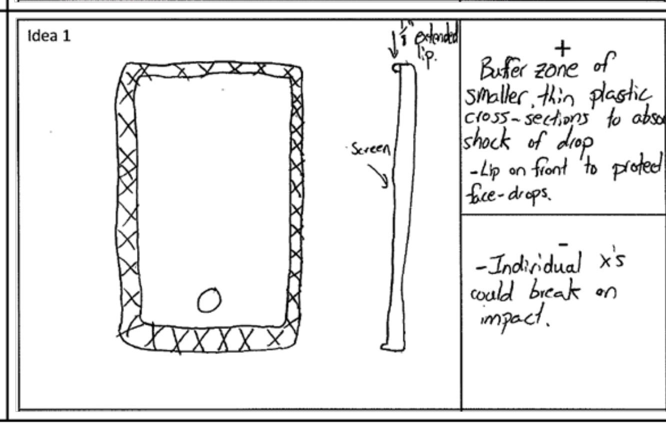
Participant ID	Technical Goodness	Idea
NEON06	2	
NGON05	3	
LYER08	4.5	

Figure 2 Sample designs from the pre-intervention design challenges with the expert-assigned technical goodness scores

4.2.2. DfAM Education Lectures:

After completing the pre-intervention survey and design challenge, the DfAM education intervention was introduced. The participants were split into three groups: (1) no DfAM (N = 94), (2) restrictive DfAM (N = 47), and (3) dual DfAM (N = 52). All three groups were first given an overview lecture on the AM process (20 minutes), with a general discussion of the material extrusion process, distinction from subtractive manufacturing, the digital thread, Cartesian coordinates, and printable materials. Following this overview lecture, the restrictive and dual DfAM groups were given a lecture on restrictive DfAM (20 minutes), which comprised of build time, feature size, support material, anisotropy, surface finish, and warping. Finally, the dual DfAM group was given an additional lecture on opportunistic DfAM (20 minutes), with a discussion of geometric complexity, mass customization, part consolidation, printed assemblies, multi-material printing, and functional component embedding. The educational intervention was divided into these groups since restrictive DfAM is critical for ensuring the success of a 3D printed part. In addition, care was taken in preparing the lectures such that the AM overview content did not include any concepts from either opportunistic or restrictive DfAM. The slides used for the lectures can be accessed here: [68]. The timeline of the lectures is discussed in Section 4.2.4.

4.2.3. Post-intervention Design Challenge and Survey:

For the third part of the experiment, all participants were asked to *individually* "Design a fully 3D-printable solution to enable hands-free viewing of content on a smartphone." Problem statements that were similar in their requirement of domain knowledge were chosen for the pre- and post-intervention design challenges, so that differences could be observed in the participants' use of DfAM while reducing design fixation [69,70]. Participants were first asked to spend 10 minutes brainstorming for ideas using an idea generation card, with 7 minutes for sketching, and 3 minutes for describing the ideas in words. The participants were then given 5 minutes to evaluate each idea and note their strengths and weaknesses, similar to the pre-intervention design challenge. The participants were then given 7 minutes to design a final idea with the freedom to redesign, combine, or brainstorm again. After completing the design challenge, the participants were asked to complete a post-intervention survey with the same DfAM self-efficacy questions as in the pre-intervention survey. Examples of the ideas generated by the participants can be seen in Figure 3.

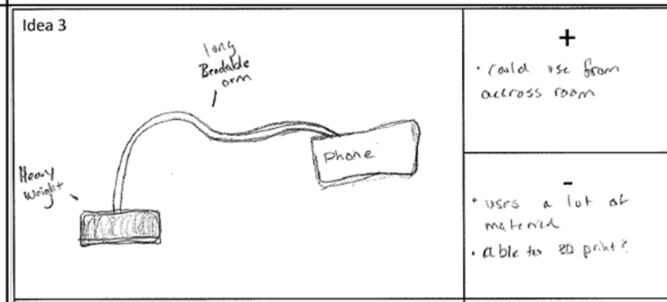
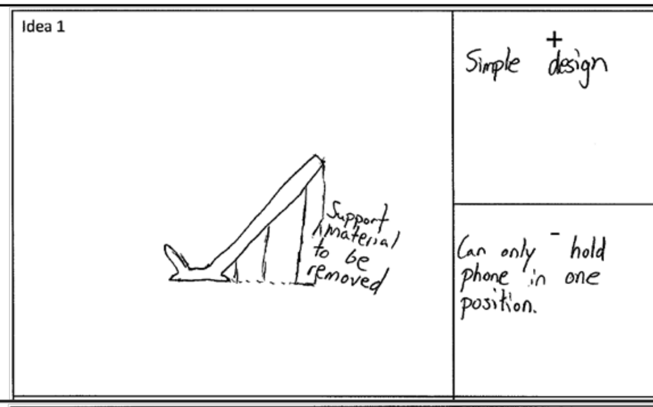
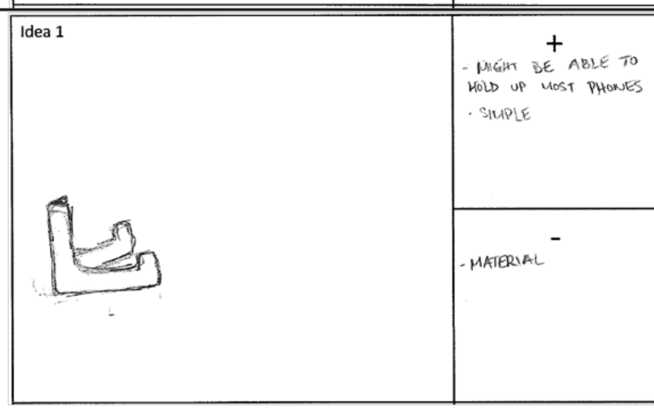
Participant ID	Technical Goodness	Idea
NEON06	1.5	
LYER08	3.25	
NGON05	3.75	

Figure 3 Sample designs from the post-intervention design challenges with the expert-assigned technical goodness scores

4.2.4. Timeline of Events:

Since the experiment was conducted with participants recruited from a junior-level course, the timeline, summarized in Figure 4, was worked out to accommodate for the time available in the course schedule. The experiment was conducted over four days, consisting of two 55-minute class sessions and two 180-minute lab sessions. The lectures were conducted on successive Wednesdays, with one-half of lab sessions (Sections 1-4) between them, on Tuesday, and the remaining sessions (Sections 5-8) after, on Thursday. The participants were divided into eight lab Sections, with Sections 1-4 as the control group (no DfAM), Sections 5-6 as the restrictive only DfAM group, and Sections 7-8 as the dual DfAM group. The events on each of the four days were as follows:

Day 1 (Wed, Class): The pre-intervention survey and design challenge were conducted in the first 10 minutes of the first class session. After completing the survey and design activity, all participants were given a 25-minute lecture with an overview of the AM process. The overview lecture did not consist of any DfAM inputs.

