Favoring Complexity: A Mixed Methods Exploration of Factors That Influence Concept Selection When Designing for Additive Manufacturing

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The capabilities of additive manufacturing (AM) open up designers' solution space and enable them to build designs previously impossible through traditional manufacturing (TM). To leverage this design freedom, designers must emphasize opportunistic design for AM (DfAM), i.e., design techniques that leverage AM capabilities. Additionally, designers must also emphasize restrictive DfAM, i.e., design considerations that account for AM limitations, to ensure that their designs can be successfully built. Therefore, designers must adopt a "dual" design mindset—emphasizing both, opportunistic and restrictive DfAM—when designing for AM. However, to leverage AM capabilities, designers must not only generate creative ideas for AM but also select these creative ideas during the concept selection stage. Design educators must specifically emphasize selecting creative ideas in DfAM, as ideas perceived as infeasible through the traditional design for manufacturing lens may now be feasible with AM. This emphasis could prevent creative but feasible ideas from being discarded due to their perceived infeasibility. While several studies have discussed the role of DfAM in encouraging creative idea generation, there is a need to investigate concept selection in DfAM. In this paper, we investigated the effects of four variations in DfAM education: (1) restrictive, (2) opportunistic, (3) restrictive followed by opportunistic (R-O), and (4) opportunistic followed by restrictive (O-R), on students' concept selection process. We compared the creativity of the concepts generated by students to the creativity of the concepts they selected. The creativity of designs was measured on four dimensions: (1) uniqueness, (2) usefulness, (3) technical goodness, and (4) overall creativity. We also performed qualitative analyses to gain insight into the rationale provided by students when making their design decisions. From the results, we see that only teams from the restrictive and dual O-R groups selected ideas of higher uniqueness and overall creativity. In contrast, teams from the dual R-O DfAM group selected ideas of lower uniqueness compared with the mean uniqueness of ideas generated. Finally, we see that students trained in opportunistic DfAM emphasized minimizing build material the most, whereas those trained only in restrictive DfAM emphasized minimizing build time. These results highlight the need for DfAM education to encourage AM designers to not just generate creative ideas but also have the courage to select them for the next stage of design. [DOI: 10.1115/1.4050303]

Keywords: design for additive manufacturing, concept selection, decision-making, creativity, creativity and concept generation, design education, design for manufacturing

1 Introduction

Additive manufacturing (AM) technologies have expanded designers' solution space by enabling the realization of geometries previously considered too expensive or impossible using traditional manufacturing (TM) techniques. This new-found design freedom can be attributed to the layer-by-layer deposition process used in AM [1]. Some capabilities of AM include the freedom to manufacture complex geometries [2–4] and the ability to economically mass customize designs [5] due to the elimination of tooling costs [6]. To help engineering designers leverage AM capabilities, researchers have developed opportunistic design for AM (DfAM) techniques. Opportunistic DfAM techniques help designers leverage AM capabilities such as (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 that waste time and materials [12]. Therefore, to account for the limitations of an AM process, researchers have introduced restrictive DfAM guidelines that include accommodations for (1) support structures [13], (2) warping due to thermal stresses [14], (3) anisotropy [15,16], (4) surface roughness due to stair-stepping [17,18], and (5) feature size and accuracy [19].

While it is 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 whether or not

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Contributed by the Design for Manufacturing Committee of ASME for publication in the JOURNAL OF MECHANICAL DESIGN. Manuscript received July 23, 2020; final manuscript received February 3, 2021; published online March 25, 2021. Assoc. Editor: Tahira Reid Smith.

these creative ideas are *selected* for development in the later stages of design. Exploring this gap 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 also demonstrated designers' tendency toward emphasizing 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 as feasible when viewed 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, then creative ideas that could have been feasible with AM might get discarded. Opportunistic DfAM encourages designers to leverage the capabilities of AM, and therefore, opportunistic DfAM education could help mitigate the discarding of creative ideas during selection. On the other hand, introducing designers to restrictive DfAM could result in the selection of ideas that can be feasibly realized with AM, but it could also inhibit the creative freedom enabled by opportunistic DfAM, which could vary based on the order of introducing DfAM content [29]. This issue is specifically 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 [30].

Our aim in this paper is to explore the effect of DfAM education on students' concept selection during DfAM tasks. Toward this aim, we conducted an experimental study consisting of a DfAM educational intervention and an associated DfAM challenge. In Sec. 2, we discuss prior research that helped inform our study. Research questions (RQs) are then presented in Sec. 3, and our experimental method is discussed in Sec. 4. The results of the experiment are presented in Sec. 5 followed by discussions and concluding remarks in Secs. 6 and 7, respectively.

2 Review of Related Work

To investigate the effects of DfAM education on students' concept selection process, we explored prior work in the areas of concept selection and decision-making, 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 Ref. [31], 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 [32], 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 [31]. A similar breakdown of design processes is also reflected in the fields of design cognition [33] and creative cognition [34].

While the initial stages of idea generation and exploration help widen the solution space [35], comparison and selection of ideas are necessary to narrow down the solution space [36]. 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 [34]. Therefore, while idea generation plays an important role in the development of creative solutions [35], concept selection influences whether these creative ideas propagate through the design process [37].

The outcomes of the concept selection process not only influence the characteristics of the final product [38] but also the cost and time consumed in the final stages of the design process [39,40]. Therefore, it is crucial that this process is 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 [41]. These iterative processes are often also accompanied by the use of formal concept selection methods using tools such as the Pugh Chart [42], House of Quality [43], and the Analytical Hierarchy Process [44]. These tools help minimize the subjectivity in the concept selection process and provide structure to it [45]. Despite the introduction of several formal concept selection tools, these decisions are often made by individuals who possess inherent individual differences [40,46]. Additionally, different domains and individuals bring different aspects to the table when evaluating and selecting designs [47]. Therefore, it is important to understand the factors considered by designers in their concept selection process and we discuss prior research in this area next.

2.2 Factors that Can Influence Concept Selection in Engineering Design. While the use of formal concept selection processes is common across domains, the time spent on each stage and the focus of the evaluation vary significantly [48]. For example, in industries with longer product development cycles such as automotive, these stages are often designed to emphasize factors such as product performance, safety, manufacturability, and cost [49]. In contrast, in more "agile" industries such as software development, the focus shifts to reliability and reusability with much shorter development times [50,51].

Feasibility is a factor most frequently used by engineering design teams in their concept selection process potentially due to its emphasis in several selection tools and methods [52]. For example, as discussed by Racheva et al. [53], 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 studies of creativity where technical feasibility has been identified as one of the three important criteria for identifying creative products [54]. Additionally, designers have 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 [55,56].

While these studies highlight the effect of characteristics of the generated idea on its selection, researchers have also demonstrated the presence of biases [57,58] and individual differences [59,60] in designers' decision-making process, some of which include ownership bias [61–63], design fixation [64], and risk attitudes [65]. Of the various cognitive factors that affect decision-making, risk-taking is of particular interest in the DfAM setting, as *designs that are feasible for AM might be considered risky when viewed from a traditional DfMA lens*. The importance of studying risk-taking is further highlighted by researchers who demonstrate that individuals' risk-taking tendencies correlate with their preferences toward creative ideas [65]. Individuals who tend to be risk-*seeking* gravitate toward 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 toward adopting DfAM [66,67] could potentially result in creative ideas being discarded early in the design process. However, effective restrictive DfAM education could introduce designers to the risks associated with AM and encourage them to *overcome* their risk-averse tendencies by integrating restrictive DfAM concepts in their designs.

These studies demonstrate designers' tendency to select ideas that are feasible but not necessarily creative. In a DfAM setting, emphasizing the feasibility of designs—by integrating restrictive DfAM—is important as it would ensure that the designs selected for development can be successfully 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 riskier and less feasible and therefore be discarded. Restrictive DfAM education could help establish this trust by teaching engineers to accommodate AM limitations in their designs. Furthermore, restrictive DfAM education could also explicate the risks involved when using AM, thereby enabling designers to make better-informed decisions.

While several studies have explored the effect of DfAM education on creative concept *generation*, there is a need to better understand the factors that influence concept *selection* in DfAM tasks, and in this study, we explore this gap in the literature. To further understand existing DfAM decision-making tools and methods, we explore research in these areas as discussed next.

2.3 Design Evaluation and Decision-Making in DfAM.

As discussed in Sec. 2.1, designers select concepts by evaluating and comparing them against one another on factors such as product requirements and feasibility. Manufacturing processes play an important role in determining the feasibility—and cost—of designs, and the factors considered by designers in their concept selection process vary based on the choice of manufacturing processes. Therefore, to help designers make concept selection decisions during explicit DfAM tasks, researchers have presented design evaluation tools that evaluate designs on either (1) resource consumption or (2) manufacturability, and these design evaluation tools are reviewed in the remainder of this section. Additionally, researchers have presented design frameworks that help designers make higher-level concept selection decisions, taking into account both, the capabilities and limitations of AM. Examples of both are discussed next.

The time and resources consumed when manufacturing a product are key factors that determine its success [68], and therefore, several researchers have presented part evaluation tools that focus on resources consumed when additively manufacturing a part. These tools assess the build material and build time needed to additively manufacture a part, and researchers have presented tools that are both, process-agnostic [69] and process-specific. Some examples of process-specific resource prediction models include those developed for stereolithography [70–72], selective laser sintering and powder bed fusion [73–76], laminated object manufacturing [70], and material extrusion [77]. Extending this idea of resource modeling, Lindemann et al. [78] present a general 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 tools that assess parts for their resource consumption, researchers have also presented tools to evaluate the manufacturability of designs. For example, Telea and Jalba [79] 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. [80] 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 computer-aided design (CAD) models for their evaluation, thereby limiting their use to the later, more detailed, 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. A similar worksheet-based part selection tool is presented by Bracken et al. [81] for laser-based powder bed fusion. Savonen [82] presents a set of criteria for assessing the sustainability of AM parts in low-cost manufacturing scenarios. This application is further extended toward the development of a DfAM triaging method for evaluating and prioritizing part production based on a series of DfAM and functional decisions [83].

