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Comparing the Impacts of Design Principles for Additive Manufacturing on Student and Experienced Designers*

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Additive manufacturing (AM) continues to play an important role in product development. Often, AM is integrated into later stages of the design process for products during detailed design, manufacturing, and production. There is an opportunity to introduce AM during early-stage design, which could inspire new business models and services in addition to re-thinking manufacturing for products and artefacts. The research objectives of this work are to first develop AM Design Principle Cards, which include a set of design principles for AM, and then demonstrate the impact of the AM design principles on designers' ideation performance. An ideation experiment was conducted to show the impact of the AM design principles on novelty and quality of ideation performance between students and experienced designers, as well as self-reported reactions and knowledge acquisition in AM. The research demonstrates that the AM Design Principle Cards can serve as a useful and meaningful design tool to support knowledge acquisition, creativity, and innovation with AM during early-stage design.

Keywords: additive manufacturing; design principles; design experience; ideation tool

1. Introduction

With the emerging technology of additive manufacturing (AM), key capabilities such as rapid prototyping, geometrical freedom, functional testing, component integration and consolidation, and highly customizable components are available [1–5]. As AM technology becomes readily available, design teams continue to integrate it into their prototyping and manufacturing efforts. Design teams also continue to push the boundaries of technology with new AM processes, material sets, and functional capabilities. Despite AM technologies being widely accepted in industries, there are still barriers to overcome for successful adoption. One major challenge is the lack of available knowledge that ensures successfully designed 'printable' components [4, 6, 7]. In order to exploit the full capabilities of AM technologies, designers of all experience levels need to understand and learn AM processes and capabilities, while having access to proven principles and tools for innovating with AM and for creating buildable parts.

Currently, several academic institutions have introduced courses covering topics on AM technologies, and their integration into the engineering curriculum often involves problem-based learning and project-based learning settings [8]. Some universities, such as the University of Texas at Austin, Virginia Tech, Pennsylvania State University and University of Maryland, offer curriculum for students to learn about different AM processes and to gain hands-on experience with AM technologies. Similarly, Lund University has employed a problem-based teaching approach to recognize practical hands-on problems and apply the theoretical learning throughout workshop settings [9]. Richter and co-authors suggested a design tool to utilize some design principles describing capabilities of AM and conducted the workshop to demonstrate the impact of the principles [10]. Later, the implementation of the design principles was demon-

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strated with application in the automotive sectors [11]. In addition, project-based learning opportunities are offered to students to explore new research in AM technologies [12]. However, the courses, workshops and projects may not include specific strategies for new opportunities provided by capabilities of AM technologies, which could be important in encouraging design innovation.

Previous research suggests some design tools for designing with AM technology during the early phase of the design process. One of the most well-known design tools is Design for Additive Manufacturing (DfAM) [13]. The objective of DfAM is defined as a synthesis of shapes, sizes, hierarchical structures, and material compositions to best utilize manufacturing process capabilities to achieve desired performance [14] and even to maximize product performance [15]. Additional AM knowledge bases or guidelines describing the capabilities of AM technologies have been suggested [16–18]. In the work of Bin Maidin et al. [16], an AM feature database was developed to provide opportunistic AM knowledge in the early design stages. Booth et al. [17] developed generalized AM guidelines in a form of worksheet that can guide and educate inexperienced designers in the best-practices for AM. It was found by Laverne et al. [18] that AM knowledge can foster creativity for both inexperienced and designers with AM experience. A combination of AM methods and tools were tested in a workshop environment to validate their practical applicability [19].

Despite the previous efforts, AM knowledge is not always helpful in terms of creative ideation performance. According to the work of Sinha et al. [20], designers who were exposed to the capabilities of AM technologies produced less feasible concepts when compared to designers who were only trained in design for conventional manufacturing. Related to this, Abdelall et al. [21] showed that designers trained in AM were influenced by the effect of design fixation, an unconscious phenomenon that can impact on the negative ideation performance because of an overreliance on features of preexisting designs, or a specific body of knowledge directly associated with a problem [22, 23]. Similarly, Richter et al. [11] found that the capabilities of AM technologies can mitigate creative ideation performance, as designers who lack knowledge fixate on already established solutions. This literature showed that the internal knowledge related to AM technology has the possibility to lead to negative impact on creative ideation.

One alternative way of sharing AM knowledge to support creative ideation is to utilize design principles or heuristics [24–31]. For instance, the 77 Design Heuristics were developed as a general set of inspirational design knowledge [24–30]. The set of the 77 Design Heuristics was empirically investigated through an experiment that showed the positive impact on overall creativity and diversity of ideas [24]. According to Daly, et al. [25], even students were able to use the heuristics and explore multiple applications of the same heuristic which did not yield prescribed solutions. In their other research [26], the use of the 77 Design Heuristics was successfully taught to engineering students how to use the heuristics with their course projects when they are trying to generate ideas in design courses, from freshman to capstone project-based courses. In a follow-up study of Gray et al. [27], it showed that students can ''internalize design knowledge as a design pattern or guiding pattern of internal coherence organizing past elements in the conceptual repertoire and preparing the repertoire for additional growth in the future.'' Similarly, Hwang and Park [31] also developed a set of design heuristics for a specific design goal X (DHSfX) and conducted an empirical study in which the DHSfX helped the students enhance their ideation performance for the creation of assistive product concepts where they have no experience in the context of assistive product concept design. Overall, the design principles or heuristics were a proven tool for novice designers or students in supporting early-stage design efforts and adopting them into their own idea solutions.