Day 2 (Tues, Lab): The post-intervention design challenge for Sections 1-4 (control group), was conducted during the first lab period. The design activity was conducted over ~45 minutes, after which participants were given time to develop CAD models and prepare the print files.

Day 3 (Wed, Class): The second lecture period was broken into two parts. First, all participants were given the restrictive DfAM lecture, after which, participants from Sections 5 and 6 (only restrictive group) were asked to leave the room. Then, the remaining participants (control and dual groups) were given the second portion of the lecture focused on opportunistic DfAM. This was possible since the control group had already completed their post-intervention design challenge and survey.

Day 4 (Thurs, Lab): The post-intervention design challenge and survey for Sections 5-8 was conducted in the second lab period. The design activity was conducted in the first ~45 minutes and the participants were asked to use the remaining time for CAD modelling and print preparation.

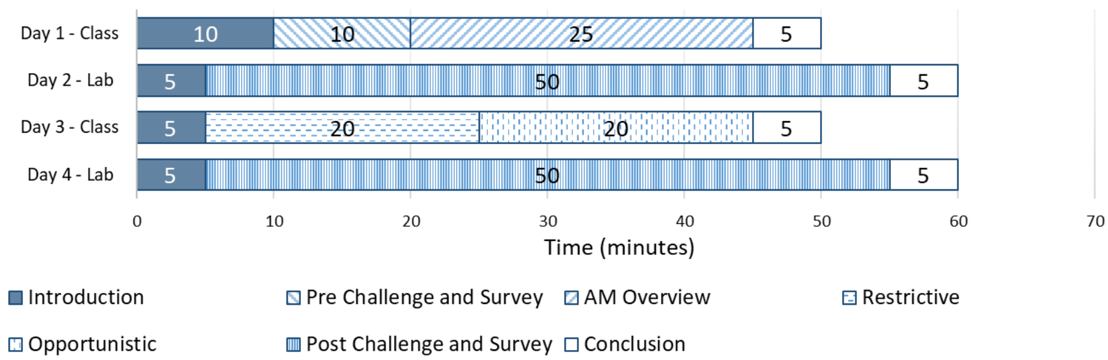


Figure 4 Timeline of events in the experiment

4.3. Metrics and Coding Schemes

To evaluate the participants' learning and use of DfAM as a result of the educational intervention, the following metrics were developed: (1) DfAM self-efficacy, (2) self-evaluation of designs, and (3) expert evaluation of the technical goodness of the designs. The details of each metric are discussed in this section.

4.3.1. DfAM Self-efficacy

In order to assess the participants' learning of DfAM, a self-efficacy survey was developed based on the two paradigms of DfAM, namely, opportunistic and restrictive [32]. Opportunistic DfAM taps into the capabilities of AM, through design principles such as (1) mass customization [71,72], (2) part consolidation [3] and printed assemblies [73], (3) free shape complexity [74–76], (4) embedding external components [77], and (5) printing with multiple materials [78]. In contrast, restrictive DfAM accommodates for the limitations of AM processes through design constraints such as (1) support structures [79], (2) warping due to thermal stresses [80], (3) anisotropy [81,82], (4) surface roughness due to stair-stepping [83,84], and (5) feature size and accuracy [85]. These design concepts were used to develop the survey items as shown in Table 1.

A 5-point scale, as seen in Table 2, was developed loosely based on the cognitive domain of Bloom's Taxonomy [58] to measure participants' learning of the DfAM concepts. Each participant was asked to report their self-efficacy with *each* DfAM concept in Table 1 (both opportunistic and restrictive), on the scale presented in Table 2. A mean opportunistic and a mean restrictive score was obtained by aggregating scores in concepts O1-5 and R6-10, respectively. A difference between participants' pre- and post-intervention scores was calculated to measure the change in self-efficacy.

Table 1 DfAM self-efficacy items

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

The internal consistency of the scale was validated by performing a reliability analysis, and a high Cronbach's α was observed [86] (pre-intervention $\alpha = 0.920$, post-intervention $\alpha = 0.882$). Similarly, the individual opportunistic and restrictive sections of the scale also showed a high internal consistency (opportunistic: pre-intervention $\alpha = 0.859$, post-intervention $\alpha = 0.819$, and restrictive: pre-intervention $\alpha = 0.894$, post-intervention $\alpha = 0.831$).

Table 2 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

4.3.2. Expert Evaluation of Design Technical Goodness

The ideas generated by the participants were evaluated using a metric derived from the Consensual Assessment Technique, which relies on the idea that any idea is creative (or useful or unique) to the extent that two or more observers trained in the domain independently agree that it is creative (or useful or unique) [70]. The design outcomes from the pre- and post-intervention design challenges were evaluated by two quasi-experts in AM as suggested by [87]. The raters were asked to evaluate the designs using their own subjective judgement for the technical goodness of the AM designs, on a scale from 1 to 6, with 1 = least technical goodness and 6 = most technical goodness (see Figure 2 and Figure 3 for sample ratings). Technical goodness is often used as a measure of the technical details of a design, such as organization of individual components and the representation of the details of the design [88,89]. The interpretation of this metric was redefined to focus on AM through discussions with AM experts. Specifically, the raters were asked to consider both the manufacturability of the design using AM as well as how well the design leverages AM capabilities. Further, based on recommendations from AM experts, the raters were asked to consider the following guidelines for the ratings: 1 = cannot be printed at all (e.g., a design that is bigger than the build volume), 3 = can be printed feasibly but not well designed for AM (e.g., a triangular wedge or rectangular block), and 6 = successfully integrates both opportunistic and restrictive DfAM (e.g., a multi-material solution with complex features and minimal support material).

