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FAVORING COMPLEXITY: A MIXED METHODS EXPLORATION OF FACTORS THAT INFLUENCE CONCEPT SELECTION IN DESIGN FOR ADDITIVE MANUFACTURING

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ABSTRACT

The capabilities of additive manufacturing (AM) open up designers' solution space and enable them to build designs previously impossible through traditional manufacturing. To leverage AM, designers must not only generate creative ideas, but also propagate these ideas without discarding them in the early design stages. This emphasis on selecting creative ideas is particularly important in design for AM (DfAM), as ideas perceived as infeasible through the traditional design for manufacturing lens could now be feasible with AM. Several studies have discussed the role of DfAM in encouraging creative idea generation; however, there is a need to understand concept selection in DfAM. In this paper, we investigated the effect of two variations in DfAM education: 1) restrictive DfAM and 2) dual DfAM (opportunistic and restrictive) on students' concept selection process. Specifically, we compared the creativity of the concepts generated by the students to the creativity of the concepts selected by them. Further, we performed qualitative analyses to explore the rationale provided by the students in making these design decisions. From the results, we see that teams from both educational groups select ideas of greater usefulness; however, only teams from the restrictive DfAM group select ideas of higher uniqueness and overall creativity. Further, we see that introducing students to opportunistic DfAM increases their emphasis on the complexity of designs when evaluating and selecting them. These results highlight the need for DfAM education to encourage AM designers to not just generate but also select creative ideas.

Keywords: design for additive manufacturing, concept selection, creativity

1. INTRODUCTION

Additive manufacturing (AM) technologies have expanded designers' solution space by enabling the manufacturing of geometries previous considered impossible using traditional manufacturing (TM). This new-found design freedom can be attributed to the capabilities of AM made possible by the layer-by-layer deposition technique [1] employed in these technologies. Some capabilities of AM include the freedom of manufacturing complex geometries [2–4] and the ability to economically mass customize designs [5] due to the elimination of tooling costs [6]. To enable the leveraging of AM capabilities in engineering design, researchers have developed opportunistic design for AM (DfAM) principles. Opportunistic DfAM principles include (1) mass customization [5], (2) part consolidation [7] and printed assemblies [8], (3) free shape complexity [2,4,9], (4) embedding external components [10], and (5) printing with multiple materials [11].

Along with these capabilities, AM processes are also characterized by certain process limitations. These limitations, if not accounted for, could potentially increase costs of production due to build failures caused by losses in build material and build time [12]. Therefore, to account for the limitations of AM, researchers have introduced restrictive DfAM guidelines which include accommodations for (1) support structures [13], (2) warping due to thermal stresses [14], (3) anisotropy [15,16], (4)

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surface roughness due to stair-stepping [17,18], and (5) feature size and accuracy [19].

While it important for designers to use DfAM, especially opportunistic DfAM, to *generate* creative ideas, it is also important to ensure that these ideas are *selected* for development in the later stages of the design process [20]. Several researchers have explored the role of DfAM in encouraging the generation of creative ideas [21–25]; however, there is a need to understand if these creative ideas are *selected* for development in the later stages of design. Exploring this is important as prior research has demonstrated that the generation of creative ideas does not necessarily result in the selection of these ideas for development in later stages of design [26].

Prior work in engineering design has demonstrated designers' tendency towards emphasizing design feasibility over creativity [27], especially when selecting ideas [28]. This is problematic in a DfAM setting because creative designs that can now feasibly be manufactured using AM, might not be considered feasible when seen from the traditional design for manufacturing and assembly (DfMA) lens. Therefore, if designers are not encouraged to take risks and think beyond the limiting traditional DfMA guidelines, creative ideas that could've been feasible with AM might get discarded. This issue is further highlighted in prior work where designers have been shown to 'simplify' ideas despite being trained in opportunistic DfAM concepts such as the freedom of complexity in AM [29].

Our aim in this research is to explore the effect of DfAM education on students' concept selection in DfAM tasks. We investigated this gap in research through an experimental study consisting of a DfAM educational intervention and a DfAM challenge. In the next section, we discuss prior research that helped inform our study. Research questions are then presented in Section 3, our experimental methodology discussed in Section 4, the results of the experiment presented in Section 5 followed by concluding remarks in Section 6.

2. RELATED WORK

To investigate the effects of DfAM education on students' concept selection process, prior work in the areas of concept selection and decision making was explored, both in the context of engineering design and DfAM, as discussed next.

2.1. Concept Selection in Engineering Design

Product design processes generally consist of a set of steps being performed in iterative cycles. As highlighted in [30], these steps typically include (1) planning, (2) concept development, (3) system design, (4) detail design, (5) testing and refinement, and (6) production and deployment. Of these steps, the concept development stage, sometimes known as the fuzzy front end of the design process [31], is of particular interest as it can determine the direction taken by the design process. This stage is often further broken down into (1) identification and defining product needs, (2) concept generation, (3) concept selection, (4) prototyping and testing, (5) final design, and (6) downstream development planning, each of which is iteratively performed [30]. A similar breakdown of design processes is also reflected in the fields of design cognition [32] and creative cognition [33]. While the initial stages of idea generation and exploration help widen the problem space [34], comparison and selection of ideas are necessary to narrow down the problem space [35]. In the concept selection stage, ideas are evaluated for their quality and compared against other ideas, and ideas that best meet the requirements of the problem statement are chosen for further development. This evaluation and validation of ideas is often done using one's domain knowledge and ideas that successfully meet this validation progress further into fruition [33]. Therefore, while idea generation plays an important role in encouraging the generation of creative solutions [34], concept selection influences whether these creative ideas propagate through the design process [36].

The outcomes of the concept selection process not only influence the characteristics of the final product [37] but also the cost and time consumed in the final stages of the design process [38,39]. Therefore, this process must be carried out effectively to encourage product innovation and product success. To achieve this, companies have adopted several forms of the stage-gate process where projects are assessed frequently, especially in their early phases [40]. This is often also accompanied by the use of formal concept selection methods and tools such as the Pugh Chart [41], House of Quality [42], and the Analytical Hierarchy Process [43]. These tools help minimize the subjectivity in the concept selection process and provide structure to it [44].