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 [30].

Accounting for this lack of emphasis on AM capabilities, Page et al. [84] 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. [85] 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. They present the merits of using the proposed framework in terms of its repeatability and efficiency when compared with manual decision-making. Similar to the feasibility analysis tools discussed earlier, these part evaluation frameworks also rely on the use of CAD models for analysis.

From these studies, we see that several researchers have presented evaluation tools that help designers make decisions during DfAM. A majority of these tools, however, are only effective in the later stages of design when designers have the CAD models ready and available, presenting a gap in the understanding of 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. Furthermore, with DfMA education being the current standard for concurrent engineering training, designers could develop an inherent preference for feasible ideas as viewed from the traditional DfMA lens. This preference could further reinforce their aversion to creative and risky ideas, despite the ideas being feasible with AM. Our aim in this research is to explore this gap in the literature by seeking answers to the two research questions introduced next.

3 Research Questions

Based on the review of the literature, our aim in this study is to investigate the effects of DfAM education on engineering students' concept selection in DfAM tasks. Specifically, we compared four variations in DfAM education: (1) restrictive only, (2) opportunistic only, (3) restrictive followed by opportunistic (dual R-O), and (4) opportunistic followed by restrictive (dual O-R). The effects of these variations in DfAM education were compared by seeking answers to the following RQs:

- ***RQ1: How do the characteristics (i.e., uniqueness, usefulness, technical goodness, and overall creativity) of the concepts selected by students relate to the characteristics of the concepts generated by them? Furthermore, how does this relationship vary based on DfAM education?*** We hypothesize that among the four components of creativity, participants will select concepts of higher usefulness and technical goodness compared with unique or creative concepts. This hypothesis is based on prior work in engineering design where students have been shown to prefer technically feasible ideas over creative ideas [28]. Moreover, we hypothesize that among the four educational intervention groups, designers trained in opportunistic DfAM will demonstrate a greater propensity to select unique and creative ideas. This hypothesis is based on prior research [86] which has demonstrated the potential for opportunistic DfAM integration to encourage design creativity. To test this hypothesis, we compared the creativity of the ideas generated by the participants to the creativity of the ideas selected by them. The creativity of the ideas was assessed on four components: uniqueness, usefulness, technical goodness, and overall creativity, and these assessments were made by quasi-experts in DfAM as discussed in Sec. 4.2.

- ***RQ2: What factors do students consider when evaluating and selecting concepts in a DfAM task? Additionally, how does DfAM education influence the factors considered by designers in their decision-making?*** We hypothesize that students will give a greater emphasis on the design functionality (objectives and constraints) and manufacturability (such as ease of manufacturing and assembly) compared with integrating specific DfAM techniques and creativity. Similar to the hypothesis for RQ1, this hypothesis is based on prior work where students reported a greater emphasis on design functionality compared with DfAM integration when describing and evaluating their ideas [30]. Furthermore, prior research in the engineering design literature has demonstrated that students primarily emphasize the technical feasibility of ideas when selecting concepts [28]. To test this hypothesis, we compared the qualitative data provided by the participants when making their concept evaluations and selection decisions. Specifically, participants were asked to report their rationale for evaluating and selecting concepts and these qualitative data were analyzed using content analysis techniques as presented in Sec. 4.2.

4 Experimental Methods

To answer these research questions, we conducted an experiment that consisted of a short-duration intervention lecture and a DfAM challenge. The details of these two components are discussed in this section, and the results follow in Sec. 5.

4.1 Participants. The participants were recruited from the fall and spring cohorts of a junior-level mechanical engineering course at a large northeastern public university focused on product design and engineering design methods ($N = 263$ not accounting for missing data). The participants comprised sophomores, juniors, and seniors, and a breakdown of the number of participants in each level is presented in Table 1. The participants' self-reported previous experience in AM and DfAM was collected at the beginning of the study as summarized in Fig. 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 consisted of four stages: (1) a pre-intervention survey, (2) DfAM educational intervention lecture, and (3) a post-intervention DfAM challenge, and (4) a post-intervention survey. The Institutional Review Board at the university 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 Fig. 2.

Table 1 Distribution of participants based on their year of study

	Fall semester	Spring semester
Sophomores	0	4
Juniors	84	134
Seniors	26	15
Missing	0	0
Total	110	153

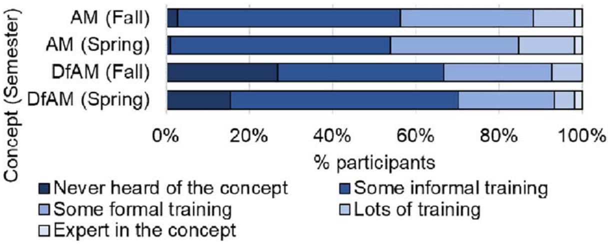


Fig. 1 Distribution of participants based on their previous AM and DfAM experience

4.2.1 Pre-Intervention Survey. At the beginning of the experiment, we asked participants to complete a pre-intervention survey. The survey captured their self-reported previous experience in AM and DfAM as summarized in Fig. 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 intervention lectures comprised content on either opportunistic DfAM, restrictive DfAM, or both. The number of teams in each educational intervention group is presented in Table 2; since the team-level data was used in our study, we only report the number of teams as opposed to the number of individual participants in each group.

All participants were first given a 20-min overview lecture on general AM process characteristics. Specifically, the instructor discussed topics including the material extrusion process (the AM process available to the students in the AM design challenge), differences from subtractive manufacturing, the digital thread, the Cartesian coordinate system, and common filament materials. The 20-min lecture on restrictive DfAM comprised topics including build time, feature size, support material, anisotropy, surface finish, and warping. The 20-min lecture on opportunistic DfAM covered topics including geometric complexity, mass customization, part consolidation, printed assemblies, multi-material printing, and embedding. The lecture slides can be accessed at [87].

The participants in the spring semester either received inputs in restrictive DfAM only or restrictive followed by opportunistic (dual R-O) DfAM. In contrast, the participants in the fall semester either received inputs in opportunistic DfAM only or opportunistic followed by restrictive (dual O-R) 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 regard to their prior AM and DfAM experience.

The short, 20-min duration of each lecture 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 [88]. 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 extending over multiple lectures and design sessions must, therefore, be explored in future research.

4.2.3 Design Challenge. After attending the DfAM lectures, we asked the participants to complete a DfAM challenge comprised

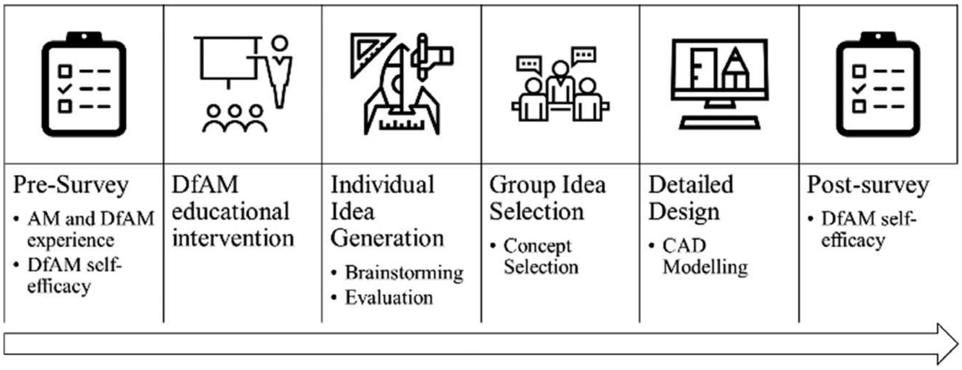


Fig. 2 Summary of the experimental procedure

Table 2 Number of teams in each educational intervention group

Educational intervention group	Number of teams
Restrictive DfAM	28
Restrictive followed by opportunistic DfAM (dual R-O)	20
Opportunistic DfAM	12
Opportunistic followed by restrictive DfAM (dual O-R)	17

of an individual and a group stage. The wind turbine DfAM task from [89] was used as the design prompt as prior research has demonstrated its effectiveness in encouraging creativity when using DfAM [89]. Moreover, the task requires minimal domain-specific knowledge beyond AM, DfAM, and basic mechanical engineering concepts such as solid mechanics (as suggested in Ref. [34]). Since the participants were recruited from a junior-level mechanical engineering course on engineering design methods, students were assumed to have a background in basic mechanical engineering concepts. The details of the individual and group stages of the design challenge are discussed next.

4.2.4 Individual Brainstorming. For the first part of the DfAM challenge, we asked participants to spend 10 min *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 min to evaluate each idea and note down its strengths and weaknesses, followed by approximately 7 min to individually design a final idea with the freedom to redesign, combine, or start over with a new design. 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.