The raters rated the ideas blind to the participants' educational intervention group, and upon obtaining a high inter-rater agreement between raters (Cronbach's $\alpha = 0.705$), a mean score was calculated for both, the pre- and post-intervention design challenges, for each participant. This was done by aggregating all the ratings for the scores for the participant's designs from the respective design challenges.

4.3.3. Self-Evaluation of Design Strengths and Weaknesses

For both, the pre- and post-intervention design challenges, the participants were asked to describe and evaluate their ideas, both in terms of the design's functional ability to solve the problem statement and its manufacturability using AM. Space was provided for the participants to note the strengths (+s) and weaknesses (-s) of each idea, as shown in Figure 2. The text from the idea evaluations was transcribed and coded using NVivo 12 by two quasi-experts in the field of AM. Upon achieving a high inter-rater agreement for 50% of the collected data (Cohen's Kappa [90] = 0.67), the primary coder coded the remaining portion of the data. The following coding scheme was followed:

- Opportunistic DfAM: This node was used to identify the use of opportunistic DfAM concepts (or lack thereof) when evaluating the designs (see O1-O5 in Table 1). For example, statements such as "combines phone case and kickstand" and "the design is simple" were coded under this node due to their focus on the use of printed assemblies and *lack* of complex geometries, respectively.
- Restrictive DfAM: This node was used to identify the use of restrictive DfAM concepts (or lack thereof) in the design evaluations (see items R6-R10 in Table 1). For example, statements such as "angle at 45° to reduce support material" and "flat base prone to warping" were coded under this node for their emphasis on reducing support material and failure to reduce warping respectively.
- Problem Solving: This node was used to understand the emphasis on the design problem when evaluating the designs, such as design features, build material, and build time. For example, statements such as "provides sufficient support to the phone" and "works at different angles" were coded under this node as they emphasized on the functionalities of the design.

This coding strategy helped capture not only the inclusion of the various DfAM concepts in the participants' designs, but also helped capture the participants' *consideration* of these concepts in describing and evaluating their designs.

5. RESULTS

To answer the above research questions, the quantitative and qualitative data collected from the experiment was analyzed using SPSS V25 and NVivo V12 respectively. A statistical significance level of 0.05 and a confidence interval of 95% was used. After accounting for any missing data, a sample size of 164 (vs. the original 193) was used, with 80 participants receiving no DfAM training, 42 receiving only restrictive, and 42 receiving dual DfAM training. A total of 1129 ideas were generated by the participants, with 517 ideas in the pre-design challenge and 612 ideas in the post-design challenge. The mean technical goodness scores for the ideas were 3.72 ± 1.90 and 3.36 ± 1.67 for the pre- and post-intervention design challenges, respectively. The results from the analyses for each research question are discussed in the remainder of this section.

RQ1: What effects do variations in DfAM educational content have on the participants' DfAM self-efficacy?

The first research question was developed to understand the effect of variations in the content of DfAM education on the participants' self-efficacy in these topics. To investigate this question, the changes in the participants' opportunistic and restrictive self-efficacies were compared between the no DfAM, restrictive DfAM, and dual DfAM groups by conducting a multivariate analysis of variance (MANOVA) [91]. Specifically, the changes in participants' opportunistic and restrictive self-efficacy scores were used as dependent variables, and the educational intervention group was used as the independent variable. The assumptions of the MANOVA – outliers, normality, homogeneity of variance and covariance, and multicollinearity – were verified before conducting the analysis.

The results showed a statistically significant effect of the educational intervention on the combined dependent variables (F (4, 320) = 5.577, $p < 0.0005$; Pillai's Trace = 0.130; partial η^2 = 0.065). While there was a statistically significant difference in the change in restrictive self-efficacy (F (2, 161) = 10.713, $p < 0.0005$; partial η^2 = 0.117), there was no significant difference in the change in opportunistic self-efficacy (F (2, 161) = 1.353, p = 0.261; partial η^2 = 0.017). A Tukey post-hoc test [92] for the restrictive self-efficacy scores showed that the group that received no DfAM training showed the lowest increase in restrictive self-efficacy, compared to the groups that received either restrictive or dual DfAM education. However, this difference was significant only with the restrictive DfAM group ($p < 0.001$), and not with the dual DfAM group ($p = 0.105$), as seen in Figure 5.

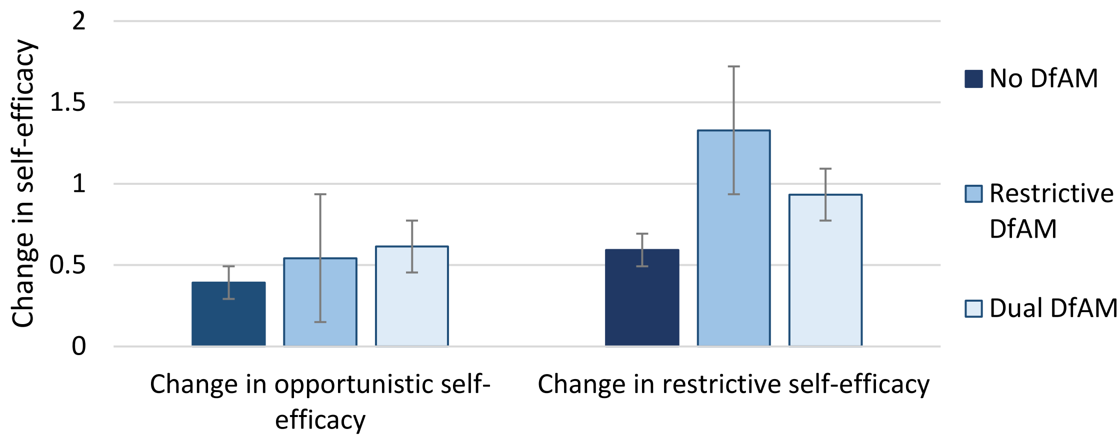


Figure 5 Comparing the change in DfAM self-efficacy between the three educational intervention groups (mean ± std. error) (see 4.3.1)

In summary, these results demonstrate that teaching participants about the capabilities of AM processes through opportunistic DfAM education did not result in a greater increase in their self-efficacy with these concepts compared to no DfAM or restrictive DfAM education. However, teaching participants only about the limitation based design concepts i.e. restrictive DfAM, results in a higher increase in their restrictive self-efficacy, compared to teaching no DfAM. Further, teaching participants about both opportunistic and restrictive DfAM did not result in a similar increase in their restrictive DfAM self-efficacy. These results support our hypothesis that restrictive DfAM education would result in a greater increase in the participants' restrictive DfAM self-efficacy. However, the results refute our hypothesis that opportunistic DfAM education would result in a greater increase in the participants' opportunistic DfAM self-efficacy.