Despite the introduction of several formal concept selection tools, these decisions are often made by individuals who possess inherent individual differences [39,45]. In addition, different domains and individuals account for different aspects of designs when evaluating and selecting them [46]. Therefore, it is important to understand the factors considered by designers in their concept selection process. Therefore, we explored prior research in this area as discussed next.

2.2. Factors that Influence Concept Selection in Engineering Design

As discussed in Section 2.1, researchers have identified concept selection as an important stage in engineering design. While the use of formal processes is common across domains, the time spent on each stage, and the focus of the evaluation vary significantly [47]. For example, in industries with longer product development cycles such as automotive, these stages are often designed to emphasize on factors such as product performance, safety, manufacturability, and cost [48]. In contrast, 'agile' industries such as software development, focus shifts to reliability and reusability with much shorter development times [49,50].

Feasibility is a factor most frequently used by engineering design teams in their concept selection process potentially due to the emphasis on it in several selection tools and methods [51]. For example, as discussed by Racheva et al. [52], software development teams that employ agile processes often reprioritize to focus on the business value and market viability of the project. This emphasis on product viability can also be seen in creativity related studies where technical feasibility has been identified as one of the three important criteria for identifying creative products [53]. Additionally, designers have also been shown to emphasize the objectives and functional needs of the design problem when evaluating their designs, especially with respect to how well they meet the customers' needs [54,55].

While these studies highlight the effect of characteristics of the generated idea on its selection, research has also demonstrated the presence of biases [56,57] and individual differences [58,59] in designers' decision-making process, some of which include ownership bias [60–62], design fixation [63], and risk attitudes [64]. Of the various cognitive factors that affect decision making, risk-taking is of particular interest in the DfAM setting, as designs feasible through AM might be considered risky when viewed from a traditional DfMA lens. This is further important as research has shown that individuals' risk-taking tendencies correlate with their preferences towards creative ideas [64]. Individuals who tend to be risk-*seeking* gravitate towards choosing ideas of higher creativity. In contrast, risk-averse individuals tend to choose safer designs with high feasibility and usefulness. Designers' risk-taking attitudes combined with their resistance to shifting from traditional DfMA methods towards adopting DfAM [65,66] could potentially result in creative ideas being discarded early in the design process.

These studies demonstrate designers' tendency to select ideas that are feasible but not necessarily creative. In a DfAM setting, emphasizing the feasibility of designs is important as it would ensure that the designs selected for development can be manufactured with AM. However, it is also important that designers emphasize AM capabilities to ensure that these process capabilities are fully leveraged. Additionally, designers must also establish trust in AM processes' ability to build parts successfully. A lack of emphasis on, and trust in AM capabilities could result in creative ideas being evaluated as risky and not feasible, and therefore be discarded. While several studies have explored the effect of DfAM on creative concept *generation*, there is a need to better understand the factors that influence concept *selection* in DfAM tasks and this study explores this gap in the literature. To further understand existing DfAM decision-making tools and methods, we explored research in these areas as discussed next.

2.3. Design Evaluation and Decision Making in DfAM

Design evaluation plays an important role in determining the success of the product development process. Therefore, researchers have presented several tools that help designers evaluate their designs when designing for AM. For example, the time and resources consumed in manufacturing a product are key factors that determine its success [67], and therefore, several researchers have presented part evaluation tools that focus on resources consumed in building a part. These tools assess the build material and build time consumed in building a part and researchers have presented tools that are both, process-agnostic [68] and process-specific. Some examples of process-specific resource prediction models include those developed for stereolithography [69–71], selective laser sintering and powder bed fusion [72–75], laminated object manufacturing [69], and material extrusion [76]. Extending this idea of resource modelling, Lindemann et al. [77] present a framework that not only evaluates candidate parts based on their economic value but also provides redesign recommendations for making the design better suited for AM.

In contrast to these tools that assess parts for their resource-consumption, Telea and Jalba [78] present a voxel-based assessment tool that helps designers identify and eliminate design features that might be too thin to be resolved by AM processes, thereby improving the printability of the designs. Ghiasian et al. [79] present a similar feasibility analysis tool for evaluating designs before starting the build process. The tool assesses designs based on (1) build volume dimensions, (2) feature assessment, (3) build orientation and supports, (4) resource consumption, and (5) post-processing requirements. The authors demonstrate the use of this decision-making tool in identifying candidate parts when using AM. These voxel-based feasibility analysis tools rely on CAD models for their evaluation, thereby limiting their use in the later design stages. To minimize this reliance on CAD, Booth et al. [12] present a DfAM worksheet that helps designers minimize build failure at both, the conceptual and CAD stages. The worksheet evaluates designs on eight components: (1) complexity, (2) functionality (load-bearing mating surfaces), (3) ease of support material removal, (4) support material accommodation (unsupported features), (5) minimum feature thickness, (6) stress concentrations, (7) tolerances for mating surfaces, and (8) the need for geometric accuracy. The authors demonstrate novice designers' use of the worksheet to successfully minimize build failure. Savonen [80] presents a set of criteria for assessing the sustainability of AM parts in low-cost manufacturing scenarios. This application is further extended towards the development of a DfAM triaging method for evaluating and prioritizing part production based on a series of DfAM and functional decisions [81].

These examples of DfAM decision-support tools highlight the importance of accounting for AM limitations when evaluating designs, especially to avoid build failure and minimize wastage of time, material, and energy. However, a lack of emphasis on AM capabilities could potentially result in the (generation and) selection of designs that do not fully leverage AM technologies. This outcome is not favorable as prior research has demonstrated designers' tendency to 'simplify' designs despite being trained in opportunistic DfAM [29]. Accounting for this lack of emphasis on AM capabilities, Page and et al. [82] propose a semi-automated process for identifying candidate parts for manufacturing using AM. The proposed framework assesses designs based on five criteria: (1) geometric complexity, (2) AM capabilities, (3) cost considerations, (4) supply chain and sustainability, and (5) alignment with organizational goals. The framework helps designers reassess their use of AM and encourages them to redesign their parts to better leverage AM capabilities. Yang et al. [83] present a similar framework for evaluating designs based on their potential for part consolidation while taking into account DfMA considerations such as the need for additional tooling, the use of standard parts, and modularization. The authors present the merits of using the proposed framework in terms of its repeatability and efficiency when compared to manual decision making. Similar to the feasibility analysis tools discussed earlier, these part evaluation frameworks also rely on the use of CAD files.