The development of design principles or heuristics for designing with AM technologies was first suggested by Perez et al. [32]. Perez et al. [32] conducted a study in which a set of design principles for AM were generated and developed through the use of a crowdsourcing method. In their later research, the impact of the AM design principles on creative ideation performance was demonstrated on an empirical basis [33]. Drawing on the work of Perez et al. [33], Lauff and co-authors restructured and formalized the set of AM Design Principle Cards and validated the cards with case studies [34]. Lauff et al. [35] also discussed the integration of the design heuristics in a design innovation framework. In addition to that, Blösch-Paidosh and Shea [36] conducted a study in which a set of design heuristics for AM was developed. In their follow-up study, an experiment was designed to test the efficacy of AM design heuristics and impact on the inexperienced designers' creativity in comparison to DfAM [37]. Lindwall and Törlind [38] also demonstrated the effect of AM design heuristics in the workshop settings. Recently, some other efforts on the development of principles and heuristics of design have been conducted to support insights into designers' use of the various principles/heuristics for AM knowledge [39, 40]. These studies produce some evidence on whether inexperienced designers can utilize the AM principles/heuristics for their creative ideation.

However, to the authors' best knowledge, it has not yet been demonstrated whether inexperienced designers, such as students in higher education, can learn from the knowledge for designing with AM technologies and fully take advantage of using the AM principles compared to experienced designers. In an attempt to address the aforementioned knowledge gaps, this study is conducted to determine answers to the following research questions: *How might we create an appropriate and useful tool to support innovations with AM early in the design process? How might this tool impact designers with different levels of AM experience in terms of creativity?*

In this study, the objective is to understand the principles of designing with AM, which are identified in prior research [32, 33] and demonstrate whether these AM design principles or heuristics produce different effects on inexperienced and experienced designers while ideating. As an ideation tool, we created the AM Design Principle Cards which are structured with analogies and external stimuli to inspire creativity. The final output is 27 AM Design Principle Cards that aim to encourage creativity when designing with AM and provide foundational knowledge of AM process capabilities, as well as a representational basis for evolving AM design methods. Building on this development, we conducted an ideation study and evaluated the effectiveness of the AM Design Principle Cards.

The remainder of the paper is organized as follows. Section 2 provides a summary of the previous studies on the development of AM principles and proposes a strategic structure of AM Design Principle Cards. Section 3 introduces the complete AM Design Principle Cards with the descriptions of four different categorization. In Section 4, the effect of AM experience level and the utility of AM principles on designers' ideation performance is demonstrated with an illustrative example. Finally, a discussion is provided in Section 5.

2. Development of AM Design Principle Cards

This section summarizes the creation of the AM Design Principle Cards based on AM principles extracted from literature and empirical studies [25, 26, 30, 32, 33, 41–45]. Strategic choices of structuring AM Design Principle Cards were made for the medium of communication (textual and visual) and the organization and structure of information (layout and categorization).

2.1 Syntax of Design Principles

The originally extracted AM principles [32, 33] followed a basic syntactic structure, without any formalization. Since the format of a design card can significantly impact the retrievability, comprehensibility, and efficacy of the card as a stimulus and knowledge-transfer mechanism, there is an opportunity to formalize the structure of the principles based on research into design principles, heuristics, and guidelines.

Syntax provides a basic structure to language which can help provide context and improve comprehension. This basic structure, or syntax, enhances communication and understanding of the language. Therefore, the AM principles should maintain a basic syntax to be useful to designers. Using the foundational elements of design principles set forth by Greer et al. [46] and furthered by Fu et al. [47, 48], we construct a syntax for the design principle as follows:

[address]	[issue]	by	[modify]	[factor]
Verb	*Noun*	*by*	*Verb*	*Noun*
	(or noun phrase)			*(or noun phrase)*

From the AM principle extraction research [32, 33], the principles were reported in a different format, such as: *"Print functional joints or interfaces directly instead of assembling them."* In this original format, the prescribed design intervention is given first *"Print functional joints or interfaces directly"* and the rationale or issue addressed is not directly given. One would have to infer from the statement *"instead of assembling them"* that the prescribed change is an improvement over assembled parts or components.

Using the new syntax prescribed in this paper, the principle can be reformatted to: *"Eliminate assembly steps and time by printing functional joints and interface directly."* In this new format, the issue and rationale are presented first followed by the design change or design approach. From this syntax representation, a designer can clearly identify the specific issue to address and the possible modifying factors (see Fig. 1).

2.2 Information Structure of Design Principles

Design principles that include images in the structure could offer benefits to designers across a range of experience and expertise levels [49–50]. However, one potential drawback of formalizing design principles with images is that the representation of images facilitates fixated thinking [51]. To mitigate the fixation effect, two representation methods have been suggested. One is to transform images into simple analytical-type graphics to invite impersonal and detached examination of the images [52]. The

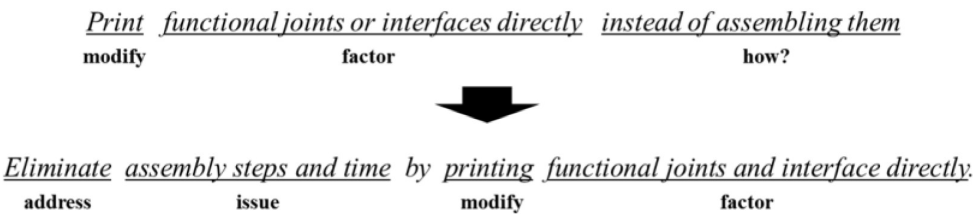

Fig. 1. An example syntax for the design principle.

second method to mitigate fixation is to provide multiple visual examples. Gadwal and Linsey [53] demonstrated that multiple visual examples enable the mapping of high-level principles. Viswanathan and Linsey [54] also show that multiple visual examples can mitigate design fixation when leveraging analogous examples as stimuli in design.