RQ2: What effects do variations in DfAM educational content have on the technical goodness of the participants' ideas during a design challenge?

The second research question was developed to investigate the effect of variations in the content of DfAM education on the technical goodness of the outcomes from the AM design challenge. As a reminder, the technical goodness of the designs was evaluated by quasi-experts in the AM domain, based on the design's feasibility and its leveraging of AM capabilities. To answer this research question, a two-way mixed ANOVA [93] was performed. The technical goodness score was taken as the dependent variable, time (before and after the intervention) was taken as the within-subjects variable, and the educational intervention group was taken as the between-subjects variable. All assumptions of the test – outliers, normality, homogeneity of covariances, and equality of variance differences – were verified before performing the analysis.

The results of the ANOVA showed no significant interaction between time and the educational intervention group (F (2, 161) = 0.152, p = 0.860, partial η^2 = 0.002). This indicates that any changes in the technical goodness of the AM design outcomes from before to after the intervention was not influenced by the educational content. In addition, while there was a statistically significant main effect of time on the technical goodness scores (F (1, 161) = 69.006, p < 0.001, partial η^2 = 0.300), there was no statistically significant effect of the educational intervention group (F (2, 164) = 0.294, p = 0.745, partial η^2 = 0.004). Pairwise comparison between the scores at the two time points revealed a significant decrease (p < 0.001) from before the DfAM intervention (3.755 ± 0.039) to after the intervention (3.371 ± 0.044), shown in Figure 6. This demonstrates that the technical goodness of the participants' ideas decreased after participating in the intervention.

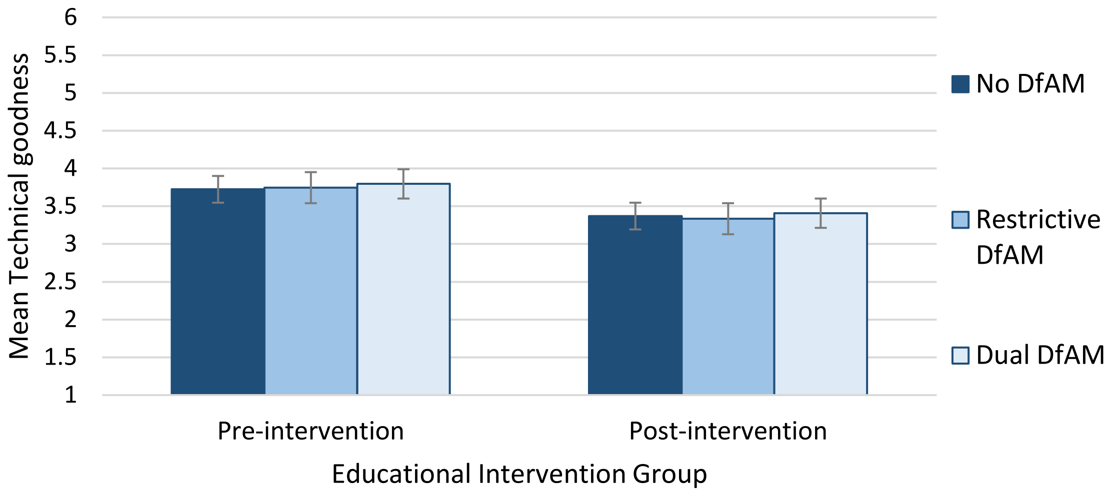


Figure 6 Summary plot of design technical goodness of the ideas (mean ± std. error)

From these results, we see that teaching different DfAM concepts does not influence the technical goodness of the participants' outcomes from the AM design challenge, as evaluated by quasi-experts in the field. This result refutes our hypothesis that teaching participants about the opportunistic DfAM concepts would result in ideas that better leverage the capabilities of DfAM. Second, we see that *before* being exposed to AM and DfAM, participants from all three educational interventions generate ideas with high technical goodness compared to the scale mean of 3.5, and all three groups show a significant decrease in their technical goodness scores *after* participating in the lectures.

RQ3: What effects do variations in DfAM educational content have on the participants' use of DfAM concepts in describing and evaluating their ideas?

The final research question was developed to investigate how teaching participants about opportunistic and restrictive DfAM affects their *use* of these concepts in the evaluation and descriptions of their designs. This was completed by performing deductive content analysis [94] on the design descriptions, strengths, and weaknesses from the idea generation cards (see Figure 2). The idea generation cards were first transcribed and then coded using NVivo 12 (see Section 4.3.3 for examples).

The coded data was analyzed using a frequency analysis, where the number of references at each node – design functionality, use of restrictive DfAM, and use of opportunistic DfAM – were investigated. The average number of references per participant at each node was used to account for the difference in the sample size for each educational intervention group. The most frequently occurring words in each node were studied to gain insight into the context in which each node was referred to.

The results of the frequency analysis, summarized in Figure 7, showed that participants evaluate their designs for functionality and problem-solving ability more than for additive manufacturing. Further, this focus on functionality increases after the DfAM intervention, irrespective of their educational intervention group. The second observation was that while all participants showed an increase in the number of references to opportunistic DfAM (even if not formally exposed to the concepts), participants who received no DfAM education showed the highest increase. In comparison, participants who received either restrictive or dual DfAM training showed a relatively smaller increase in their number of references to opportunistic DfAM. The third observation is that while all participants showed an increase in their number of references to restrictive DfAM, those who received restrictive DfAM education, either with or without opportunistic DfAM education, show a much greater increase compared to those who received no DfAM education. This result further supports findings from the first research question, where participants who received restrictive DfAM training showed a greater increase in their restrictive DfAM self-efficacy.