From these studies, we see that several researchers have presented evaluation tools that help designers make decisions in DfAM. These decision-making tools help designers account for factors such as resource consumption, printability and feasibility, suitability with AM, and sustainability when selecting ideas. However, a majority of these tools are effective in the later stages of design – when designers have the CAD models ready and available. However, it is also important to understand how designers select ideas in the early, conceptual stages of design. A lack of emphasis on the opportunities enabled by AM in the early stages of design could result in designers discarding creative ideas that could be feasible with AM. Our aim in this research is to explore this gap in literature by seeking answers to the research questions discussed next.

3. RESEARCH QUESTIONS

Based on the review of the literature, our aim in this study was to understand the effects of DfAM education on student designers' concept selection process. Specifically, we compared two variations in DfAM education: (1) restrictive DfAM and (2) dual (opportunistic and restrictive) DfAM. These variations were compared by seeking answers to the following research questions (RQs):

- *RQ1: What effects do design characteristics have on students' concept selection and how does this effect vary based on DfAM education?* We hypothesize that participants will prefer useful ideas over unique or creative ideas and that DfAM education would not have a significant influence on this. This hypothesis is based on prior work in engineering design where students have been shown to prefer technically feasible ideas over creative ideas [28].
- *RQ2: What factors do students consider when evaluating and selecting concepts in a DfAM task and how does DfAM education influence this decision-making?* We hypothesize that students will give a greater emphasis on the design functionality (objectives and constraints) and general manufacturability (such as ease of manufacturing and assembly) compared to integrating specific DfAM techniques and creativity. This hypothesis is based on prior work where students reported a greater emphasis on design functionality compared to DfAM integration when describing and evaluating their ideas [29]. Further, prior work in engineering design has also demonstrated that students primarily emphasize the technical feasibility of ideas when selecting concepts [28].

4. METHODOLOGY

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

4.1. Participants

The experiment was conducted at a large northeastern public university, where participants (N = 99) were recruited from a junior-level mechanical engineering course focused on product design and engineering design methods. The participants consisted of sophomores (N = 1), juniors (N = 83), and seniors (N = 7). The remaining participants did not specify their year of study. The participants' self-reported previous experience in AM and DfAM was collected at the beginning of the study as summarized in Figure 1. As seen in the figure, a majority of the participants had little to no formal training in either AM or DfAM.

4.2. Procedure

The experiment was conducted in the third week of the spring semester as prior research has demonstrated the greater effectiveness of DfAM education early in the semester [84]. The experiment comprised of four stages: (1) a pre-intervention survey, (2) a DfAM education lecture, and (3) a post-intervention DfAM challenge and (4) post-intervention survey. The Institutional Review Board approved the study, and we obtained implied consent from the participants before conducting the experiment. The progression of the different experimental stages is summarized in Figure 2.

4.2.1. Pre-intervention survey

At the beginning of the experiment, we asked the participants to complete a pre-intervention survey. The survey captured their previous experience in AM and DfAM as summarized in Figure 1. This data provided a baseline for their initial knowledge and was collected as part of a larger study.

4.2.2. DfAM educational intervention

The DfAM educational content was presented to the participants after they completed the pre-intervention survey. The participants were split into two different groups: (1) restrictive DfAM and (2) opportunistic and restrictive (dual) DfAM. Since the participants were recruited from a lab-based course, the assignment to the groups was based on the days of their labs. Participants who had their lab sessions on Tuesdays were part of the restrictive DfAM group, and those who had their labs on Thursdays were assigned to dual DfAM. Therefore, these assignments could be considered to be random in regards to their prior AM and DfAM experience. These groups were chosen as prior research has demonstrated the need for restrictive DfAM in ensuring the manufacturability of AM designs [12]. However, we acknowledge the need to compare the effects of only

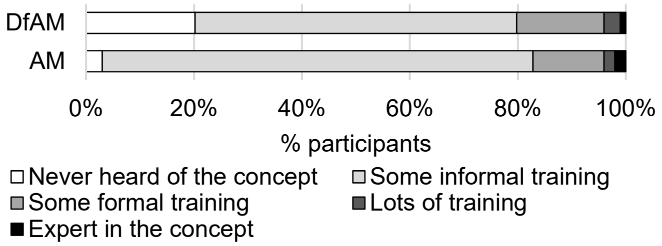


Figure 1 Distribution of participants' previous experience

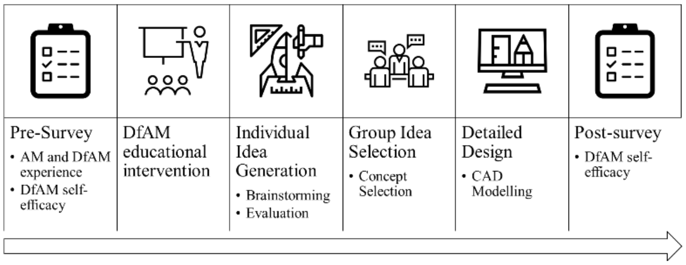


Figure 2 Summary of the experimental procedure

opportunistic DfAM education; this will be achieved in a planned extension of this study.