Based on the previous research, we propose that the AM Design Principle Cards include both a simple analytical graphic to illustrate the corresponding design principle and also a few visual examples of the corresponding AM principle. These visual examples may be based on design by analogy examples or external stimuli, which are described in the two following sub-sections. We believe that this visual structure will enhance the transfer of knowledge of the design principles to individuals, while mitigating fixation.

2.2.1 Design by Analogy Examples

Design by analogy is the use of solution examples from analogically similar problem spaces to inspire new creative solutions through the transfer of some elements of the analogical example. Several studies have demonstrated the utility of design by analogy in ideation [55–57]. With respect to the creation of the AM Design Principle Cards, design by analogy is used as a mechanism to help designers transfer the effective use of a design principle to their own opportunity spaces.

2.2.2 External stimuli

The effect of external stimuli for creative thinking has been studied extensively in the field of design science [51]. In general, researchers have studied both textual [58] and visual [59] examples as stimuli. However, research suggests that designers are more inspired by visual stimuli [60], but they may also be susceptible to negative effects from visual stimuli [61]. In order to mitigate the negative effect of the external stimuli, it is suggested that the structure of multi-modal stimuli is more beneficial during ideation [62]. Based on the literature, multi-modal examples as external stimuli were included in the AM Design Principle Cards, as a means to boost the novelty and quality of ideas generated.

3. AM Design Principle Cards

Based on the literature considering best practices to organize and disseminate information, as described in Section 2, the design tool needs and the corresponding features for the AM Design Principle Cards are extracted and described in Table 1. The AM Design Principle Cards need to have clear comprehension, encourage creativity, and mitigate fixation.

3.1 AM Design Principle Card Structure

The AM Design Principle Card structure was developed out of the needs described in Table 1. An example card is dissected in Fig. 2 to explain the key features of the structure of the cards. The corresponding features become the basis for the AM Design Principle Cards, as shown in Fig. 2.

The textual descriptions with consistent syntax and low-level analytical illustrations on the front side of the cards are included to aid the designer to make inferences regarding how the principle is useful and build a mental model of how it could be applied to their design challenge. Following the guidelines set forth by Kress and van Leeuwen [52], the cards include left to right panelized images that show a given concept on the left (as-is) and the new concept on the right (to-be) to show how a given design principle accomplishes the intent. These integrated features create an easy to apply understanding of the design principles.

The analogous case-study examples shown on the back side of the cards are provided to further facilitate the transfer of the principle to the designers' own opportunity and knowledge space.

Table 1. Design tool needs and proposed features

Design Tool Needs	Design Tool Features/Solutions
Enhance Comprehension	Textual Description Simple Analytical Illustration Consistent Syntax Left *As-Is* to Right *Should-Be* Format
Encourage Creativity	Analogous Examples Real Examples
Mitigate Fixation	Front/Back Two-Sided Layout Multiple Examples Given

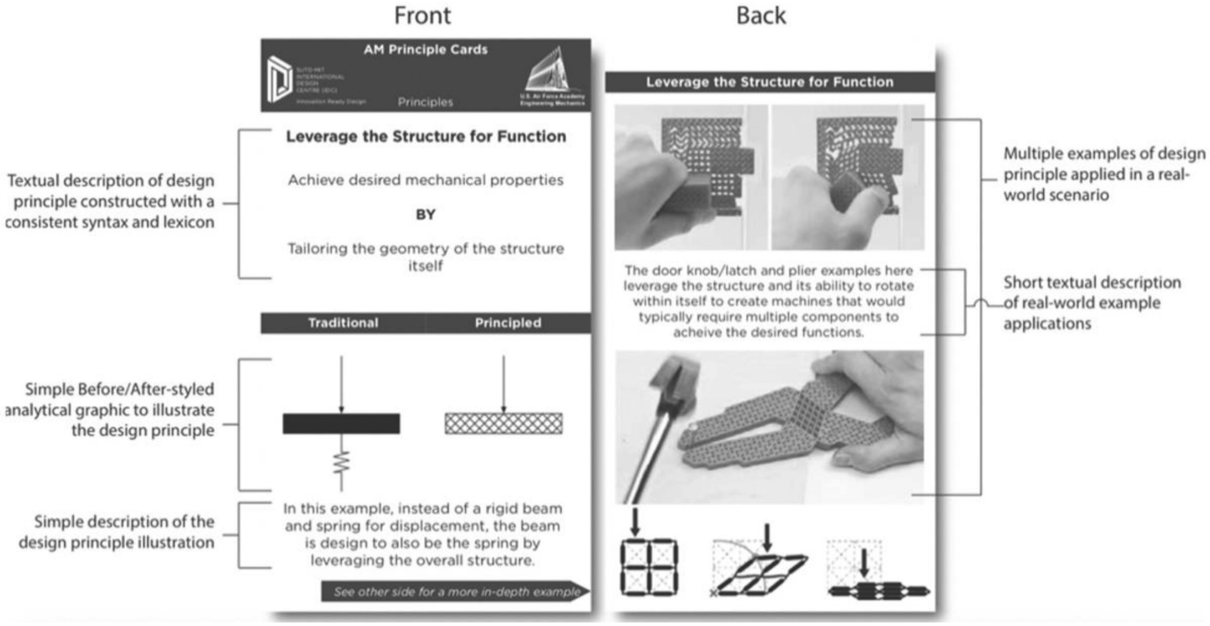

Fig. 2. AM Design Principle Card structure.

The examples encourage the transfer of information, encourage development of other creative solutions and are intended to create an experience that encourages creativity. These examples are analogous inspiration and/or design stimuli. The back side of the cards are multi-modal with visual images, text, and real-world examples. Moreover, the use of multiple examples helps to mitigate fixation as does the front/back layout and organization of the cards.