To investigate the context of how these concepts appeared in their evaluations, a word frequency analysis was performed. The analysis of the sections coded under 'opportunistic DfAM use' showed that while all three groups frequently use phrases such as 'two materials', 'rubber-plastic combination' and 'shock absorbing internal structure' to describe and evaluate their designs in the pre-intervention challenge. This suggests the use of concepts such as multi-material printing and complex geometries. However, all three groups show a dramatic increase in their frequency of use of the word 'simple' in the post-intervention challenge, possibly accounting for the increase in the number of references to opportunistic DfAM, with the word having the highest number of occurrences for all three groups.

A similar analysis of the participants' frequency of use of restrictive concepts showed a frequent occurrence of phrases such as 'could easily break' and 'breaks easily' in their pre-design descriptions and evaluations, suggesting the use of concepts such as material strength and anisotropy. This shifts towards an increase in the frequency of 'support materials' by all three groups, thus suggesting that a large portion of participants tend to report the printability of their designs in terms of the need for support material. These observations do not support our hypothesis that opportunistic and restrictive DfAM education would result in an increase in the participants' references to these concepts when describing and evaluating their own designs.

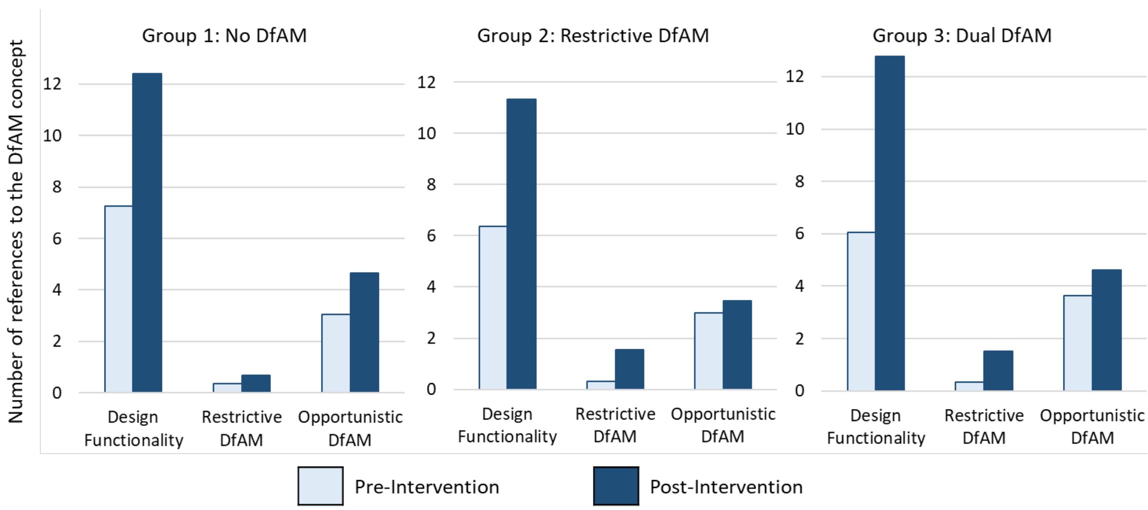


Figure 7 Graphic demonstrating the average frequency of references per participant (post-intervention includes initial brainstorming and final designs)

6. DISCUSSION

The aim of this study was to investigate the effects of variations in DfAM education content on the technical goodness of the participants' design outcomes, and the role of DfAM in bringing about these effects. The main findings from the experiment were:

- Teaching participants only about restrictive DfAM results in a significantly higher increase in their *restrictive* self-efficacy, compared to no DfAM education and dual DfAM education.
- Variations in DfAM education content does not affect the technical goodness of the participants' outcomes from the AM design challenge.
- As observed in the descriptions of their designs, participants tend to simplify their designs when given an opportunity to do so, and variations in the content of the DfAM intervention does not impact this.

The first key finding was that the studied DfAM educational intervention succeeds in bringing about an increase in the participants' self-efficacy in using DfAM principles. However, variations in DfAM education content did not result in significantly different changes in the participants' *opportunistic* self-efficacy. On the other hand, participants who received only restrictive DfAM showed a significantly higher increase in their *restrictive* DfAM self-efficacy, compared to those who received no DfAM education or dual DfAM education. These results suggest that, first, the participants find it relatively easier to learn about and use restrictive DfAM concepts, compared to opportunistic DfAM. While this result could be attributed to the widespread presence of restrictive DfAM focused instructions on university makerspaces [26,27], it could also be due to its similarity to traditional DFMA. These results also suggest that introducing opportunistic DfAM in addition to restrictive DfAM could potentially *decrease the effectiveness* of the restrictive DfAM education, compared to only restrictive education. This outcome might not be desirable, as it could result in the *generation of designs that leverage the capabilities of AM processes but have low printability*. Therefore, it is important for a DfAM educational intervention to emphasize the use of *both* opportunistic and restrictive DfAM domains by providing students with opportunities to practice and apply both these concept domains.

The second key finding was that variations in DfAM education content do not impact the technical goodness of the participants' outcomes from the AM design challenge. All three educational intervention groups show a similar decrease in their design technical goodness from before to after attending the AM/DfAM lectures. This refutes our hypothesis that teaching participants about the opportunistic and restrictive DfAM concepts would result in them using these concepts to generate AM-appropriate designs. This result supports the above finding that the studied DfAM intervention is not sufficient in encouraging the use of these concepts in the design process. This could possibly be explained by the nature of the intervention, where participants are rapidly introduced to the various DfAM concepts, without giving them adequate time to reflect on and rehearse the concepts [95]. Further, we also see that all three groups show a significant decrease in their design technical goodness scores after participating in the intervention. This could potentially be explained by the use of different design tasks, where the design of a protective solution could have resulted in a greater exploration of the design space due to higher functional requirements compared to a solution for hands-free viewing. This further supports previous research, where the choice of the design task has shown to influence the creativity and effectiveness of participants' design outcomes [96].