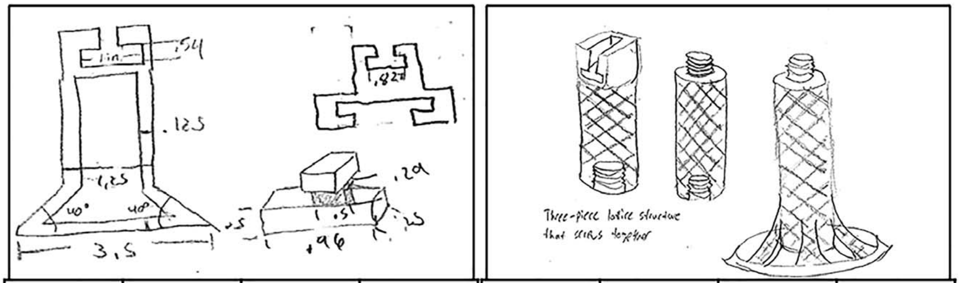
The creativity of participants' final designs from the individual brainstorming stage was assessed using the Consensual Assessment Technique [90]. The designs were independently evaluated by two quasi-experts with a background in DfAM (as suggested by [91,92]). A moderate to high inter-rater reliability was observed between the two raters, as verified by an Intraclass Correlation Coefficient = 0.71 [93]. The following metrics were provided to the raters, as suggested by the three-factor model [94,95]:

- *Usefulness*: Assesses the quality of the design in its ability to solve the given design problem. This metric focuses on the value and appropriateness of the resulting solution. It should be noted that the raters were given the freedom to use their subjective definition of usefulness and were not given any explicit instructions, especially with regard to accounting for DfAM utilization.
- *Uniqueness*: Assesses the originality and novelty of each solution; uniqueness is evaluated in comparison with the pool of solutions generated in the sample from the entire experiment [34]. Similar to the usefulness ratings, the raters were given the freedom to rate the ideas using their subjective definition of design uniqueness in relation to other ideas in the sample. Moreover, the raters were not provided any explicit instructions for considering DfAM utilization in the designs.
- *AM Technical goodness*: Assesses the level to which each solution suits the AM processes, both in terms of capabilities and limitations [25,30]. Using this component, the raters evaluated the extent to which DfAM—opportunistic and restrictive—was utilized in the designs.
- *Overall creativity*: Provides a subjective evaluation of the overall creativity of the idea as measured by experts. This measure helped capture any factors that might not have been captured in uniqueness, usefulness, and technical goodness.

Raters evaluated 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. An example of a participant's design along with its corresponding creativity score is presented in Fig. 3.

4.2.5 Team Concept Selection and Computer-Aided Design. After completing the individual concept generation, the participants were split into nominal teams [20] of three to five participants each. This resulted in a total of 77 teams (48 in the spring and 29 in the fall), and the distribution of the number of teams based on the educational intervention group is summarized in Table 2. After being split into teams, members were given time to present their individual final ideas to the other team 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 Fig. 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. It should be noted that in this stage, student teams were only given the freedom to select one idea and were asked to not make any significant modifications to their design. However, engineering design is an iterative process and future research must, therefore, extend this study to include multiple design–redesign stages. After selecting one idea, the participants were asked 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-h lab session. After completing the design challenge, we asked the participants to complete a post-intervention survey. It should be noted that both the CAD files and



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

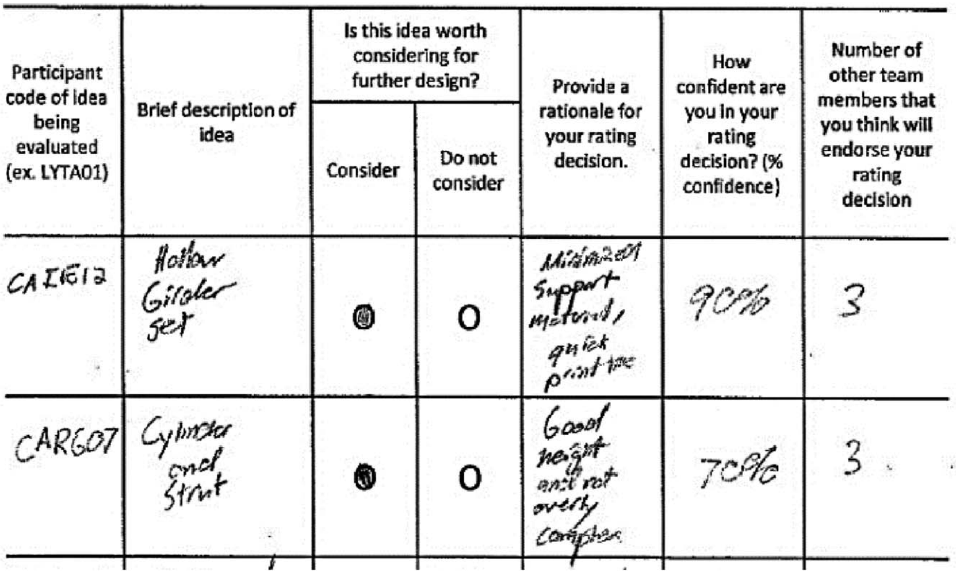
Fig. 3 Examples of ideas generated by the participants and the corresponding creativity scores

post-intervention survey responses were collected as part of a larger study.

The qualitative data, namely, participants' individual assessment of ideas generated in the team, 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 (average Cohen's Kappa >0.70 [98]). A summary of the coding scheme is presented in Table 3, 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 divided into sub-nodes corresponding to each opportunistic design concept (e.g., 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 divided into sub-nodes corresponding to each restrictive DfAM concept (for example, material anisotropy and support material), with all child nodes aggregating into the parent node.
- *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 (e.g., "easy to build").
- *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, and (3) design objectives.
- *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.

It should be noted that the coding scheme did not take into account the context in which these nodes were referred to and



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	●	○	Minimal support material, quick print time	90%	3
CARG07	Cylinder and Strut	●	○	Good height and not overly complex	70%	3

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

Table 3 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 × 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"

this is a limitation of our study. For example, a reference to "geometric complexity" does not necessarily highlight a preference for or against complex solutions. Therefore, future research must investigate the context in which designers emphasize the various nodes, in addition to the frequencies of their occurrence.

5 Data Analysis and Results

The data collected from the experiment were analyzed using a variety of statistical analyses. The statistical tests used to answer each research question and the results obtained therein are discussed in the remainder of this section. It should be noted that nonparametric tests were used for the analyses given the differences in sample size between the four educational intervention groups (see Table 2).

5.1 RQ1: How do the Characteristics (i.e., Uniqueness, Usefulness, Technical Goodness, and Overall Creativity) of the Concepts Selected by Students Relate to the Characteristics of the Concepts Generated by Them? Furthermore, How Does This Relationship Vary Based on DfAM Education?. We hypothesized that participants will prefer useful ideas over unique or creative ideas and that DfAM education would not influence this preference. To answer this first research question, two statistical tests were performed. First, the mean and final creativity scores were compared using repeated measures tests [99], and this was done independently for each educational intervention group. This was followed by independent samples tests comparing the difference between the final and the mean scores across the four educational intervention groups. The details of each test and the corresponding results are discussed next.

First, related samples Wilcoxon Signed Rank Tests [99] were performed independently for all four educational intervention groups with the mean and final scores of each component (i.e., uniqueness, usefulness, AM technical goodness, and overall creativity) as the test fields. From the results summarized in Table 4 and Fig. 5, we see that all four groups selected ideas of higher usefulness compared with the mean usefulness score in the team. However, we see that only teams from the restrictive DfAM and dual O-R DfAM educational groups selected ideas of higher uniqueness and overall creativity compared with the respective mean scores in the teams. Additionally, to compare if the mean of the creativity scores within the teams varied between the educational intervention groups, Kruskal–Wallis tests were performed [99] and no differences were observed ($p > 0.05$). Therefore, teams from all four educational intervention groups generated ideas of similar creativity; however, they varied in their preference for creative ideas.

Table 4 Difference between the creativity score of the selected idea and the mean creativity of ideas generated by the team

Creativity metric	DfAM educational group	z	p	Difference (Final—Mean) Negative	Tie	Positive
Usefulness	Restrictive	2.44	0.02**	6	0	16
	Dual R-O	1.88	0.06*	5	0	10
	Opportunistic	2.20	0.03**	2	0	10
	Dual O-R	2.13	0.03**	3	0	14
Uniqueness	Restrictive	1.90	0.06*	8	0	14
	Dual R-O	0.77	0.44	9	0	6
	Opportunistic	0.12	0.91	6	0	6
	Dual O-R	2.13	0.03**	4	0	13
Technical goodness	Restrictive	1.44	0.15	5	1	16
	Dual R-O	0.82	0.41	6	0	9
	Opportunistic	1.18	0.24	5	0	7
	Dual O-R	2.25	0.02**	3	0	14
Overall creativity	Restrictive	2.10	0.04**	8	0	14
	Dual R-O	0.31	0.75	5	1	9
	Opportunistic	1.02	0.31	5	0	7
	Dual O-R	1.71	0.09*	4	0	13

*Significant to 0.1 level, **significant to 0.05 level.