The user experience is meant to be such that the designer can move through the deck of AM Design Principle Cards and from the front-side alone assess if the principle might be helpful to their understanding or design opportunity. At that point, the designer could choose to review the back of the card to view the analogous examples. This information helps to limit the designers' exposure to irrelevant examples and potentially misguided examples that could encourage fixation effects. These graphical features and multiple examples help to mitigate fixation when using the cards.

3.2 The Categories of AM Design Principle Cards

Categorization is a useful approach for representing and storing information, especially to assist human cognition [63–65]. In extracting the AM principles, it was observed that some principles related to the design of parts themselves, whereas some principles provided new insights to the printing, design, and business processes [32, 33]. During the creation of the AM Design Principle Cards, experimentation with different examples and illustrations led to the insight of categorizing them by applications. The categories for the cards are displayed in Fig. 3 and described as follows:

- **Product** (Fig. 3A) – These AM principles provide innovative avenues for the physical design of parts and products. There are 13 product cards in the following areas: leverage cellular structures, integrate functions and components, functional joints and interfaces, leverage structure for function, scale for requirement, reuse digital geometries, enable 3D scanned personal interfaces, modularity, incorporate internal functionality, incorporate snap fits, combine parts, incorporate standard interfaces, and computationally driven design.
- **Business Process** (Fig. 3B) – These AM principles provide innovative avenues to change the larger business process around a product. There are 5 business process cards in the following areas: rapid customization, rapid replacement, point of consumption, part obsolescence, and rapid repair.
- **Design Process** (Fig. 3C) – These AM principles provide innovative avenues for leveraging AM to enhance the product design process, and not necessarily as a means of manufacturing the final product. There are 4 design process cards in the following areas: rapid prototype assessment, scaled testing, printed perturbation study, and enhanced concept generation.
- **Printability** (Fig. 3D) – These AM principles provide innovative avenues for improving printability of components, specifically around the topic of DfAM. There are 5 printing principle

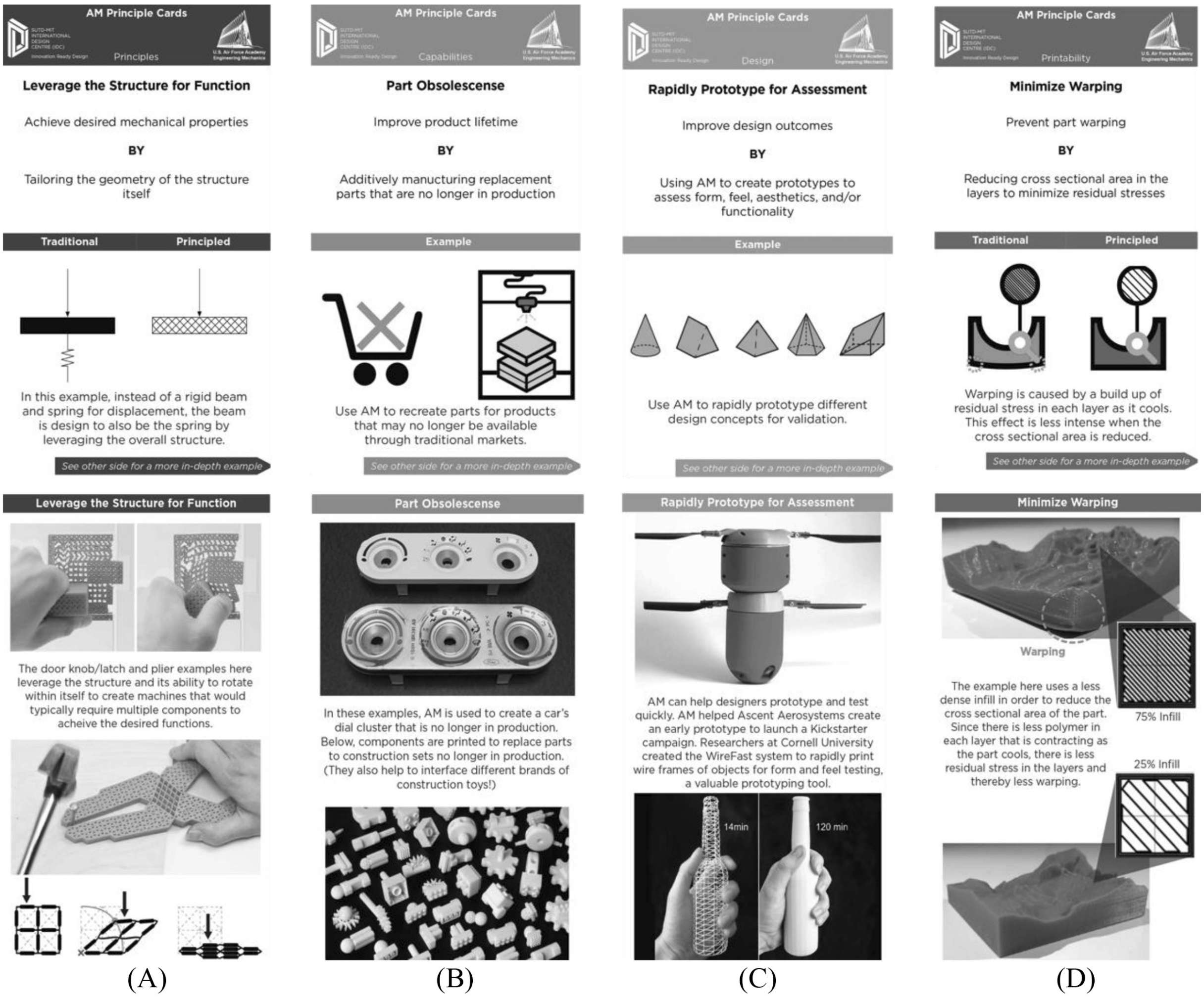

Fig. 3. Examples of AM Design Principle Card categories: (A) Product, (B) Business process, (C) Design process, (D) Printability principles of designing with AM.

cards in the following areas: minimize vertical aspect ratio, reduce print time, divide large artifacts, preserve small features, and minimize warping.