The third key finding was that participants who receive restrictive DfAM training, either with or without opportunistic DfAM, show a greater increase in the frequency of references to *restrictive DfAM*, compared to participants who received no DfAM inputs. On the other hand, participants who received only AM process knowledge, with no DfAM inputs, showed a greater increase in their frequency of references to *opportunistic DfAM* compared to those who received DfAM training. This finding supports our previous inferences that participants who receive DfAM inputs tend to exhibit a greater comfort and therefore a higher use of restrictive DfAM concepts compared to opportunistic DfAM. Further, we see that while participants use opportunistic concepts to generate complex designs before the intervention, this shifts towards simplification of their designs after the intervention. This simplification, i.e. lack of design complexity could also explain the increase in the number of references to opportunistic DfAM among participants who received no DfAM inputs. This result suggests that when given an opportunity, participants tend to simplify their designs possibly to improve manufacturability and could explain the decrease in the design technical goodness. This is not a favourable outcome, given that "the understanding that complexity is free in AM" was recommended as one of the most important traits of a successful AM designer, by AM researchers and industry leaders at the 2013 NSF workshop [9,19]. This simplification of the designs could also be attributed to the use of different design tasks, wherein the greater functional requirements from a solution to protect a cell phone provide more opportunities for applying the opportunistic DfAM concepts that encourage design complexity. These results, therefore, emphasize the need for DfAM educational interventions that encourage a combined emphasis on both the capabilities and limitations of a manufacturing process. This could potentially be achieved through a longer, more thorough intervention where students are given an opportunity to practice each DfAM concept.

7. CONCLUSION, LIMITATIONS, AND FUTURE WORK

The main objective of this research was to explore the effects of variations in the content of DfAM education on the technical goodness of the participants' design outcomes, and the role of DfAM in bringing about these effects. The educational interventions studied included an introduction to AM processes, combined with (1) no DfAM, (2) restrictive DfAM, and (3) dual DfAM inputs. The effects of these interventions were measured through investigating the changes in the participants' self-efficacy in using the DfAM concepts, changes in the technical goodness of their AM design outcomes, and differences in their use of AM in describing and evaluating their designs. The results of the study showed that participants who received only restrictive DfAM education showed a significantly higher increase in their *restrictive* DfAM self-efficacy, compared to the other intervention groups. On the other hand, no differences were seen in their change in opportunistic self-efficacy. However, we see that despite the increase in the participants' self-efficacy, the variations in the DfAM education content did not affect the technical goodness of their AM design outcomes. A deductive content analysis of their design sheets revealed that participants from all three educational groups tend to simplify their designs in the post-intervention design challenge, suggesting the use of the traditional design for manufacturing mindset where simplicity helps improve the ease of manufacturing. The results of this study, therefore, suggest that despite an increase in the participants' opportunistic and restrictive self-efficacies due to the intervention, participants fail to tap into the opportunistic DfAM concepts. This demonstrated the need for educational interventions that emphasize the use of opportunistic DfAM concepts for better leveraging the offerings of AM.

While this study provides insights into the effects of DfAM education on the technical goodness of design outcomes and the role of DfAM use on this, it has several limitations. First, results suggest that the design problem statement has a potential effect on the participants' use of DfAM. Therefore, further research must explore this interaction by comparing different task structures and complexities. Next, the study aggregates multiple DfAM techniques into opportunistic and restrictive. While this classification is supported by previous research, the aggregation could possibly normalize the higher increase in certain individual techniques, compared to others. For example, participants might demonstrate a higher familiarity with concepts such as support structures due to their presence in informal AM experiences compared to their familiarity with material anisotropy. This is particularly important given the short duration of the lectures, where participants might have absorbed some topics more than the others. Therefore, future research must investigate the change in participants' self-efficacy with each DfAM technique. A similar recommendation could also be made in the content analysis performed, where the coding scheme aggregated the reference to all opportunistic (and restrictive) DfAM techniques under one node. A deeper analysis could possibly reveal differences in the participants' use of the individual techniques, thus giving better insights into their comfort with the same. This recommendation could also be extended towards the lectures, where participants are given more time to absorb and possibly rehearse both opportunistic and restrictive concepts instead of a continuous lecture, as suggested by inductive learning research. Finally, the evaluation of the design outcomes could be broken down into opportunistic and restrictive technical goodness scores, as opposed to a single evaluation, as this would give better clarity into the changes in the participants' design outcomes from before to after the intervention.

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NOMENCLATURE

DfAM	Design for Additive Manufacturing
DFMA	Design for Manufacturing and Assembly
AM	Additive Manufacturing
NSF	National Science Foundation
MANOVA	Multivariate Analysis of Variance
ANOVA	Analysis of Variance