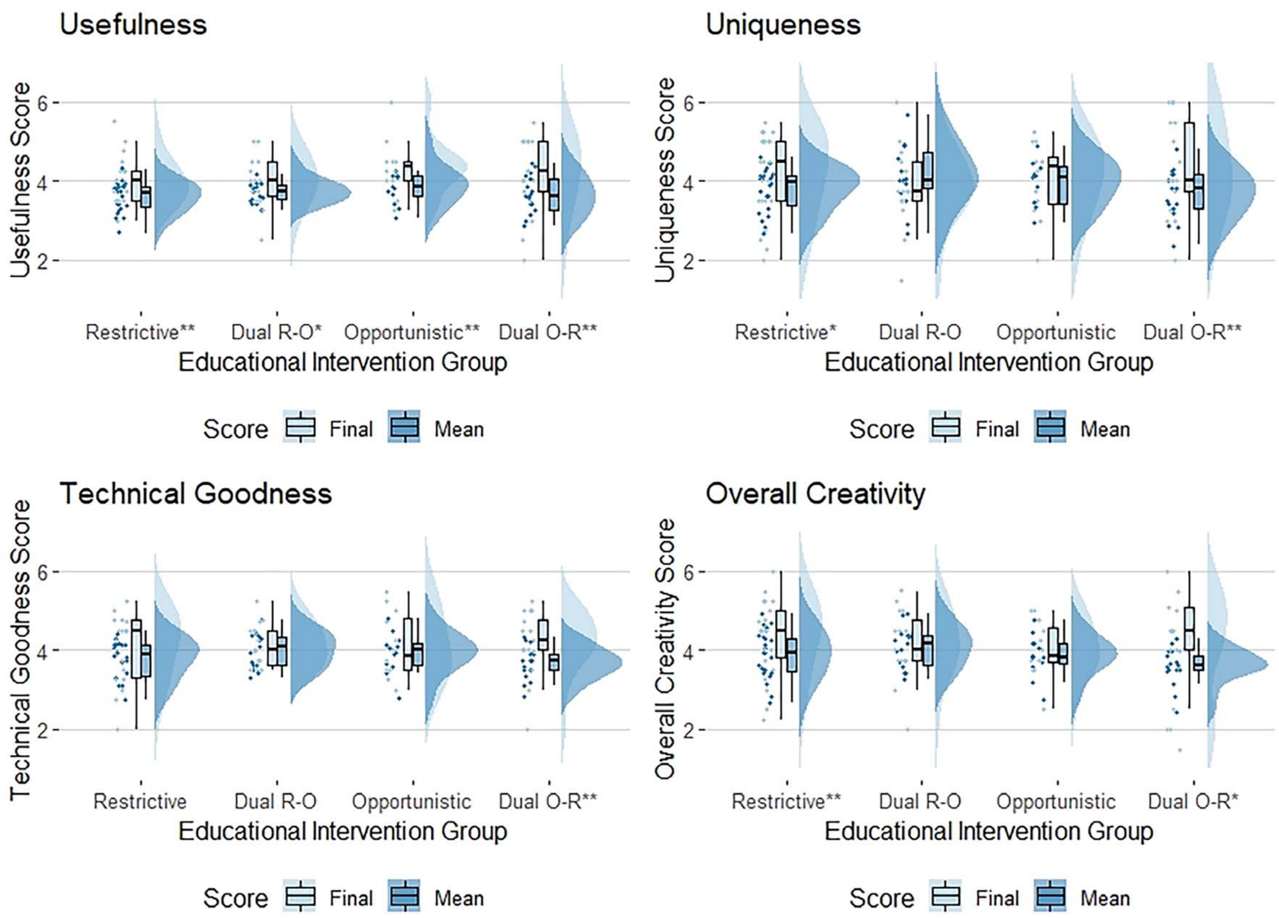


Fig. 5 Comparing the mean of the creativity scores of ideas generated in a team to the creativity of the final idea selected by them using raincloud plots [100] (*$p < 0.1$ and **$p < 0.05$)

Next, the difference between the creativity of the final selected idea and the mean creativity of all of a team's ideas was calculated. This was done for all four components (i.e., uniqueness, usefulness, technical goodness, and overall creativity). Independent samples Kruskal–Wallis tests [101] were then 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 showed a significant effect of the educational intervention group on the uniqueness of the ideas ($\chi^2(66) = 8.86$, $p = 0.03$) with no other significant effects observed ($p > 0.05$). Pairwise comparisons of the difference in uniqueness showed a significant difference between the two dual DfAM groups when tested with a Bonferroni correction ($\chi^2(66) = -2.69$, $p_{unadj} = 0.01$, $p_{adj} = 0.04$). Additionally, the restrictive DfAM group showed a significant difference compared with the dual R-O group when tested without Bonferroni's correction ($\chi^2(66) = 2.20$, $p_{unadj} = 0.03$, $p_{adj} = 0.17$). Both, the restrictive DfAM and the dual O-R groups showed a positive median difference (*Median* = 0.63 and 0.63, respectively), indicating the selection of ideas of higher uniqueness compared with the mean. On the other hand, the dual R-O group showed a negative median difference (*Median* = −0.25), indicating the selection of ideas with lower uniqueness compared with the mean. The implications of these results are discussed in Sec. 6.

5.2 RQ2: What Factors do Students Consider When Evaluating and Selecting Concepts in a DfAM Task? Additionally, How Does DfAM Education Influence the Factors Considered by Designers in Their Decision-Making?.

The second research question was developed to explore the factors participants considered when making their concept selection decisions. We hypothesized that students will give a greater emphasis on the design functionality and manufacturability compared with integrating specific DfAM techniques and creativity. 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 3, and frequency analyses were performed to identify themes that occurred most frequently (Table 5). Seven main themes were identified as presented in Fig. 6, each of which is discussed in detail next. Further, in Table 6, we have summarized the most frequently observed words in each node according to weighted percentages.

5.2.1 Design Task Constraints. Design task constraints was the topic most emphasized by the participants when evaluating ideas, and this high level of emphasis was observed among participants from all four educational intervention groups. However, as seen in Fig. 6, participants from the opportunistic DfAM group mentioned design task constraints the least compared with the other educational intervention groups. The words "base," "stable/unstable," "support," and "sturdy" were most frequently used, and this was uniform across all educational intervention groups (see Table 6). 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 achieving the task objectives.

5.2.2 Design Task Objectives. Design task objectives were the second most referenced topic by the participants when evaluating

Table 5 Frequently observed subtopics in each node averaged across the number of teams in each educational intervention group (only subtopics with at least one group's frequency >1 are reported)

		Frequency per team			
Node	Subtopic	Restrictive DfAM	Dual R-O DfAM	Opportunistic DfAM	Dual O-R DfAM
Design constraints	Supports motor and blade assembly	6.25	6.3	4.33	6.41
	Fits in one build	0.71	0.5	1.08	1.18
	Operating conditions	0.64	0.75	0.33	1.65
	Tower base and footprint	0.64	0.15	0.75	1.24
Design objectives	Build material	2.46	5.3	4	4.35
	Build time	1.96	2.05	1.08	1.35
Opportunistic DfAM	Assembly features	2.82	1.05	0.83	0.18
	Part complexity	2.93	3	1.92	1.35
	Part consolidation	0.79	0.4	1.08	0.24
Manufacturing	Ease of assembly	1.36	0.2	0.67	1.17
	Feasibility and practicality	2.14	1.7	2.92	2.88
Restrictive DfAM	Strength and anisotropy	1.64	2.85	2.92	2.41
	Support material	1	0.55	0.67	1.12
Design goodness		1.79	1.95	2.83	2.41
Aesthetics, uniqueness, and creativity		0.79	0.85	1.08	1.24

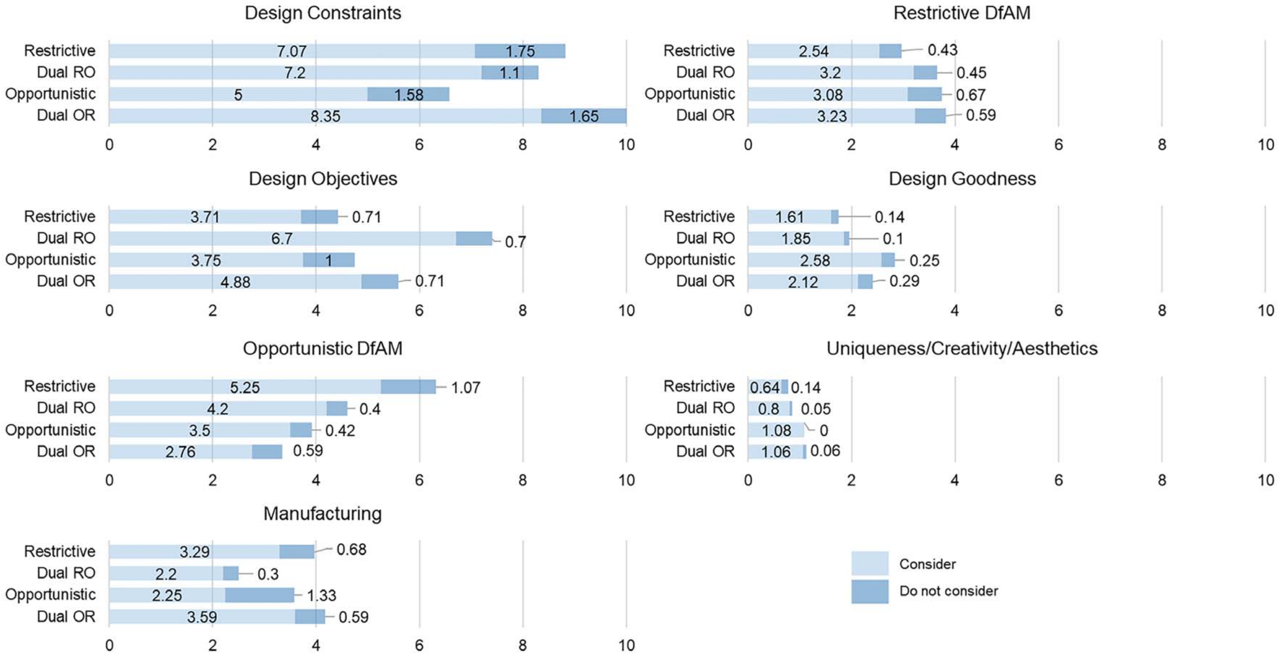


Fig. 6 Frequency of references to the various nodes averaged per team in the educational intervention group

ideas. As seen in Fig. 6, the two dual DfAM groups had the highest frequency of references to task objectives compared with the restrictive and opportunistic DfAM groups. Specifically, we see that the dual R-O DfAM group emphasized task objectives the most, followed by the dual O-R DfAM group. Further, we see that when rejecting ideas, participants from the opportunistic DfAM group gave the greatest emphasis on design task objectives compared with the other educational intervention groups. A word frequency analysis revealed that the words "material," "time," "less/low," "long," and "light" were most frequently observed as presented in Table 6. However, an interesting observation was that participants from the restrictive DfAM educational group referenced "material" the least (12.24%) compared with the other educational intervention groups (dual R-O = 17.17%, opportunistic = 25.83%, and dual O-R = 21.65%). In contrast, participants from the restrictive DfAM group referenced "time" the most (10.75%) compared with the other educational intervention groups (dual R-O = 7.32%, opportunistic = 4.64%, and dual O-R = 4.72%).