From this categorization, the utility of the principles at different stages of the design process can be realized. The 'design process' principles are applicable to all stages of the design process. They relate to *how* something is designed rather than *what* is to be designed. The 'business process' principles are useful both in the early stages of the design process during discovery, problem definition, and concept development. The 'product' principles are useful in the concept development phase. These cards contain new ideas, analogies, and innovative avenues for exploring product development with AM. The 'printability' principles are useful during the detailed design stages of product development. These principles help transform ideas into manufacturable solutions. Overall, the four categories of 27 principles lend themselves to transfer of knowledge and sparking new ideas for design opportunities with AM across the design process, products, and business models. The full set of 27 Design Principle Cards is available for download at [66] and [67].

4. The Effect of AM Experience Level and the Utility of AM Design Principle Cards on Designers' Ideation Performance

4.1 Method

In order to demonstrate whether the AM Design Principle Cards might serve different purposes when used by designers with a range of design experience, a study was conducted to assess the efficacy of the AM principles, and test whether the level of experience and the utility of the AM principles impacted ideation performance. We hypothesize that the AM principles will impact more on inexperienced designers when compared

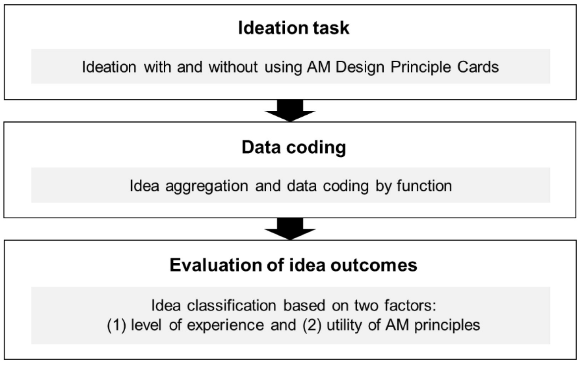

Fig. 4. Overall research methodology.

with experienced designers who have tacit knowledge and hands-on experience using the AM technology. The overall research methodology is shown in Fig. 4.

A total of 56 participants were recruited from an introductory design engineering classroom, a product redesign course and an AM technology development course at the Pennsylvania State University. Participants recruited in this study were engineering students with various levels of education and experience including first- and second-year engineering students and graduate students. Their years of experience with AM range from 0 to 25 years with an average of 1.67 years.

This study asked the participants to generate ideas with and without the AM Design Principle Cards, and then evaluate the ideation outcomes in terms of ideation performance measures. The design brief was to enhance the capabilities of mobile phones using AM. This design brief was selected because the participants likely have a personal connection to their own mobile phones, and therefore, are likely able to provide an array of concepts. Along with the design brief, participants were given seven example functional categories of mobile phones; these categories included charging, viewing, protecting, carrying, listening, talking, and texting. Participants were allotted two equally timed rounds (15-minutes per round) to ideate solutions for the design brief, and they were given a set of the AM Design Principle Cards as an intervention between the first and second round. The participants were given a set of selective AM Design Principle Cards and allowed 10 min to review them. Each group was given only a subset of the entire set of cards due to limited incubation time.

The participants generated ideas in the form of idea statements, sketches with descriptions, or a combination of both. The authors evaluated the idea statements or sketches generated from all participants by following the coding scheme suggested in the work of Blake et al. [45]. The coding scheme included placing individual ideas from all participants into a spreadsheet by a single coder based on function, and then discarding repeated ideas if they were already proposed by the same individual in the first round. Sketches were translated into ideas by function. If a sketch consisted of multiple explicit functions, it was split into multiple ideas (Fig. 5). Then, a second coder was asked to code a sample of the full data set to ensure reliability

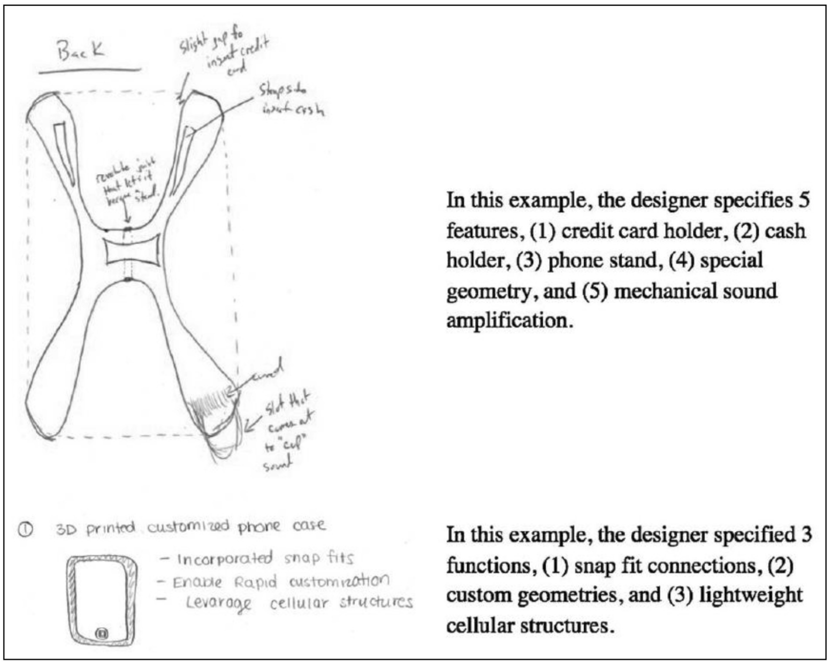

Fig. 5. Examples of coding ideas from participant sketches [45].

of the coding scheme. On the sample set containing 50 functions from the original coder, an 86% inter-rater agreement was measured to extensionally validate the original coding scheme.