All participants were first given a 20-minute overview lecture on general AM process characteristics. In this lecture, the instructor discussed topics including the material extrusion process (the AM process available to the students in the AM design challenge), differences with subtractive manufacturing, the digital thread, the Cartesian coordinate system, and common filament materials. Next, all participants were given a 20-minute lecture on restrictive DfAM considerations, including build time, feature size, support material, anisotropy, surface finish, and warping. Finally, approximately half of the participants – the dual DfAM group – were given a 20-minute lecture on opportunistic DfAM considerations, including geometric complexity, mass customization, part consolidation, printed assemblies, multi-material printing, and embedding. The lecture slides can be accessed at [85].

The short, 20-minute duration of the lectures was chosen to ensure that the intervention could be completed with the class hours of the course from which the participants were recruited. Such lecture-based interventions have been demonstrated to be effective for DfAM education [86]. However, we acknowledge that the rapid introduction of concepts might not have been sufficient to introduce the various concepts in detail as well as to ensure the deep learning of the various techniques. The use of a longer intervention spaced out over multiple lectures and design sessions must, therefore, be explored in future research.

4.2.3. DfAM challenge

After attending the DfAM lectures, we asked the participants to complete a DfAM challenge comprising of an individual and a group stage. The wind turbine DfAM task from [87] was used as the design prompt as prior research has demonstrated its effectiveness in encouraging creativity when using DfAM [87]. The DfAM task presents specific design objectives – minimizing build material and build time – and constraints – e.g., build volume and tower height – and the use of these objectives and constraints has been shown to be effective in encouraging creativity. Further, the task requires minimal domain-specific knowledge beyond AM and DfAM (as suggested in [33]). The DfAM challenge comprised of an individual stage and a group stage and we discuss the details of each stage next.

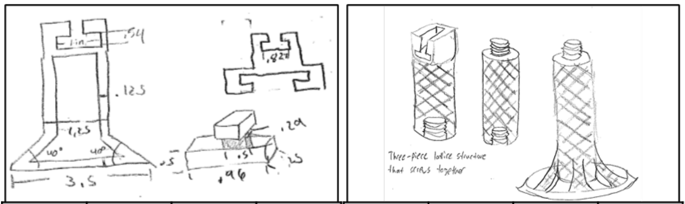
Individual Brainstorming

For the first part of the DfAM challenge, we asked the participants to spend 10 minutes *individually* brainstorming their own solutions using idea generation cards. They were instructed to both, sketch and describe the ideas in words. The participants were then given approximately 5 minutes to evaluate each idea and note down their strengths and weaknesses, followed by approximately 7 minutes to individually design a final idea with the freedom to redesign, combine, or brainstorm again. These times were primarily used to keep the participants moving through the various stages of the experiment and ensure that all parts of the experiment were completed within the allotted class time. An example idea is presented in Figure 3.

The creativity of participants' final designs from the individual brainstorming stage was assessed using the Consensual Assessment Technique (CAT) [33,88,89]. The designs were independently evaluated by two quasi-experts with a background in DfAM (as suggested by [90,91]). A moderate to high inter-rater reliability was observed between the two raters, as verified by an Intraclass Correlation Coefficient = 0.71 [92]. The following metrics were provided to the raters, as suggested by the three-factor model [93,94]:

- *Usefulness*: Assesses the quality of the design in its ability to solve the given design problem. This metric focusses on the value and appropriateness of the resulting solution.
- *Uniqueness*: Assesses the originality and novelty of each solution. The uniqueness is evaluated in comparison to the pool of solutions generated in the sample from the entire experiment [33].
- *AM Technical Goodness*: Assesses the level to which each solution suits the AM processes, both in terms of capabilities and limitations [29,95].
- *Overall Creativity*: Provides a subjective evaluation of the overall creativity of the idea as measured by experts.

The raters were asked to rate the ideas on a scale from 1 to 6, where, for example, 1 = least useful and 6 = most useful. We calculated an average score for each metric by taking a mean of the scores from the two raters for each design.



Uniqueness	Usefulness	Technical Goodness	Overall Creativity
2.75	3.75	3.25	4.5

Uniqueness	Usefulness	Technical Goodness	Overall Creativity
5.5	6	6	6

Figure 3 Examples of an idea generated by the participants and the corresponding creativity scores

Team Concept Selection and CAD

After completing the individual concept generation, the participants were split into nominal groups [20] of 3 or 4 participants each. This resulted in a total of 48 groups with 28 groups having received restrictive DfAM training and 20 groups having received dual DfAM training. After being split into groups, each member was given time to present their individual final ideas to the other group members. The participants were then asked to individually assess each team members' ideas without talking to one another using the concept screening sheet accessible at [96]. In addition to assessing each idea for its consideration into the next stage of the design process, we also asked the participants to provide a rationale for this decision. In Figure 4, we present an example of a participants' evaluation of ideas generated by members in their team, as well as their own idea.

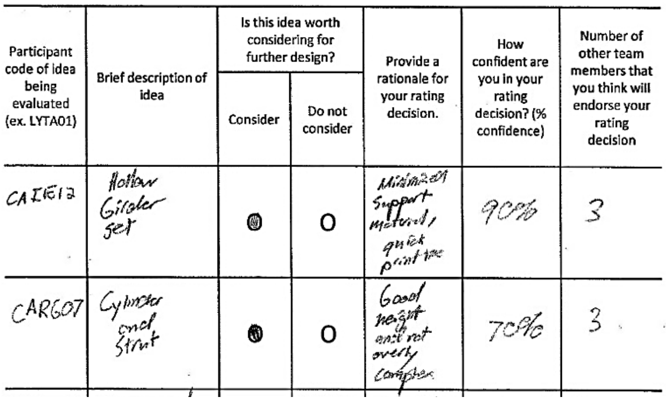
After assessing each idea in their team, we asked the participants to select one idea to represent the team. We then asked the participants to create a 3D solid model of their group's final idea using CAD and prepare a build orientation file. The CAD and build orientation files were collected from the participants at the end of the 3-hour lab session. After completing the design challenge, we asked the participants to complete a post-intervention survey, collected as part of a larger study.