5.2.3 Opportunistic DfAM. The third topic most discussed by the participants was opportunistic DfAM. The results showed that participants from the restrictive only DfAM group showed a higher number of references to opportunistic DfAM compared with participants from the other three educational groups. Furthermore, we see that participants from the restrictive only DfAM group referenced opportunistic DfAM considerations for evaluating *rejected* ideas almost twice as much as the other DfAM groups. A word frequency analysis showed that the words "simple" and "[number of] parts" occurred most frequently in evaluations by all four educational groups (see Table 6). For example, phrases such as "simple assembly" and "easy to connect pieces" were commonly observed. However, the results also showed that participants from the dual R-O DfAM group frequently used the words "complex" to evaluate ideas. Therefore, while participants from all educational groups emphasized the simplicity of the designs, dual R-O DfAM education shifted this focus to emphasize the complexity of designs.

Table 6 Frequently observed words (weighted % > 3) in each node based on the educational intervention group

Node	Words	Weighted % Restrictive DfAM	 Dual R-O DfAM	 Opportunistic DfAM	 Dual O-R DfAM
Design constraints	Base	7.14	4.15	4.89	6.07
	Stable/unstable	5.81	6.34	3.26	4.67
	Sturdy	5.81	3.66	11.41	5.84
	Strong	4.32	5.37	5.98	7.48
	Support	3.16	4.39		3.27
Design objectives	Material	12.24	17.17	25.83	21.65
	Time	10.75	7.32	4.64	4.72
	Less/low	4.48	8.84	4.64	4.72
	Long	4.18			
	Light		3.79		
Opportunistic DfAM	Simple	10.15	12.50	7.87	11.11
	Complex		6.50		
	Parts	3.38	4.50	4.72	
Manufacturing	Easy/easily	10.60	16.53	11.21	16.85
	Hard			9.48	
	Assemble	3.31			6.74
Restrictive DfAM	Support	10.48	5.85	7.07	11.35
	Strong/strength	7.86	16.38	11.11	22.70
	Material	5.24		5.05	7.09
	Structure		3.51		3.55
Design goodness	Good/great	11.76	13.89	7.59	15.41
	Work	11.74		8.86	11.36
	Potential	3.36			
	Function			3.80	
	Efficient				3.41
Aesthetics, uniqueness, and creativity	Unique	12.50			6.52
	Similar			6.25	
	Different			3.12	
	Creative	6.25		3.12	
	Innovative	3.12		3.12	
	Inventive	3.12			
	Looks/looking	6.25	17.64	6.25	
	Aesthetic	3.12			
	Exciting	3.12			
	Interesting	3.12	5.88	6.25	4.35
	Cool		17.65	9.38	10.87

Note: Blanks indicate weighted % < 3.

5.2.4 Manufacturing. The fourth most-used topic was execution and manufacturing. We see that participants from all four educational groups gave similar emphases on manufacturing when evaluating ideas worth considering. In contrast, we see that participants trained only in opportunistic DfAM gave almost twice the emphasis on manufacturing considerations when evaluating ideas *not worth considering* compared with other educational intervention groups. A word frequency analysis showed that "easy" or "easily" were the most frequent words used by participants from all four educational intervention groups, as seen in Table 6. For example, "easily printed" and "easy to make" were frequently used phrases.

5.2.5 Restrictive DfAM. The fifth most-occurring topic in the participants' evaluation of the designs was restrictive DfAM. The results showed that all four educational intervention groups presented similar frequencies of occurrence of restrictive DfAM topics when evaluating ideas worth and not worth considering. All four groups referred to support materials and part strength when evaluating ideas. Phrases such as "strong enough to support loads" and "doesn't require a lot of support material" were observed under this node. However, as seen in Table 6, participants from the two dual DfAM groups gave twice and thrice as much emphasis on part strength compared with those trained only in opportunistic or restrictive DfAM, respectively.

5.2.6 Design Goodness. Design goodness was the sixth frequent subtopic used by the participants. Participants often referred to the general goodness of the ideas through phrases such as "seems like a good idea," "has the potential to work," and "is a nice idea." Participants from all four educational intervention groups gave a similar emphasis on this subtopic. However, the results in Fig. 6 showed that participants from the opportunistic and dual O-R DfAM groups emphasized design goodness twice as much when evaluating ideas not worth considering compared with the restrictive and dual R-O DfAM groups.

5.2.7 Aesthetics, Uniqueness, and Creativity. 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 opportunistic and restrictive DfAM groups frequently used words such as "unique," "creative," "innovative/inventive," and "looks." The participants from the dual DfAM groups most frequently used the words "looks," "cool," and "interesting." Examples of phrases observed under this node are "[this design] looks cool" and "innovative idea". Therefore, while some participants emphasized the creative and aesthetic aspects of designs when evaluating them, these were the least mentioned subtopics.

6 Discussion

Our aim in this research is to investigate the effect of DfAM education on the outcomes of students' concept selection process. The main findings from the results are discussed next.

The first key finding is that teams from all four educational intervention groups demonstrated a preference for ideas of higher usefulness compared with the mean usefulness of ideas generated in the team. This finding suggests that teams tend to show a greater preference for ideas that meet the requirements of the problem statement. Furthermore, teams from the four educational intervention groups did not vary in terms of the mean usefulness scores of ideas generated by the teams. This observation resonates with prior findings where designers have been shown to prefer solutions that better meet the requirements of the problem [55,102]. 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. This direction of research is particularly important as *only* teams trained in dual O-R DfAM selected ideas of high technical goodness. Therefore, future research must further explore the role of opportunistic and restrictive DfAM utilization on the usefulness of designs (e.g., see Ref. [103]). Such an investigation could also employ objective metrics for evaluating DfAM utilization (e.g., see Ref. [104]).

The second key finding is that teams from the restrictive and dual O-R DfAM groups selected ideas with higher uniqueness and overall creativity compared with the mean scores in the team; however, this preference for creative ideas was not seen among teams from the dual R-O DfAM. Furthermore, we see from the results that the teams from the dual R-O group also chose ideas of lower uniqueness compared with the mean uniqueness of ideas in the team. Additionally, teams from the four educational intervention groups did not vary in terms of the mean creativity scores of ideas generated by the teams. Two inferences can be made from this result. First, this finding suggests that teams trained in restrictive DfAM potentially valued the creativity in their designs and were more inclined to take risks toward choosing unique ideas. Moreover, this finding suggests that under certain conditions, introducing opportunistic DfAM potentially results in risk-averse tendencies among designers. This finding could also be attributed to an increase in students' confidence and trust in AM processes through the introduction of restrictive DfAM; by being aware of the limitations of AM processes, students might be more trusting of AM processes' ability to build their creative designs and therefore, more likely to select these creative ideas. On the other hand, introducing students to opportunistic DfAM might not have been sufficient to build a sense of trust in AM processes' abilities to successfully build unique and potentially risky ideas.

Second, it suggests that the order of dual DfAM education influences their concept selection outcomes. Specifically, the results suggest that teams trained in restrictive DfAM after opportunistic DfAM present similar design behaviors as those trained in restrictive DfAM only—both, in their concept generation and selection. In contrast to the restrictive and dual O-R groups, the teams from the dual R-O DfAM were possibly 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 corroborates prior research that found that designers rarely accounted for the creativity and novelty of their designs when making concept selection decisions [28,102]. Furthermore, design educators must also account for the order of presenting opportunistic and restrictive DfAM content, given its influence on students' concept selection decisions, corroborating previous findings [29]. Finally, these findings suggest that participants trained only in restrictive DfAM or dual O-R DfAM demonstrated a greater trust in AM's ability to fabricate their creative ideas. Being introduced to AM's limitations after being introduced to its capabilities potentially instills a sense of confidence in AM capabilities among the students. This confidence, in turn, could translate into a propensity for selecting 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. Additionally, as observed in the inferences from the first finding, the lack of differences in the technical goodness of the ideas selected by the teams indicates that the differences in uniqueness might not be a direct outcome of DfAM utilization in the designs. Therefore, future research must investigate the role of opportunistic and restrictive DfAM utilization on the uniqueness of the designs. Such an investigation could also employ objective DfAM integration metrics such as those proposed in Ref. [104].

The third key finding is that the participants emphasized the functionality of the designs—its ability to meet the objectives and constraints of the design task—the most when evaluating their designs for selection. While we see that all four educational groups equally emphasized design task constraints, we observed differences in their emphasis on design task objectives. Specifically, when *rejecting* ideas, participants from the opportunistic DfAM group emphasized design task objectives the most compared with the other educational intervention groups. 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 toward meeting the objectives of the design task—suggesting a shift from the traditional limitation-based DfMA approach toward a dual DfAM approach. This could be attributed to prior research suggesting the use of AM capabilities such as geometric complexity toward improving design functionality and performance [105]. However, the lack of such an emphasis among participants trained in restrictive DfAM, with or without opportunistic DfAM, suggests that restrictive DfAM education potentially shifts participants' focus away from rejecting poor-performing designs.

Furthermore, we see that participants trained only in opportunistic DfAM emphasized the design objective of minimizing build material the most compared with the other educational groups. In contrast, the participants trained only in restrictive DfAM emphasized the design task objective of minimizing build time the most compared with the other educational intervention groups. This result further reinforces the earlier observation that opportunistic DfAM education encourages participants to focus on the performance-based objective of minimizing build material by using opportunistic DfAM techniques such as part complexity and part consolidation. On the other hand, restrictive DfAM education encourages participants to minimize build time—a manufacturability-based objective—by incorporating restrictive DfAM concepts such as build orientation. While these are positive outcomes, 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 using metrics such as in Ref. [104]. Such an investigation could also highlight the context in which participants emphasize the various DfAM and manufacturing characteristics of their designs when evaluating and selecting them.