To test whether the level of experience had any impact on ideation performance, we divided ideation outcomes into two groups based on the participants' years of experience in design: one group of ideas generated from participants with little-to-no experience (named the "inexperienced group"), and the other group of ideas generated from participants who have previously taken an engineering design course and/or had prior experience in design (named the "experienced group"). According to Persky and Robinson [68], designers can accomplish skills and/or expertise at an acceptable level of performance over 50 hours of practice. With this rationale, we set a threshold of 1 year of time as an acceptable level of experience in design. The participants in the inexperienced group had 0 to 1 year of experience with an average of 0.33 year of experience, while the participants in the experienced group had 1 to 25 years of experience with an average of 4.76 years of experience. Fig. 6 shows the distribution of participants' experience in design recruited in this study.

To assess the implementation of the AM principles in the ideation outcomes, the authors reviewed the idea statements and/or sketches generated from all participants. The ideas were classified into one of two categories based on whether the AM principles were implemented or not. If any element of the AM principle is identified within the idea, then the utility of the AM principle is evaluated with a score of 1 (utility, uses AM principles), and if no AM principles are identified then the idea is evaluated with a score of 0 (no utility, does not use AM principles). In this design of experiments, we considered both the first and second rounds of ideation for the utility analysis in order to assess how the implementation of the AM principles influenced the ideation performance.

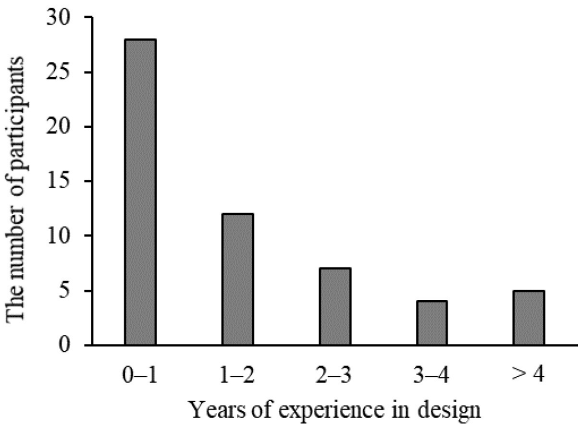

Fig. 6. Participants' years of experience.

The ideation performance was evaluated using two criteria: novelty and quality. These criteria have been widely used to evaluate design ideation outcomes in the previous research studies [69–75]. Novelty refers to how unusual or unexpected an idea is as compared to other ideas. Novelty scores were computed by using the posteriori method suggested by Shah, et al. [76]. The novelty scores were ranging from 8.59 to 9.96 on a scale of 0–10 where the low scores in novelty indicate the more ideas included in the similar categories of ideas and the high scores indicate only a few ideas belonging to a specific category of ideas. Quality pertains to the feasibility of an idea and how close it comes to meeting the intended design goal. As for the quality, Linsey's 0–2 scale [77] that measures the general feasibility of an idea has been utilized.

Three judges evaluated the individual ideas generated from all participants using the quality evaluation metrics. These judges were considered experts in DfAM; they were design professionals, where each had a bachelor's degree in mechanical engineering and had participated in numerous DfAM projects. Cohen's Kappa coefficients for evaluating inter-rater agreement were 0.68 for quality. According to Landis and Koch [78], these kappa coefficients of quality indicate substantial agreements between two raters.

A two-way ANOVA was conducted to explore the effect of the level of experience (inexperienced and experienced) and the utility (0: no implementation of any AM principles, 1: the implementation of any AM principles) of the AM principles on novelty and quality of ideas generated. In this study, both novelty and quality as dependent variables were found to be normally distributed. Also, the assumption for homogeneity of variance was validated for all the analysis. The Levene's test was conducted to examine the homogeneity of variance and statistical significance level was 0.05.

4.2 Results

In this study, participants generated a total of 273 idea statements and/or sketches as ideation outcomes, and 418 ideas by function. The results of a two-way between groups ANOVA on novelty shows that there is a statistically significant main effect for the level of experience, with $F(1, 406) = 4.269$, $p = 0.039$, and $\eta_{p^2} = 0.010$. As shown in Fig. 7, the experienced designers generated ideas with higher novelty ($M = 9.613$, $SD = 0.393$) than inexperienced designers ($M = 9.539$, $SD = 0.386$). The main effect for the utility is also significant, with $F(1, 406) = 4.757$, $p = 0.030$, and $\eta_{p^2} = 0.012$. This result indicates that the ideas with the utility of

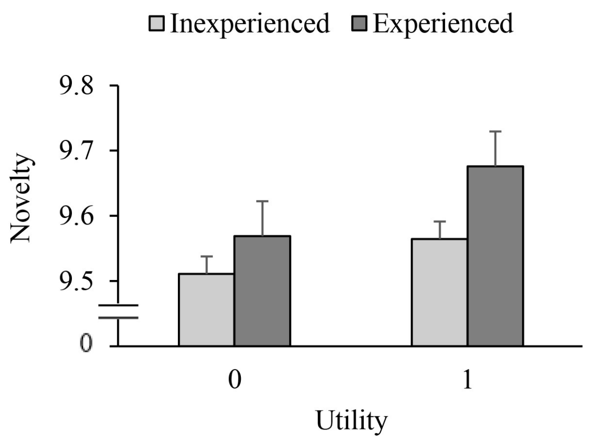

Fig. 7. Effects of level of experience and the utility of the AM principles on mean novelty.

the AM principles are assessed with higher novelty scores (M = 9.628, SD = 0.307) as compared with those without the utility of the AM principles (M = 9.543, SD = 0.445) (Fig. 7). However, there is no interaction effect between the level of experience and the utility, with $F(1, 406) = 0.472$, $p = 0.493$, and $\eta_{p^2} = 0.001$.