The qualitative data – i.e., participants' individual assessment of ideas generated in the team and the factors considered by the team in selecting an idea – were analyzed using content analysis [97]. The text responses were transcribed and coded by two raters with a background in AM and DfAM. The coding was performed using NVivo 12 and sufficient inter-rater reliability was achieved between the two raters as measured using Cohen's Kappa = 0.70 [98]. A summary of the coding scheme is presented in Table 1, with examples of statements coded under each node. The raters used the following coding scheme:

- *Opportunistic DfAM:* This node captured the participants' use of opportunistic DfAM concepts when assessing the designs generated by the team and in the concept selection process. This node was further broken down into sub-nodes corresponding to each opportunistic design concept (for example, part complexity), with the child nodes aggregating into the parent node.
- *Restrictive DfAM:* This node captured the participants' use of restrictive DfAM concepts when assessing the designs generated by the team and in the concept selection process. This node was further broken down into sub-nodes corresponding to each restrictive DfAM concept (for example material anisotropy and support material), with the child nodes aggregating into the parent node.
- *Functionality:* This node captured the participants' emphasis on the objectives and constraints of the design challenge when selecting the concept. This node was further expanded into sub-nodes focusing on 1) general idea 'goodness', 2) design constraints, 3) design objectives.
- *Manufacturing:* This node captured the participants' consideration of the manufacturability and execution of the designs. Specifically, this node was broken into sub-nodes capturing emphases on 1) CAD, 2) feasibility, 3) repeatability, and 4) ease of assembly. While feasibility and manufacturability are related to restrictive DfAM, references that were not linked to specific restrictive DfAM techniques were coded in this node – for example, "easy to build".

Table 1 Codebook used for qualitative analysis with example statements

Level 3	Level 2	Level 1	Examples
DfAM	Opportunistic DfAM	Part complexity	"Simple design"
		Assembly complexity	"Strong connection between parts"
		Mass customization	"Can be easily modified in future"
		Embedding	-
		Multi-material	-
		Part consolidation	"Too many pieces"
	Restrictive DfAM	Support material	"Doesn't need a lot of support material"
		Warping	-
		Strength and anisotropy	"Strong and can support load"
		Feature size	"Might not fit in the build volume"
		Surface roughness	-
Functionality	General Idea Goodness		"The idea is nice"
	Task Objectives	Build material	"This needs too much material"
		Build time	"Can be printed quickly"
	Task Constraints	Supports motor-blade assembly	"Sturdy" and "Supportive"
		Operating conditions	"Cannot handle moment"
		Height of tower	"Less than 18 in"
		Tower footprint	"Won't fit in 3.5 x 3.5"
		Fits in one build	"Makes good use of print space"
Manufacturing		Feasibility and Practicality	"Can be printed easily"
		Repeatability	"Can be easily replicated"
		Ease of assembly	"Assembly looks questionable"
		CAD	"Easy to CAD"
		Cost	
Aesthetics			"Looks cool"
Idea Ownership			"This idea is mine"
Uniqueness/Creativity			"This idea is unique compared to others"



Participant code of idea being evaluated (ex. LYTA01)	Brief description of idea	Is this idea worth considering for further design?		Provide a rationale for your rating decision.	How confident are you in your rating decision? (% confidence)	Number of other team members that you think will endorse your rating decision
		Consider	Do not consider			
CAIE12	Hollow Girder set	●	○	Minimized support material, quick print time	90%	3
CARG07	Cylinder and Strut	●	○	Good height and not overly complex	70%	3

Figure 4 Example of a participants' assessment of other designs in the team using the concept screening sheet

- *Aesthetics:* This node captured the participants' consideration of the appearance of the design in their selection of the idea.
- *Uniqueness/creativity:* This node captured the participants' tendency to choose an idea based on its perceived uniqueness or creativity.
- *Idea ownership:* This node captured references to the participants' ownership of the ideas. However, this node was ultimately not used in the analysis as a very small number of references were observed.

5. DATA ANALYSIS AND RESULTS

To answer the research questions presented in Section 3, a statistical analysis was performed using a statistical significance level of α = 0.05 and a 95% confidence interval.

5.1. RQ1: What effects do design characteristics have on students' concept selection and how does this effect vary based on DfAM education?

To answer the first research question, related samples Wilcoxon Signed Rank Tests were performed independently for the restrictive and dual DfAM groups with the mean and final scores of each component (uniqueness, usefulness, AM technical goodness, and overall creativity) as the test fields. From the results summarized in Table 2 and Figure 5, we see that the restrictive DfAM group tends to select ideas with higher creativity scores compared to the team average, with usefulness and overall creativity being statistically significant to $p < 0.05$ level and uniqueness to the $p < 0.1$ level. Further, we also see this tendency in the dual DfAM group but only with the usefulness of the designs at the $p < 0.1$ level of significance.

To further explore these effects, the difference between the creativity of the final selected idea and the mean creativity of a team's ideas was calculated. This was done for all four components – uniqueness, usefulness, technical goodness, and overall creativity. Next, a Mann-Whitney U test was performed with the difference between final and mean score for each component as the dependent variable and the educational intervention group as the independent variable. The results of the analyses are summarized in Table 3 and Figure 6.

From the results, we see that there is a significant effect of the educational intervention group on the difference between the *uniqueness* of the selected idea and the mean uniqueness in the team. However, this effect was not seen in the case of the usefulness, technical goodness, or overall creativity. Specifically, we see that while the difference between the final and the mean uniqueness scores is *positive* for the group that received restrictive education (median = 0.63), this difference was negative in the group that received dual DfAM education (median = -0.25).