The final key finding is that dual R-O DfAM training encourages students to emphasize design complexity when making concept selection decisions; however, this does not necessarily indicate a preference for complex ideas. We see from the results that opportunistic DfAM was the third most emphasized topic when evaluating and selecting designs and we see this emphasis among participants from all four educational intervention groups. However, we see that participants from the restrictive, opportunistic, and dual O-R DfAM groups primarily focused on the simplicity of their designs. Therefore, despite emphasizing opportunistic DfAM, this emphasis focused on the simplicity of ideas as opposed to leveraging AM capabilities by adding geometric complexity, a finding observed in prior research [30]. This emphasis on design simplicity could indicate the pervasive assumption that simple ideas are more feasible compared with complex ideas.

In contrast, participants from the dual R-O 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 opportunistic DfAM encourages them to think about some of these opportunities, especially the freedom of geometric complexity when evaluating their designs. This finding, therefore, presents the potential for opportunistic DfAM training to encourage the selection of ideas by accounting for both, AM capabilities and limitations, and making these decisions beyond the limitations of manufacturing processes. 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 Conclusions, Limitations, and Future Work

Additive manufacturing 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 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 in (1) restrictive DfAM only, (2) opportunistic DfAM only, (3) restrictive followed by opportunistic (dual R-O) DfAM, or (4) opportunistic followed by restrictive (dual O-R) DfAM. From the results, we see that of the ideas generated in the team, teams from all four educational intervention groups select ideas of high usefulness compared with the mean usefulness of ideas in the team. However, only teams trained in restrictive DfAM and dual O-R DfAM selected ideas of high uniqueness and overall creativity compared with the mean creativity score in the corresponding teams. Teams trained in opportunistic DfAM and dual R-O DfAM did not demonstrate this behavior. The importance of this finding is further highlighted by the lack of differences in the mean creativity scores between the four educational intervention groups, suggesting similarities in the creativity of the ideas generated. This finding suggests that the educational intervention influenced teams' concept selection decisions but not their concept generation. In addition, the teams trained in dual R-O DfAM demonstrated risk-averse tendencies and chose ideas of significantly lower uniqueness compared with the mean team uniqueness. Furthermore, we see that participants trained in opportunistic DfAM only emphasized minimizing build material the most, whereas those trained only in restrictive DfAM emphasized minimizing build time. Finally, dual R-O 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 students when selecting design 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 [106]. However, the present research does not take into account the individual team members' risk attitudes, and future research must work toward capturing these effects. Second, researchers have demonstrated that risk-taking varies based on the domain of interest [107]; however, the present study only focuses on engineering design, especially mechanical engineering students. Future research must investigate the effect of DfAM education on the concept selection processes of students 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, designers' risk-taking tendencies might vary based on their prior engineering experience and domain knowledge and future research must explore these differences. Future research must also extend this research to investigate concept selection decisions between industry practitioners and novice designers (e.g., students). Fourth, our study was limited to designers' concept selection decisions in DfAM tasks; however, engineering design is often considered to be an iterative process with several stages of design and redesign. Therefore, future research must study how designers employ DfAM, both opportunistic and restrictive in multiple design–redesign stages. Finally, the short duration of the intervention might not have been sufficient to result in deep learning and consolidation of the various DfAM concepts. Future research must, therefore, study these effects using a longer intervention spanning several days and lectures. Moreover, such a study must also test the retention of these concepts over longer periods.

Acknowledgment

This research was funded by the National Science Foundation under Grant No. CMMI-1712234. Any opinions, findings, and conclusions expressed in this paper are those of the authors and do not necessarily reflect the views of the NSF. We would like to acknowledge the help from the ME340 TAs for their help in conducting the experiment and Dr. Stephanie Cutler for her help at several stages of this research. An earlier version of this paper [108] was presented at the 2020 ASME International Design Engineering Technical Conferences.

Conflict of Interest

There are no conflicts of interest.

Data Availability Statement

The datasets generated and supporting the findings of this article are obtainable from the corresponding author upon reasonable request.

References

[1] Campbell, I., Bourell, D., and Gibson, I., 2012, "Additive Manufacturing: Rapid Prototyping Comes of Age," Rapid Prototyp. J., **18**(4), pp. 255–258.

[2] Chu, C., Graf, G., and Rosen, D. W., 2008, "Design for Additive Manufacturing of Cellular Structures," Comput. Aided Des. Appl., **5**(5), pp. 686–696.

[3] Rosen, D. W., 2007, "Design for Additive Manufacturing: A Method to Explore Unexplored Regions of the Design Space," 18th Solid Freeform Fabrication Symposium, SFF 2007, Austin, TX, pp. 402–415.

[4] Murr, L. E., Gaytan, S. M., Medina, F., Lopez, H., Martinez, E., MacHado, B. I., Hernandez, D. H., Martinez, L., Lopez, M. I., Wicker, R. B., and Bracke, J., 2010, "Next-Generation Biomedical Implants Using Additive Manufacturing of Complex Cellular and Functional Mesh Arrays," Philos. Trans. R. Soc. A Math. Phys. Eng. Sci., **368**(1917), pp. 1999–2032.

[5] Pallari, J. H. P., Dalgarno, K. W., and Woodburn, J., 2010, "Mass Customization of Foot Orthoses for Rheumatoid Arthritis Using Selective Laser Sintering," IEEE Trans. Biomed. Eng., **57**(7), pp. 1750–1756.

[6] Hopkinson, N., and Dickens, P., 2003, "Analysis of Rapid Manufacturing—Using Layer Manufacturing Processes for Production," Proc. Inst. Mech. Eng. Part C: J. Mech. Eng. Sci., **217**(1), pp. 31–40.

[7] Schmelzle, J., Kline, E. V., Dickman, C. J., Reutzel, E. W., Jones, G., and Simpson, T. W., 2015, "(Re)Designing for Part Consolidation: Understanding the Challenges of Metal Additive Manufacturing," ASME J. Mech. Des., **137**(11), p. 111404.

[8] Calì, J., Calian, D. A., Amati, C., Kleinberger, R., Steed, A., Kautz, J., and Weyrich, T., 2012, "3D-Printing of Non-Assembly, Articulated Models," ACM Trans. Graph., **31**(6), pp. 1–8.

[9] Rosen, D. W., 2007, "Computer-Aided Design for Additive Manufacturing of Cellular Structures," Comput. Aided Des. Appl., **4**(1–6), pp. 585–594.

[10] De Laurentis, K. J., Kong, F. F., and Mavroidis, C., 2002, "Procedure for Rapid Fabrication of Non-Assembly Mechanisms with Embedded