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Figure Captions List

Table Caption List

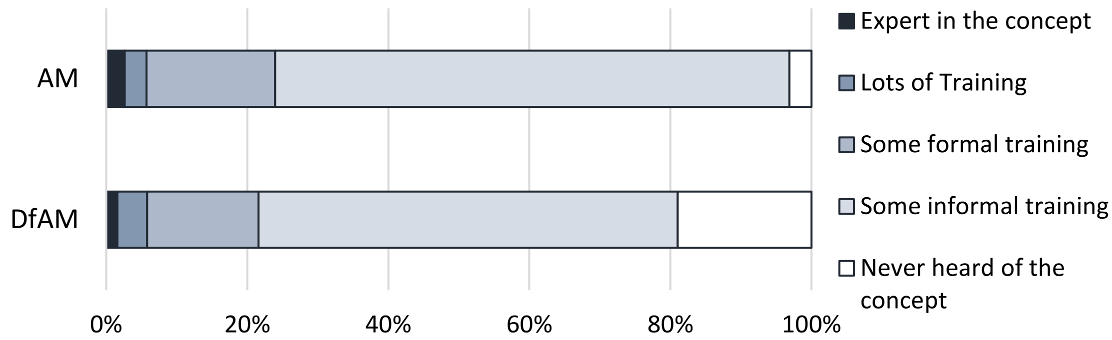

Figure 1 Distribution of participants' previous experience

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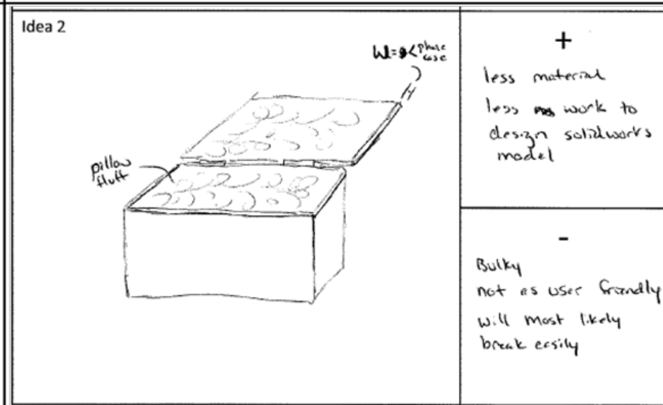
<tr><td>NEON06</td><td>2</td><td>
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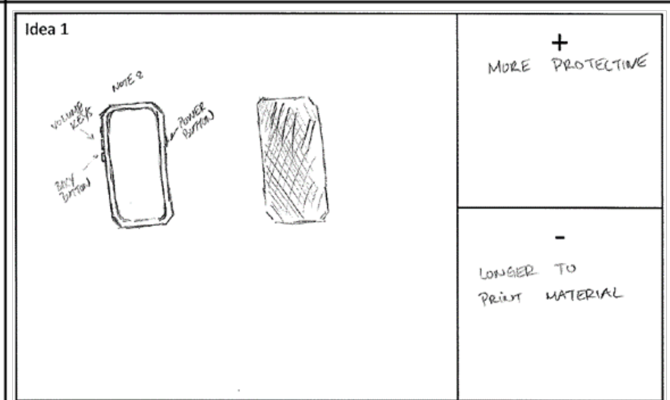
<tr><td>NGON05</td><td>3</td><td>
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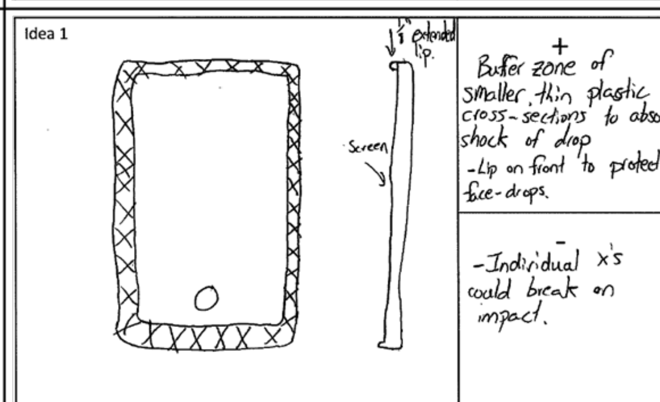
<tr><td>LYER08</td><td>4.5</td><td>
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Figure 2 Sample designs from the pre-intervention design challenges with the expert-assigned technical goodness scores

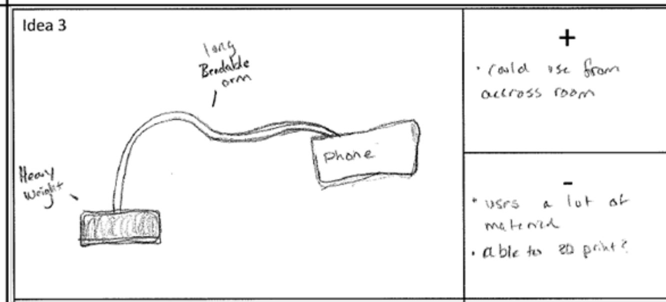
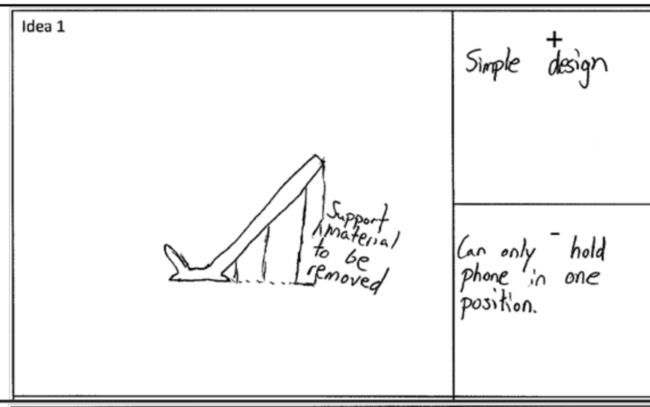
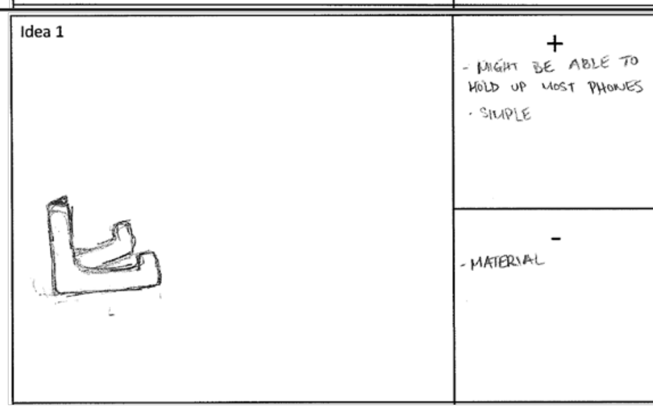
Participant ID	Technical Goodness	Idea
NEON06	1.5	
LYER08	3.25	
NGON05	3.75	

Figure 3 Sample designs from the post-intervention design challenges with the expert-assigned technical goodness scores