As for the quality, the main effect for the level of experience is significantly different, $F(1, 406) = 4.319$, $p = 0.038$, and $\eta_{p^2} = 0.011$. As shown in Fig. 8, the inexperienced designers produced more quality ideas (M = 1.832, SD = 0.390) than experienced designers (M = 1.768, SD = 0.522). However, the two-way ANOVA found no main effect for the utility, with $F(1, 406) = 1.578$, $p = 0.210$, $\eta_{p^2} = 0.004$, and no interaction effect between the level of experience and the utility, with $F(1, 406) = 0.005$, $p = 0.941$, and $\eta_{p^2} < 0.001$.

Overall, this study demonstrates that the AM principles and associated card tool can help designers generate novel ideation outcomes regardless of their level of experience. It also shows that

Fig. 8. Effects of level of experience and the utility of the AM principles on mean quality.

experienced designers can benefit more in novelty of ideas when using the AM principles than inexperienced designers. As for the quality measure, however, the inexperienced designers generated higher quality ideas when using the AM principles as compared with experienced designers. In all cases, the study demonstrates that the AM Design Principle Cards can assist designers, across experience levels, in generating novel and high-quality designs.

5. Discussion

5.1 Study Insights and Implications

In this study, we addressed the following research questions: *(1) how might we create an appropriate and useful tool to support innovations with AM early in the design process? and (2) how might this tool impact designers with different levels of AM experience in terms of creativity?* The first research objective is to develop an appropriate and useful tool to support innovations with AM early in the design process. We successfully achieved this first objective by creating the AM Design Principle Cards, which were strategically developed with foundational groundings from the literature and later awarded the 2019 Singapore Good Design Mark award [79]. The second research objective is to validate if this tool supports designers' creative thinking in the domain of AM and has an impact on designers with different levels of experience. The research objective was achieved through conducting a study to validate the effect of the utility of AM principles and the level of experience of designers (ideators) on ideation performance. The study determines if the concepts inspired by AM principles include novel designs, and higher quality. The study also includes a demonstration on whether the level of experience in designing with AM affects designers' ideation performance.

This research shows that novel concepts are developed with the AM principles. The research demonstrated that the AM principles positively affected the novelty of ideation outcomes regardless of the level of experience. This outcome is contrary to that of Blake et al. [45] who found that ideas evidenced from the utility of AM design principles were assessed with lower novelty scores than those without the utility of AM design principles. This may be due to the fact that this study takes the idea set before referencing AM Design Principle Cards into account. The majority of the ideas before referencing AM Design Principle Cards show no indication of AM principles and are assessed with low novelty. This finding indicates that the utility of AM principles indeed positively impacts on the novelty of ideation outcomes. From this result, we may draw a conclusion that the AM principles provided in the AM Design Principle Cards are helpful for generating novel solutions.

This research also shows that relatively higher novelty scores of ideation outcomes are observed in experienced designers. While some AM principles may not be new to experienced designers, it is the experienced designers who demonstrated the highest proficiency in translating the AM principles to actionable concepts. This result likely can be explained because experienced designers can retrieve important aspects of their knowledge with little attentional effort [68]. The experienced designers may find it easier to recognize meaningful patterns of information, and then associate that information into generating novel solutions. The more connections and experiences that individuals have, the more that information becomes "sticky" in the brain [68]. On the contrary, inexperienced designers may have more difficulty retrieving relevant and appropriate AM information and mapping concepts from disparate domains due to a lack of experience [80]. As the experienced designers more frequently generate ideas, consequently, they have more novel ideas according to the maxim 'quantity breeds quality' [81, 82].

Inexperienced designers benefit from the AM principles in terms of quality. One possible explanation of this finding might be that inexperienced designers can learn and better understand the AM principles, thus generating more feasible solutions. This means that the informing structure of the AM Design Principle Cards with the multi-modal AM principles and the corresponding real-world example applications were indeed beneficial for inexperienced designers to better implement the principles rather than experienced designers.

The implication of the aforementioned findings is that the instruction of enhancing novel ideas will help stimulate more creative and innovative designs for inexperienced designers. On the contrary, the experienced designers should be instructed with more utility and examples of the AM Design Principles Cards. Thus, different strategies need to be adopted depending on the level of experience.

5.2 Education: Classroom and Curricula Inferences

The study reported in this paper clearly demonstrates the value of tools, such as the AM Design Principle Cards, for imparting contemporary and emerging knowledge and technologies to participants with varying levels of experience. A focus of the study is regarding creativity and ideation, especially in terms of developing novel and high-quality concepts.

As a complement to this focus of the study, a wider set of participants (n = 114), across a range of experience (inexperienced to experienced) were asked to assess (self-efficacy) a number of aspects of the AM Design Principle Cards tool, including knowledge transfer, layout, and modality of information. The participants who used the AM cards reflected on their experiences with the cards upon completing the same design brief of mobile phones design challenge. Table 2 shows the results of a post survey of the participants, and their responses to a number of probing queries. The participants answered 6 survey questions on a 5-point Likert scale as to what degree they agreed or disagreed with the statements (5 = Strongly Agree, 4 = Agree; 3 = Neutral; 2 = Disagree; 1 = Strongly Disagree).

Based on the results shown in Table 2, the participants' responses to the AM Design Principle Cards were overwhelmingly positive (i.e., 4 = agree, 5 = strongly agree). These reactions include the effects of the AM Cards on knowledge transfer, content, and media expressed on the cards and the perceived enhancement of creativity.