Components," Proc. 2002 ASME Des. Eng. Tech. Conf. Comput. Inf. Eng. Conf., Montreal, Canada, Sept. 29–Oct. 2.
[11] Doubrovski, E. L., Tsai, E. Y., Dikovsky, D., Geraedts, J. M. P., Herr, H., and Oxman, N., 2015, "Voxel-Based Fabrication Through Material Property Mapping: A Design Method for Bitmap Printing," CAD Comput. Aided Des., **60**, pp. 3–13.
[12] Booth, J. W., Alperovich, J., Chawla, P., Ma, J., Reid, T. N., and Ramani, K., 2017, "The Design for Additive Manufacturing Worksheet," ASME J. Mech. Des., **139**(10), p. 100904.
[13] Hu, K., Jin, S., and Wang, C. C. L., 2015, "Support Slimming for Single Material Based Additive Manufacturing," CAD Comput. Aided Des., **65**, pp. 1–10.
[14] Zhu, Z., Dhokia, V., Nassehi, A., and Newman, S. T., 2016, "Investigation of Part Distortions as a Result of Hybrid Manufacturing," Robot. Comput. Integr. Manuf., **37**, pp. 23–32.
[15] Carroll, B. E., Palmer, T. A., and Beese, A. M., 2015, "Anisotropic Tensile Behavior of Ti-6Al-4V Components Fabricated With Directed Energy Deposition Additive Manufacturing," Acta Mater., **87**, pp. 309–320.
[16] Ahn, S., Montero, M., Odell, D., Roundy, S., and Wright, P. K., 2002, "Anisotropic Material Properties of Fused Deposition Modeling ABS," Rapid Prototyp. J., **8**(4), pp. 248–257.
[17] Boschetto, A., and Bottini, L., 2016, "Design for Manufacturing of Surfaces to Improve Accuracy in Fused Deposition Modeling," Robot. Comput. Integr. Manuf., **37**, pp. 103–114.
[18] Boschetto, A., Bottini, L., and Veniali, F., 2016, "Finishing of Fused Deposition Modeling Parts by CNC Machining," Robot. Comput. Integr. Manuf., **41**, pp. 92–101.
[19] Fahad, M., and Hopkinson, N., 2012, "A New Benchmarking Part for Evaluating the Accuracy and Repeatability of Additive Manufacturing (AM) Processes," 2nd International Conference on Mechanical and Automobile Engineering., Singapore, Apr. 28–29.
[20] Rietzschel, E. F., Nijstad, B. A., and Stroebe, W., 2006, "Productivity is not Enough: A Comparison of Interactive and Nominal Brainstorming Groups on Idea Generation and Selection," J. Exp. Soc. Psychol., **42**(2), pp. 244–251.
[21] Floriane, L., Frédéric, S., Gianluca, D. A., and Marc, L. C., 2016, "AM Knowledge Integration to Foster Innovation Process: A Methodological Proposal," Virtual Concept Workshop 2016: Major Trends in Product Design, Bordeaux, France, March, pp. 1–5.
[22] Yang, S., Page, T., and Zhao, Y. F., 2018, "Understanding the Role of Additive Manufacturing Knowledge in Stimulating Design Innovation for Novice Designers," ASME J. Mech. Des., **141**(2), p. 021703.
[23] Richter, T., Watschke, H., Schumacher, F., and Vietor, T., 2018, "Exploitation of Potentials of Additive Manufacturing in Ideation Workshops," Proceedings of The Fifth International Conference on Design Creativity (ICDC 2018), University of Bath, Bath, UK, Jan. 31–Feb. 2, pp. 1–8.
[24] Watschke, H., Bavendiek, A.-K., Giannakos, A., and Vietor, T., 2017, "A Methodical Approach to Support Ideation for Additive Manufacturing in Design Education," ICED17 21st Int. Conf. Eng. Des., **5**(DS87-5), pp. 41–50.
[25] Prabhu, R., Miller, S. R., Simpson, T. W., and Meisel, N. A., 2020, "Teaching Design Freedom: Understanding the Effects of Variations in Design for Additive Manufacturing Education on Students' Creativity," ASME J. Mech. Des., **142**(9), p. 094501.
[26] Rietzschel, E. F., Nijstad, B. A., and Stroebe, W., 2010, "The Selection of Creative Ideas After Individual Idea Generation: Choosing Between Creativity and Impact," Br. J. Psychol., **101**(1), pp. 47–68.
[27] Kazerounian, K., and Foley, S., 2007, "Barriers to Creativity in Engineering Education: A Study of Instructors and Students Perceptions," ASME J. Mech. Des., **129**(7), pp. 761–768.
[28] Toh, C. A., and Miller, S. R., 2015, "How Engineering Teams Select Design Concepts: A View Through the Lens of Creativity," Des. Stud., **38**, pp. 111–138.
[29] Prabhu, R., Simpson, T. W., Miller, S. R., and Meisel, N. A., 2021, "Fresh in My Mind! Investigating the Effects of the Order of Presenting Opportunistic and Restrictive Design for Additive Manufacturing Content on Creativity," J. Eng. Des.
[30] Prabhu, R., Miller, S. R., Simpson, T. W., and Meisel, N. A., 2020, "Exploring the Effects of Additive Manufacturing Education on Students' Engineering Design Process and its Outcomes," ASME J. Mech. Des., **142**(4), p. 042001.
[31] Ulrich, K. T., and Eppinger, S. D., and Yang, M. C.,, 2012, *Product Design and Development*, 7th ed., McGraw-Hill Education.
[32] Koen, P., Ajamian, G., Burkart, R., Clamen, A., Davidson, J., D'Amore, R., Elkins, C., Herald, K., Incorvia, M., Johnson, A., Karol, R., Seibert, R., Slavejkov, A., and Wagner, K., 2001, "Providing Clarity and a Common Language to the 'Fuzzy Front End'," Res. Technol. Manag., **44**(2), pp. 46–55.
[33] Stempfle, J., and Badke-Schaub, P., 2002, "Thinking in Design Teams—An Analysis of Team Communication," Des. Stud., **23**(5), pp. 473–496.
[34] Amabile, T. M., 1996, *Creativity in Context: Update to the Social Psychology of Creativity*, Westview Press, Boulder, CO.
[35] Ward, T. B., Smith, S. M., and Finke, R. A., 1999, "Creative Cognition," *Handbook of Creativity*, R. J. Sternberg, ed., Cambridge University Press, Cambridge, pp. 189–212.
[36] Campbell, D. T., 1960, "Blind Variation and Selective Retentions in Creative Thought as in Other Knowledge Processes," Psychol. Rev., **67**(6), pp. 380–400.
[37] Huang, H. Z., Liu, Y., Li, Y., Xue, L., and Wang, Z., 2013, "New Evaluation Methods for Conceptual Design Selection Using Computational Intelligence Techniques," J. Mech. Sci. Technol., **27**(3), pp. 733–746.
[38] Mattson, C. A., and Messac, A., 2005, "Pareto Frontier Based Concept Selection Under Uncertainty, With Visualization," Optim. Eng., **6**(1), pp. 85–115.
[39] Pahl, G., Beitz, W., Feldhusen, J., and Grote, K.-H., 2007, *Engineering Design*, Springer London, London.
[40] Calantone, R. J., and Schmidt, J. B., 2002, "Escalation of Commitment During New Product Development," J. Acad. Mark. Sci., **30**(2), pp. 103–118.
[41] Cooper, R. G., 1990, "Stage-Gate Systems: A New Tool for Managing new Products," Bus. Horiz., **33**(3), 44–54.
[42] Pugh, S., 1991, *Total Design: Integrated Methods for Successful Product Engineering*, Addison-Wesley, Reading, MA.
[43] Hauser, J. R., and Clausing, D., 1988, "The House of Quality," Harv. Bus. Rev., **34**(3), pp. 63–73.
[44] Saaty, T. L., 2008, "Decision Making With the Analytic Hierarchy Process," Int. J. Serv. Sci., **1**(1), p. 83.
[45] López-Mesa, B., and Bylund, N., 2011, "A Study of the Use of Concept Selection Methods From Inside a Company," Res. Eng. Des., **22**(1), pp. 7–27.
[46] Toh, C. A., Miele, L. M., and Miller, S. R., 2016, "Which One Should I Pick ? Concept Selection in Engineering Design Industry," Proc. ASME 2015 Int. Des. Eng. Tech. Conf. Comput. Inf. Eng. Conf., Boston, MA, Aug. 2–5.
[47] Kruger, C., and Cross, N., 2006, "Solution Driven Versus Problem Driven Design: Strategies and Outcomes," Des. Stud., **27**(5), pp. 527–548.
[48] Cooper, R. G., 2008, "Perspective: The Stage-Gate Idea-to-Launch Process—Update, What's New, and Nexgen Systems," J. Prod. Innov. Manag., **25**(3), pp. 213–232.
[49] Bylund, N., 2006, "Concept Selection in the Automotive Industry With Examples," International Design Conference—DESIGN 2016, Dubrovnik, Croatia, May 15–18.
[50] Batory, D., and O'Malley, S., 1992, "The Design and Implementation of Hierarchical Software Systems With Reusable Components," ACM Trans. Softw. Eng. Methodol., **1**(4), pp. 355–398.
[51] Zhang, P., Sadler, C. M., Lyon, S. A., and Martonosi, M., 2005, "Hardware Design Experiences in ZebraNet," Proceedings of the 2nd International Conference on Embedded Networked Sensor Systems (SenSys'04), New York, Association for Computing Machinery, pp. 227–238.
[52] Shah, J., Vargas-Hernandez, N., and Smith, S. M., 2003, "Metrics for Measuring Ideation Effectiveness," Des. Stud., **24**(2), pp. 111–134.
[53] Racheva, Z., Daneva, M., and Buglione, L., 2008, "Supporting the Dynamic Reprioritization of Requirements in Agile Development of Software Products," 2008 2nd Int. Work. Softw. Prod. Manag. ISWPM'08, (i)., Barcelona, Spain, Sept. 9.
[54] Kudrowitz, B. M., and Wallace, D., 2013, "Assessing the Quality of Ideas From Prolific, Early-Stage Product Ideation," J. Eng. Des., **24**(2), pp. 120–139.
[55] Saaty, T. L., and Vargas, L. G., 2003, *Models, Methods, Concepts & Applications of the Analytic Hierarchy Process*, Springer Science & Business Media, London.
[56] Simonson, I., 1993, "Get Closer to Your Customers by Understanding How They Make Choices," Calif. Manage. Rev., **35**(4), pp. 68–84.
[57] Kahneman, D., and Tversky, A., 1979, "Prospect Theory: An Analysis of Decision Under Risk," Econometrica, **47**(2), pp. 263–292.
[58] Hammond, J. S., Keeney, R. L., and Raiffa, H., 1998, "The Hidden Traps in Decision Making," Harv. Bus. Rev., **84**, p. 1.
[59] Stanovich, K. E., and West, R. F., 2003, "Individual Differences in Reasoning: Implications for the Rationality Debate?," Behav. Brain Sci., **26**(4), p. 527.
[60] Stanovich, K. E., and West, R. F., 1998, "Individual Differences in Rational Thought," J. Exp. Psychol. Gen., **127**(2), pp. 161–188.
[61] Nikander, J. B., Liikkanen, L. A., and Laakso, M., 2014, "The Preference Effect in Design Concept Evaluation," Des. Stud., **35**(5), pp. 473–499.
[62] Zheng, X., and Miller, S., 2019, "Is Ownership Bias Bad? The Influence of Idea Goodness and Creativity on Design Professionals Concept Selection Practices," ASME J. Mech. Des., **141**(2), p. 021106.
[63] Toh, C. A., Patel, A. H., Strohmetz, A. A., and Miller, S. R., 2015, "My Idea is Best! Ownership Bias and its Influence on Engineering Concept Selection," ASME 2015 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, Boston, MA, Aug. 2–5.
[64] Jansson, D. G., and Smith, S. M., 1991, "Design Fixation," Des. Stud., **12**(1), pp. 3–11.
[65] Toh, C. A., and Miller, S. R., 2016, "Choosing Creativity : The Role of Individual Risk and Ambiguity Aversion on Creative Concept Selection in Engineering Design," Res. Eng. Des., **27**(3), pp. 195–219.
[66] Mellor, S., Hao, L., and Zhang, D., 2014, "Additive Manufacturing: A Framework for Implementation," Int. J. Prod. Econ., **149**, pp. 194–201.
[67] Dwivedi, G., Srivastava, S. K., and Srivastava, R. K., 2017, "Analysis of Barriers to Implement Additive Manufacturing Technology in the Indian Automotive Sector," Int. J. Phys. Distrib. Logist. Manag., **47**(10), pp. 972–991.
[68] Saunders, M. N., Seepersad, C. C., and Holtta-Otto, K., 2011, "The Characteristics of Innovative, Mechanical Products," ASME J. Mech. Des., **133**(2), p. 021009.
[69] Alexander, P., Allen, S., and Dutta, D., 1998, "Part Orientation and Build Cost Determination in Layered Manufacturing," CAD Comput. Aided Des., **30**(5), pp. 343–356.
[70] Kechagias, J., Anagnostopoulos, V., Zervos, S., and Chryssolouris, G., 1997, "Estimation of Build Times in," Proc. 6th Eur. Conf. Rapid Prototyp. Manuf. Univ. Nottingham, Nottingham, UK, July 1–3, pp. 1–11.
[71] Chen, C. C., and Sullivan, P. A., 1996, "Predicting Total Build-Time and the Resultant Cure Depth of the 3D Stereolithography Process," Rapid Prototyp. J., **2**(4), pp. 27–40.