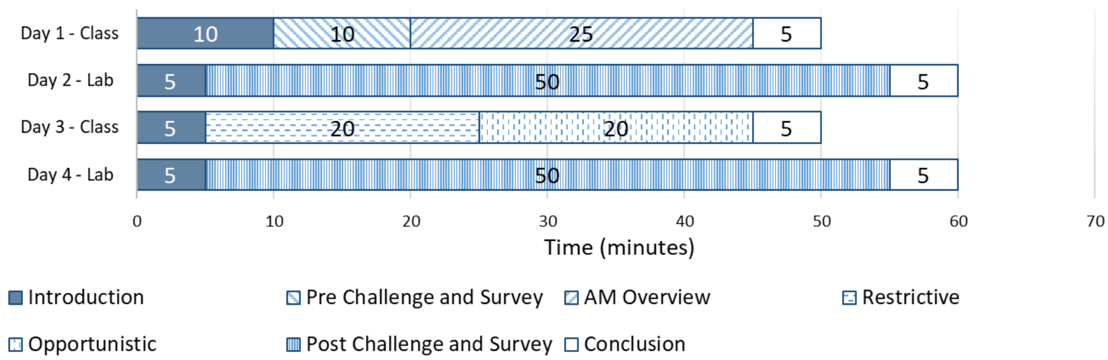


Figure 4 Timeline of events in the experiment

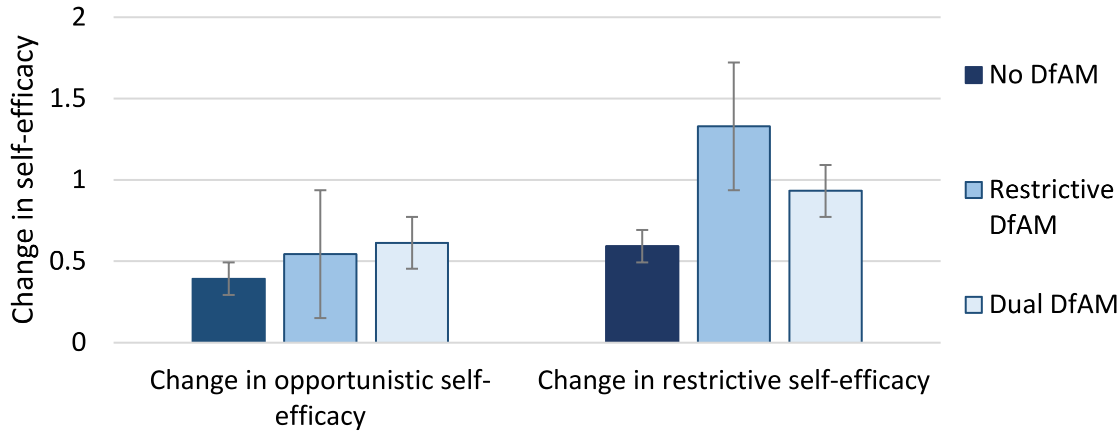


Figure 5 Comparing the change in DfAM self-efficacy between the three educational intervention groups (mean ± std. error) (see 4.3.1)

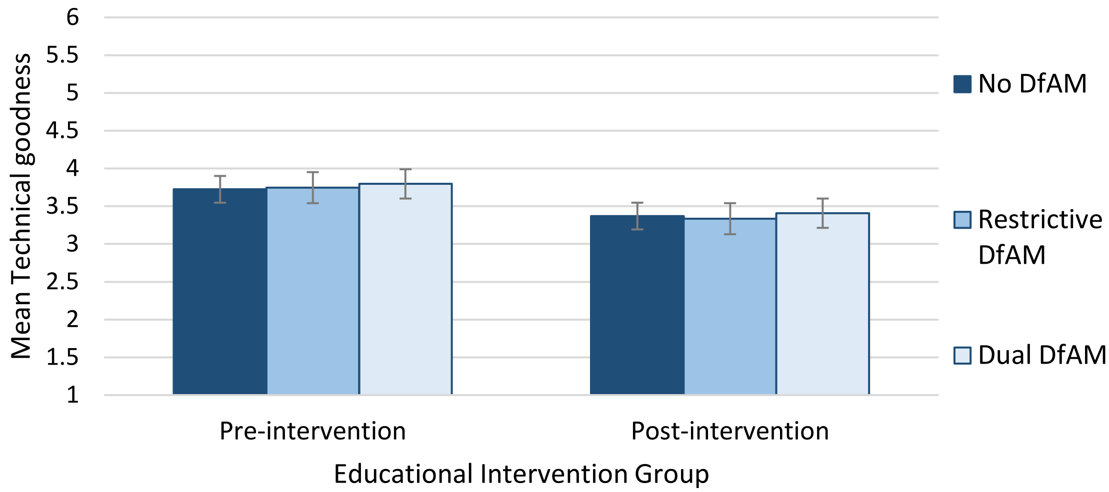


Figure 6 Summary plot of design technical goodness of the ideas (mean ± std. error)

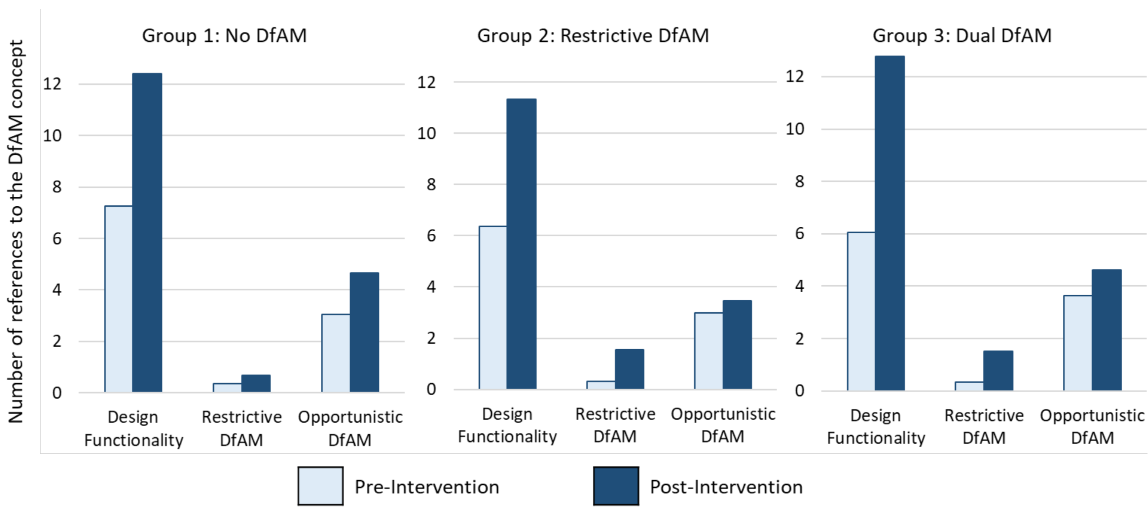


Figure 7 Graphic demonstrating the average frequency of references per participant (post-intervention includes initial brainstorming and final designs