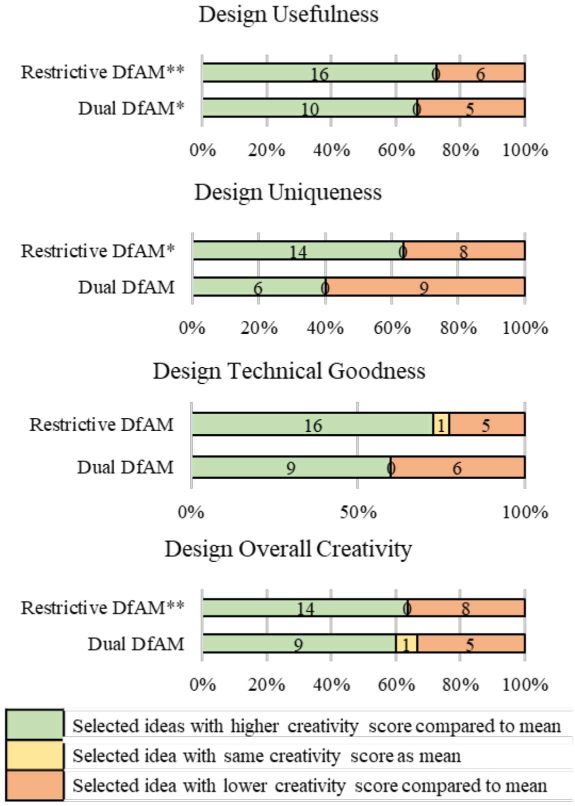


*Figure 5 Distribution of teams based on the creativity score of the selected idea compared against mean creativity scores in the team (*significant to 0.1 level, **significant to 0.05 level)*

Table 2 Difference between the creativity score of the selected idea and the mean creativity of ideas generated by the team

Creativity Metric	DfAM Group	z	p	Difference (Final - Mean)		
				-ve	Tie	+ve
Usefulness	**Restrictive**	**-2.44**	**0.02****	**6**	**0**	**16**
	Dual	**-1.88**	**0.06***	**5**	**0**	**10**
Uniqueness	**Restrictive**	**-1.90**	**0.06***	**8**	**0**	**14**
	Dual	0.77	0.44	9	0	6
AM Technical Goodness	Restrictive	-1.44	0.15	5	1	16
	Dual	-0.82	0.41	6	0	9
Overall Creativity	**Restrictive**	**-2.10**	**0.04****	**8**	**0**	**14**
	Dual	-0.31	0.75	5	1	9

(*significant to 0.1 level, **significant to 0.05 level)

Table 3 Comparing the educational intervention groups based on the difference between the creativity of the selected idea and the mean creativity of ideas generated by the team

Creativity Metric	*z*	*U*	*p*	Mean Rank (Median)	
				Restrictive DfAM	**Dual DfAM**
Usefulness	-0.43	151.00	0.68	19.64 (0.37)	18.07 (0.31)
Uniqueness	**-2.31**	**90.50**	**0.02**	**22.39 (0.63)**	**14.03 (-0.25)**
Technical Goodness	-0.96	134.00	0.35	20.41 (0.50)	16.93 (0.13)
Overall Creativity	-1.43	119.00	0.16	21.09 (0.65)	15.93 (0.13)

(*significant to 0.1 level, **significant to 0.05 level)

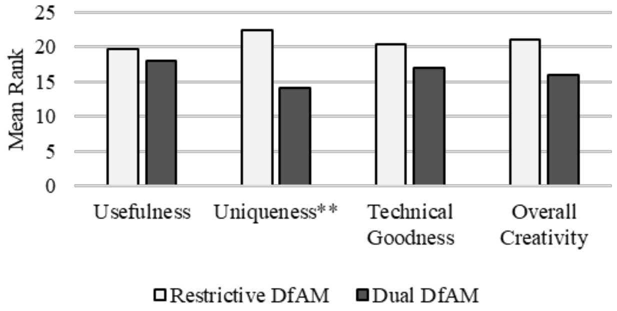


Figure 6 Comparing the educational intervention groups based on the difference between the creativity of selected idea and the mean creativity of ideas generated in the team

In summary, we see from the results of RQ1 that teams trained in restrictive DfAM selected ideas of higher creativity compared to the mean creativity of ideas generated in the team. While teams from the dual DfAM show a similar outcome with respect to the idea usefulness, a contrasting outcome is seen in terms of the idea uniqueness, where ideas of lower uniqueness were selected. The implications of these results are discussed in Section 6.

5.2. RQ2: What factors do students consider when evaluating and selecting concepts in a DfAM task and how does DfAM education influence this decision-making?

The first research question explored the effect of design creativity on participants' selection; however, it was important to understand what factors participants considered when making these decisions and the second research question was developed to explore these considerations. To answer this research question, we performed a qualitative analysis. The factors considered by the participants in the concept selection process were coded using the themes presented in Table 1, and frequency analyses were performed to identify themes that occurred most frequently. Six main themes were identified as presented in Figure 7, each of which is discussed in detail next. It should be noted that all %s presented in this section are in weighted %s.

5.2.1. Functionality: Participants from both restrictive and dual DfAM groups gave the highest emphasis on design functionality when evaluating the designs for consideration into the next stage. Both educational groups gave a similar emphasis on functionality when evaluating ideas *worth* considering; however, the restrictive group referred to functionality almost twice as much for ideas *not worth* considering compared to the dual DfAM group. This suggests that participants from the restrictive group showed a higher tendency for rejecting ideas based on their functionality. A further investigation showed that participants from both groups focused more on the task constraints when evaluating their ideas (restrictive DfAM group = 247, dual DfAM group = 166) in comparison to the task objectives (restrictive DfAM group = 124, dual DfAM group = 148). For example, several teams referred to the height of the tower ("is tall enough") and the design's ability to support loads ("sturdy and supportive") when evaluating them. Therefore, participants value the functionality of designs the most and higher importance is given to a designs' ability to meet the design task constraints as opposed to the achievement of the task objectives. Further, both educational groups presented similar emphases on general idea goodness.