[72] Giannatsis, J., Dedoussis, V., and Laios, L., 2001, "A Study of the Build-Time Estimation Problem for Stereolithography Systems," Robot. Comput. Integr. Manuf., **17**(4), pp. 295–304.

[73] Pham, D. T., and Wang, X., 2000, "Prediction and Reduction of Build Times for the Selective Laser Sintering Process," Proc. Inst. Mech. Eng. Part B J. Eng. Manuf., **214**(6), pp. 425–430.

[74] Ruffo, M., Tuck, C., and Hague, R., 2006, "Cost Estimation for Rapid Manufacturing—Laser Sintering Production for Low to Medium Volumes," Proc. Inst. Mech. Eng. Part B: J. Eng. Manuf., **220**(9), pp. 1417–1427.

[75] Barclift, M., Armstrong, A., Simpson, T. W., and Joshi, S. B., 2017, "CAD-Integrated Cost Estimation and Build Orientation Optimization to Support Design for Metal Additive Manufacturing," Proceedings of the ASME Design Engineering Technical Conference, Cleveland, OH, Aug. 6–9, pp. 1–11.

[76] Michael, B., Sanjay, J., Timothy, S., and Corey, D., 2016, "Cost Modeling and Depreciation for Reused Powder Feedstocks in Powder Bed Fusion Additive Manufacturing," Proc. 27th Annu. Int. Solid Free. Fabr. Symp., **44**(3), pp. 52–54.

[77] Dinda, S., Modi, D., Simpson, T. W., Tedia, S., and Williams, C. B., 2017, "Expediting Build Time, Material, and Cost Estimation for Material Extrusion Processes to Enable Mobile Applications," Proceedings of the ASME Design Engineering Technical Conference., Cleveland, OH, Aug. 6–9.

[78] Lindemann, C., Reiher, T., Jahnke, U., and Koch, R., 2015, "Towards a Sustainable and Economic Selection of Part Candidates for Additive Manufacturing," Rapid Prototyp. J., **21**(2), pp. 216–227.

[79] Telea, A., and Jalba, A., 2011, "Voxel-Based Assessment of Printability of 3D Shapes," Lect. Notes Comput. Sci. (including Subser. Lect. Notes Artif. Intell. Lect. Notes Bioinformatics), **6671**(LNCS), pp. 393–404.

[80] Ghiasian, S. E., Jaiswal, P., Rai, R., and Lewis, K., 2020, "A Preference-Based Approach to Assess a Component's Design Readiness for Additive Manufacturing," ASME J. Mech. Des., **142**(8), p. 082001.

[81] Bracken, J., Pomorski, T., Armstrong, C., Prabhu, R., Simpson, T. W., Jablokow, K., Cleary, W., and Meisel, N. A., 2020, "Design for Metal Powder Bed Fusion: The Geometry for Additive Part Selection (GAPS) Worksheet," Addit. Manuf., **35**, p. 101163.

[82] Savonen, B. L., 2015, *Criteria for Sustainable Product Design With 3D Printing in the Developing World*, Michigan Technological University, Houghton, MI.

[83] Savonen, B. L., 2019, *A Methodology for Triaging Product Needs for Localized Manfacturing with 3D Printing in Low-Resource Environments*, The Pennsylvania State University, University Park, PA.

[84] Page, T. D., Yang, S., and Zhao, Y. F., 2019, "Automated Candidate Detection for Additive Manufacturing: A Framework Proposal," Proc. Des. Soc. Int. Conf. Eng. Des., **1**(1), pp. 679–688.

[85] Yang, S., Santoro, F., and Zhao, Y. F., 2018, "Towards a Numerical Approach of Finding Candidates for Additive Manufacturing-Enabled Part Consolidation," ASME J. Mech. Des., **140**(4), p. 041701.

[86] Blösch-Paidosh, A., Ahmed-Kristensen, S., and Shea, K., 2019, "Evaluating the Potential of Design for Additive Manufacturing Heuristic Cards to Stimulate Novel Product Redesigns," Volume 2A: 45th Design Automation Conference, American Society of Mechanical Engineers, Anaheim, CA, Aug. 18–21, pp. 1–10.

[87] "Design Thinking—Made By Design Lab," http://sites.psu.edu/madebydesign/design-thinking/, Accessed April 24, 2019.

[88] Ferchow, J., Klahn, C., and Meboldt, M., 2018, "Enabling Graduate Students to Design for Additive Manufacturing Through Teaching and Experience Transfer," Proceedings of the 20th International Conference on Engineering and Product Design Education, E and PDE 2018., London, UK, Sept. 6–7.

[89] Prabhu, R., Miller, S. R., Simpson, T. W., and Meisel, N. A., 2020, "Complex Solutions for Complex Problems? Exploring the Role of Design Task Choice on Learning, Design for Additive Manufacturing Use, and Creativity," ASME J. Mech. Des., **142**(3), p. 031121

[90] Baer, J., and McKool, S. S., 2009, "Assessing Creativity Using the Consensual Assessment Technique," *Handboof of Res. Assess. Technol. Methods, Appl. High. Educ.*, C. S. Schreiner, ed., IGI Global, USA, pp. 65–77.

[91] Kaufman, J. C., and Baer, J., 2012, "Beyond New and Appropriate: Who Decides What is Creative?," Creat. Res. J., **24**(1), pp. 83–91.

[92] Kaufman, J. C., Baer, J., Cropley, D. H., Reiter-Palmon, R., and Sinnett, S., 2013, "Furious Activity vs. Understanding: How Much Expertise is Needed to Evaluate Creative Work?," Psychol. Aesthetics, Creat. Arts, **7**(4), pp. 332–340.

[93] Shrout, P. E., and Fleiss, J. L., 1979, "Intraclass Correlations: Uses in Assessing Rater Reliability," Psychol. Bull., **86**(2), pp. 420–428.

[94] Besemer, S. P., 1998, "Creative Product Analysis Matrix: Testing the Model Structure and a Comparison Among Products-Three Novel Chairs," Creat. Res. J., **11**(4), pp. 333–346.

[95] Besemer, S. P., and O'Quin, K., 1999, "Confirming the Three-Factor Creative Product Analysis Matrix Model in an American Sample," Creat. Res. J., **12**(4), pp. 329–337.

[96] "Concept Screening Sheet," https://www.engr.psu.edu/britelab/resources/Concept Screening Sheets.pdf, Accessed July 18, 2019.

[97] Elo, S., and Kyngäs, H., 2008, "The Qualitative Content Analysis Process," J. Adv. Nurs., **62**(1), pp. 107–115.

[98] Cohen, J., 1960, "A Coefficient of Agreement for Nominal Scales," Educ. Psychol. Meas., **20**(1), pp. 37–46.

[99] Sheskin, D. J., 2004, *Handbook of Parametric and Nonparametric Statistical Procedures*, Chapman and Hall/CRC, London.

[100] Allen, M., Poggiali, D., Whitaker, K., Marshall, T. R., and Kievit, R. A., 2019, "Raincloud Plots: A Multi-Platform Tool for Robust Data Visualization [Version 1; Peer Review: 2 Approved]," Wellcome Open Res., **4**(63), pp. 1–41.

[101] Vargha, A., and Delaney, H. D., 1998, "The Kruskal-Wallis Test and Stochastic Homogeneity," J. Educ. Behav. Stat., **23**(2), pp. 170–192.

[102] Zheng, X., and Miller, S. R., 2016, "How Do I Choose ? The Influence of Concept Selection Methods on Student Team Decision-Making," ASME 2016 Int. Des. Eng. Tech. Conf. Comput. Inf. Eng. Conf., Charlotte, NC, Aug. 21–24, pp. 1–10.

[103] Prabhu, R., Bracken, J., Armstrong, C. B., Jablokow, K., Simpson, T. W., and Meisel, N. A., 2020, "Additive Creativity: Investigating the Use of Design for Additive Manufacturing to Encourage Creativity in the Engineering Design Industry," Int. J. Des. Creat. Innov., **8**(4), pp. 198–222.

[104] Prabhu, R., Miller, S. R., Simpson, T. W., and Meisel, N. A., 2020, "But will it Build? Assessing Student Engineering Designers' Use of Design for Additive Manufacturing Considerations in Design Outcomes," ASME J. Mech. Des., **142**(9), p. 092001.

[105] Tang, Y., and Zhao, Y. F., 2016, "A Survey of the Design Methods for Additive Manufacturing to Improve Functional Performance," Rapid Prototyp. J., **22**(3), pp. 569–590.

[106] Zheng, X., and Miller, S. R., 2017, "Risky Business : The Driving Factors of Creative Risk Taking," Proc. ASME 2017 Int. Des. Eng. Tech. Conf. Comput. Inf. Eng. Conf., Cleveland, OH, Aug. 6–9.

[107] Blais, A., and Weber, E. U., 2006, "A Domain-Specific Risk-Taking (DOSPERT) Scale for Adult Populations," A Domain-Specific Risk-Taking Scale Adult Popul., **1**(1), pp. 33–47.

[108] Prabhu, R., Leguarda, R. L., Miller, S. R., Simpson, T. W., and Meisel, N. A., 2020, "Favoring Complexity: A Mixed Methods Exploration of Factors That Influence Concept Selection in," Volume 11A: 46th Design Automation Conference (DAC), Virtual, Online, Aug. 17–19, American Society of Mechanical Engineers.