Given the positive outcomes of the creativity study and complementary assessments by participants, there are a number of implications on education, ranging from higher education (university students) to professional development with practicing professionals (engineers). At one level, professional development with active-learning and organizational workshops appear to be especially attractive and feasible [83–91]. At the university level of education, tools such as the AM Design Principle Cards may be integrated into freshman year cornerstone design offerings, across departmental and interdisciplinary curricula through

Table 2. Participants' responses (self-efficacy) regarding the AM Design Principle Cards Tool (n = 114 – number of participants; Likert responses to survey: 5 = Strongly Agree, 4 = Agree; 3 = Neutral; 2 = Disagree; 1 = Strongly Disagree)

Survey Statements	Average Response	Standard Deviation	Standard Error
The AM Cards helped me to generate more concepts	4.04	0.803	0.0757
The AM Cards helped me to be more creative	4.02	0.804	0.0757
The AM Cards helped me to create new concepts	3.92	0.826	0.0780
The textual descriptions of the principles are easy to understand	4.35	0.714	0.0671
The illustrations on the front of the Cards convey the principles clearly	4.47	0.705	0.0662
The AM Cards helped me to understand AM better	4.23	0.859	0.0808

designettes [84, 88, 89, 92, 93], and within senior capstone design offerings [94].

5.3 Limitations and Future Work

Even with these promising results, there are limitations to the development of the AM Design Principle Cards and corresponding ideation study. First, the study only presents evidence for one case in supporting the efficacy of the AM principles. In order to further generalize the impact of the AM Design Principle Cards, more empirical studies demonstrating the effect of the AM Design Principle Cards will need to be conducted. It could be also interesting to see how the AM Design Principle Cards influence the final designed solution when introduced at different points in time during the design process. Second, the study was limited in terms of overall ideation performance. More studies need to be conducted to evaluate how the AM Design Principle Cards can influence other aspects of the design process outside of ideation, such as the likelihood of influencing decisions to consider new business models with AM for a company or project. This type of study would require analysis of the full design process from idea to implementation. Third, the entire set of the AM Design Principle Cards was not distributed to participants; only selected subset of the AM Design Principle Cards was given to the participants, so as to align with ideation goals and not overwhelm the participants with too much information. The efficacy of the entire set of the AM Design Principle Cards needs to be demonstrated in the future work.

Some opportunities for future work are suggested here. First, qualitative research using semi-structured interviews or focus groups can be conducted to investigate how the use of the AM Design Principle Cards enhances creative thinking process of students, and how the students retain and master the cards in their design practices. This future study may help us understand on the students' perceptions of the cards and identify how the cards can be improved to support innovations with AM by the students. Second, future work would like to address digital versions of the design cards, the addition of more information with the cards, and the overall layout and chronological flow of the cards. The cards provide a two-dimensional representation of many three-dimensional examples, so we hypothesize that these examples could be further enhanced and explained using other modalities and media, such as video and digital graphics to simulate their three-dimensional nature. Third, the procedure of developing the design principles can be applied to many other applications such as innovative products, new architecture and products or systems with emerging technologies. With the capabilities in applying different applications, we may also think of this process as a design educational activity to derive design heuristics by collecting extensive data, extracting underlying design ideas and implementing them into their own design solutions. The finding would give us a clear understanding of how students "learn" to design from the design activities, and how they can be encouraged to become creative and novel designers.

6. Conclusion

This paper explores the development of a design tool to support innovative thinking around Additive Manufacturing in the early stages of the design process. AM Design Principle Cards were developed on the basis of extracted and representing AM principles. The strategic development of the cards is detailed based on literature and best practices in creativity, learning theory, design by analogy, and external stimuli. The two-sided cards are presented using a consistent syntax and include narrative and analytical graphics to assist in explaining concepts. Multiple examples and analogies are used to encourage creativity, while mitigating fixation effects found when using one analogy or example. Further, the cards are divided into four categories to support efforts related to products, business processes, design processes, and printing principles.

Through systematic studies, this paper demonstrates whether the level of experience may impact on the use of AM principles. As supported by empirical results, the AM principles are impactful on ideation performance in terms of novelty and quality. However, the impact on ideation performance may vary depending on the level of experience in AM. While the AM principles show benefits in novelty and quality of ideation across experience levels, we suggest that designers with more than one year of experience in AM need to focus on the quality of generated concepts. Complementary, those with less than one year of experience in AM should focus on the novelty ideas. The different strategies need to be presented depending on the level of experience.

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Kristin L. Wood is a Visiting Professor, Founding Head of Pillar, Engineering and Product Development (EPD, epd.sutd.edu.sg) and Director of Design Innovation as part of the SUTD-MIT International Design Center (IDC, idc.sutd.edu.sg) at the Singapore University of Technology and Design (SUTD, sutd.edu.sg)*. Dr. Wood completed his M.S. and Ph.D. degrees in the Division of Engineering and Applied Science at the California Institute of Technology (Caltech), where he was an AT&T Bell Laboratories Ph.D. Scholar. Dr. Wood joined the faculty at the University of Texas in September 1989 and established a computational and experimental laboratory for research in engineering design and manufacturing, in addition to a teaching laboratory for prototyping, reverse engineering measurements, and testing. During the 1997–98 academic year, Dr. Wood was a Distinguished Visiting Professor at the United States Air Force Academy. Through 2011, Dr. Wood was a Professor of Mechanical Engineering, Design & Manufacturing Division at The University of Texas at Austin. He was a National Science Foundation Young Investigator, the Cullen Trust for Higher Education Endowed Professor in Engineering, University Distinguished Teaching Professor, and the Director of the Manufacturing and Design Laboratory (MaDLab) and MORPH Laboratory. Dr. Wood has published more than 550 refereed articles and books, has received more than 110 national and international awards in design, research, and education, consulted with more than 100 companies (MNCs, SMEs, and startups) and government organizations on Design Innovation and Design Thinking, and is a Fellow of the American Society of Mechanical Engineers (ASME).

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