5.2.2. Opportunistic DfAM: The second topic most discussed by the participants was opportunistic DfAM. The results showed that participants from the restrictive DfAM group showed a higher number of references to opportunistic DfAM compared to participants from the dual DfAM group. Of the various opportunistic DfAM topics, four subtopics occurred most frequently: (1) part complexity (restrictive DfAM group = 82, dual DfAM group = 60), (2) assembly complexity (restrictive DfAM group = 75, dual DfAM group = 21), (3) part consolidation (restrictive DfAM group = 22, dual DfAM group = 8), and (4) customization (restrictive DfAM group = 22, dual DfAM group = 8). A word frequency analysis showed that the most commonly occurring words in evaluations by the restrictive DfAM group were 'simple' = 10.15%, followed by 'connect' = 4.02%, 'assembly' = 3.81%. A similar analysis of the evaluations by the dual DfAM group revealed the most common words to be 'simple' = 12.50% followed by 'complex' = 6.50%, and 'connections' = 4.00%. All other words had weighted %s < 3. For example, phrases such as "simple assembly" and "easy to connect pieces" were commonly observed. Therefore, participants from the restrictive DfAM group emphasized the simplicity of the designs and opportunistic DfAM training shifted this focus to include the complexity of designs.

5.2.3. Manufacturing: The third most-used topic was execution and manufacturing. Under this topic, the three most occurring sub-topics were: (1) feasibility and practicality (restrictive DfAM group = 59, dual DfAM group = 34), (2) ease of assembly (restrictive DfAM group = 38, dual DfAM group = 4), and (3) CAD (restrictive DfAM group = 9, dual DfAM group = 13). A word frequency analysis showed that among participants from the restrictive DfAM group, the most frequent words were 'printed' = 13.25%, 'easy' = 10.60%, and 'assembly' = 4.97%. A similar result was seen in the dual DfAM group – the most frequently occurring words were 'easy' = 14.46%, 'printed' = 12.40%, and 'easily' = 4.13%. For example, "easily printed" and "easy to make" were frequently used phrases. Therefore,

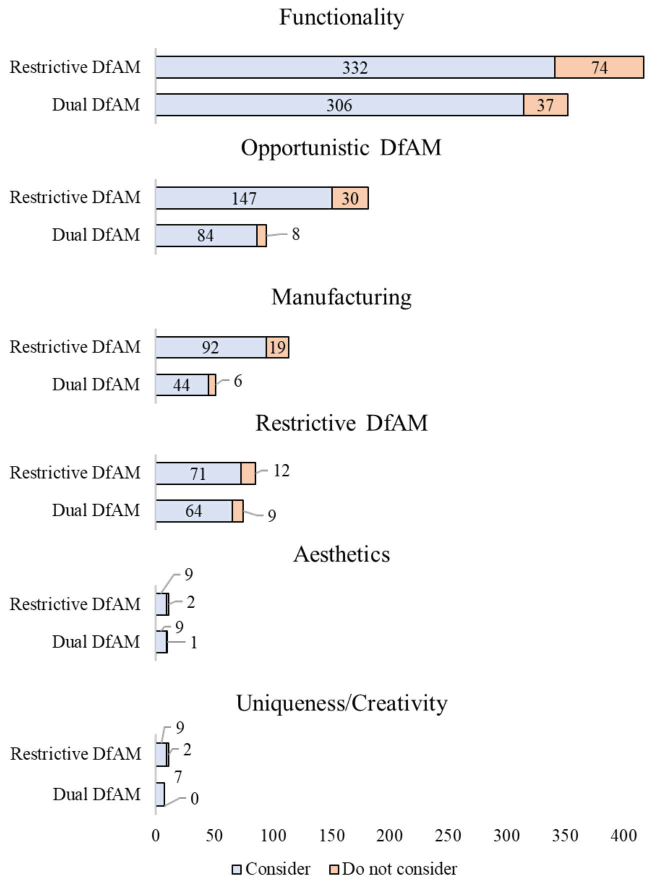


Figure 7 Frequency of occurrence of the various themes in the participants' rationale for selecting the design

participants from both the restrictive and dual DfAM groups focus on the ease of manufacturing and assembly when evaluating and selecting their designs.

5.2.4. Restrictive DfAM: The fourth most-occurring topic in the participants' evaluation of the designs was restrictive DfAM. The results showed that both the restrictive and dual DfAM groups presented similar frequencies of occurrence of restrictive DfAM topics. Of the various restrictive DfAM concepts, participants emphasized on four topics: (1) strength and anisotropy (restrictive DfAM group = 46, dual DfAM group = 57), (2) support material (restrictive DfAM group = 27, dual DfAM group = 11), (3) warping (restrictive DfAM group = 6, dual DfAM group = 2), and (4) surface roughness (restrictive DfAM group = 4, dual DfAM group = 2). A word frequency analysis showed that the words frequently used by participants from the restrictive DfAM group were 'support' = 10.48%, 'strong' = 7.68%, and 'sturdy' = 3.93%. A similar distribution was seen among the participants from the dual DfAM group – the most frequently occurring words were 'strong' = 12.87%, 'sturdy' = 8.77%, 'support' = 5.85%, 'strength' = 3.51%, and 'structure' = 3.51%. Phrases such as "strong enough to support loads" and "doesn't require a lot of support material" were observed under this node. Therefore, participants emphasize most on the restrictive DfAM concepts of strength and anisotropy when evaluating their designs. This is followed by an emphasis on the need for support material when manufacturing the part.

5.2.5. Aesthetics and Uniqueness: Finally, the last subtopics identified were aesthetics and creativity. A word frequency analysis of the items coded under these nodes showed that participants from the restrictive DfAM group most used the words 'unique' = 12.50%, and 'creative', 'looks', and 'pretty' = 6.25% each. The participants from the dual DfAM group most used the words 'looks' = 20.59%, 'cool' = 17.65%, and 'interesting' = 5.88%. An example of a phrase observed under this node is "[this design] looks cool". Therefore, while some participants emphasized the creative and aesthetic aspects of designs when evaluating them, this was the least mentioned topics.

6. DISCUSSION AND IMPLICATIONS

Our aim in this research was to investigate the effect of DfAM education on the outcomes of students' concept selection process. The main findings from the results of the study were:

1. Teams from both the restrictive and dual DfAM educational groups selected ideas with greater usefulness.
2. Only teams from the restrictive DfAM group selected ideas with higher uniqueness and overall creativity.
3. A majority of the participants emphasized the functionality of the designs – participants trained in restrictive emphasized more on task constraints whereas participants trained in dual DfAM emphasized more on task objectives.
4. Dual DfAM training encourages students to take into account the complexity of designs when making concept selection decisions, but not necessarily preferring complex ideas.

The first key finding from the results was that teams from both the restrictive and dual DfAM groups chose ideas of higher usefulness compared to the mean usefulness in the team. This finding suggests that teams tend to show a greater preference for ideas that meet the requirements of the problem statement. This observation resonates prior findings where designers have been shown to prefer solutions that better meet the requirements of the problem [54,99]. This is a positive outcome as it suggests that the design freedoms introduced through opportunistic DfAM education retain participants' emphasis on the usefulness of ideas when selecting concepts. However, this could also be attributed to the participants' preference for less risky ideas that solve the design problem without necessarily leveraging AM capabilities and future research must explore these preferences.

The second key finding was that while teams from the restrictive DfAM group chose ideas with a higher uniqueness and overall creativity compared to the mean scores in the team, this was not seen among teams from the dual DfAM. Further, we see from the results that the teams from the dual group also chose ideas of lower uniqueness compared to mean uniqueness in the team. This finding suggests that teams trained in restrictive DfAM potentially valued the creativity in their designs and were more inclined to take risks towards choosing unique ideas. In contrast, the teams trained in dual DfAM were probably more risk-averse, therefore choosing ideas of higher usefulness but low uniqueness. This observation presents the need for DfAM education – especially opportunistic DfAM education – to encourage participants to value creativity in their designs. This finding further resonates prior research that designers rarely accounted for the creativity and novelty of their designs when making concept selection decisions [28,99]. Additionally, this finding also suggests that participants trained only in restrictive DfAM demonstrated a greater trust in AM processes' ability to build their creative ideas. However, this aspect of trust and confidence in AM processes was not specifically tested in this study and future research must investigate these effects.

The third key finding from the results was that the functionality of the designs – its ability to meet the objectives and constraints of the design task – was most focused on by the participants when evaluating their designs for selection. Additionally, participants from the restrictive group gave a higher relative emphasis on the designs' ability to meet the constraints of the design task compared to the participants trained in dual DfAM, who gave a higher relative emphasis on the objectives of the design task. This is a positive outcome as it suggests that introducing participants to the capabilities of AM potentially encourages them to think about leveraging these opportunities towards meeting the objectives of the design task – suggesting a shift from the traditional limitation-based DfMA approach towards a dual DfAM approach. This could also suggest that introducing students to opportunistic DfAM encourages them to employ the various design techniques – such as geometric complexity – to meet the objectives of the design task – i.e. minimizing build material and build time. However, future research must specifically explore how the various DfAM concepts manifest in the participants' designs and how they influence design performance with respect to the objectives and constraints of the DfAM task.

Finally, we see from the results that opportunistic DfAM was the second most emphasized topic when evaluating and selecting designs and we see this emphasis among participants trained in both restrictive and dual DfAM. However, we see that participants from the restrictive DfAM group primarily focused on the simplicity of their designs. Therefore, despite emphasizing opportunistic DfAM, this emphasis focused on preventing build failure by simplifying ideas as opposed to leveraging AM capabilities by adding geometric complexity, a finding observed in prior research [29].

In contrast, participants from the dual DfAM group emphasized opportunistic DfAM with a focus on both, the simplicity as well as the complexity of the designs. This is a positive outcome as it suggests that informing participants about the opportunities enabled by AM encourages them to think about some of these opportunities, especially the freedom of geometric complexity when evaluating their designs. This finding further resonates the recommendations of the 2013 NSF workshop on AM education where the understanding of the freedom of complexity with AM was identified as an important characteristic of successful AM engineers [100]. The importance of this finding is further reinforced by prior research where student designers' have been shown to demonstrate a tendency to simplify their designs despite being exposed to AM's capabilities towards manufacturing complex geometries [29]. However, we must be careful when making this inference as the results of this study do not provide evidence to demonstrate participants' *preference* for complex ideas over simpler ideas and future research must investigate these tendencies.

7. CONCLUSION, LIMITATIONS, AND FUTURE WORK

AM processes have enabled designers to manufacture designs that were previously considered infeasible with traditional manufacturing processes. However, to sufficiently leverage the capabilities of AM, designers must not only employ DfAM to generate creative ideas, but also ensure that these creative ideas are not discarded early in the design process. Our aim in this study was to understand the factors that influence students' concept selection process in a DfAM task and the influence of DfAM education on these effects. Specifically, we compared the outcomes of the concept selection process of teams trained either in restrictive DfAM only or both opportunistic and restrictive (dual) DfAM. From the results, we see that students from both restrictive and dual DfAM groups select ideas of high usefulness. Further, while teams trained only in restrictive DfAM select ideas of high uniqueness and overall creativity, teams trained in dual DfAM did not demonstrate this behavior. In addition, the teams trained in dual DfAM demonstrated risk-averse tendencies and chose ideas of significantly lower uniqueness compared to the mean team uniqueness. Finally, participants trained in dual DfAM emphasized more on the objectives of the design task when evaluating their designs compared to those trained in restrictive DfAM, who demonstrated a higher emphasis on the constraints of the task. Additionally, dual DfAM training encouraged participants to think about the freedom of complexity enabled by AM when evaluating their designs.

The results of this study highlight the factors considered by designers when selecting concepts in a DfAM task; however, it has some limitations. First, researchers have demonstrated the relationship between individuals' risk-taking tendencies and their concept selection preferences [101]. However, the present research does not take into account the individual team members' risk attitudes and future research must work towards capturing these effects. Second, researchers have demonstrated that risk-taking varies based on the domain of interest [102]. However, we only focused on engineering design, especially mechanical engineering students. Future research must investigate the effect of DfAM education on the concept selection processes of designers from different domains. Third, the present research only investigates concept selection among junior and senior-level students, with a majority of participants having received some informal AM and DfAM training. However, risk-taking tendencies might vary based on students' prior engineering experience and domain knowledge and therefore, these differences must be explored in future research.

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