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Understanding the role of additive manufacturing knowledge in stimulating design innovation for novice designers

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Abstract

Additive manufacturing (AM) is recognized as a disruptive technology that offers significant potentials for innovative design. Prior experimental studies have revealed that novice designers provided with AM knowledge (AMK) resources can generate a higher quantity and quality of solutions in contrast with the control groups. However, these studies have adopted coarse-grain evaluation metrics that fall short in correlating AMK with radical or architectural innovation. This deficiency directly affects the way of capturing, modeling, and delivering AMK so that novel opportunities may be more efficiently utilized in ideation stage. To refine the understanding of AMK's role in stimulating design innovation, an experimental study is conducted with two design projects: (a) a mixer design project, and (b) a hairdryer redesign project. The former of which aims to discover whether AMK inspiration increases the quantity and novelty of working principles (i.e. radical innovation), while the latter examines the influence of AMK on layout and feature novelty (i.e. architectural innovation). The experimental study indicates that AMK does have a positive influence on architectural innovation while the effects on radical innovation are very limited if the example illustrating the AMK is functionally irrelevant to the design problem. Two strategies are proposed to aid the ideation process in maximizing the possibility of identifying AM potentials to facilitate radical innovation. The limitations of this study and future research plans are discussed.

Key words: design innovation, additive manufacturing, knowledge modeling, design for additive manufacturing

1. Introduction

Additive manufacturing (AM) has evolved into one of the main enablers of design innovation in material, form, and functionality due to its unique layer-wise building principle [1, 2]. Consequently, a desire to take advantage of these specialities has led to a new design paradigm collectively called design for additive manufacturing (DfAM) [3]. One emerging research field of DfAM involves investigating the impacts of AM knowledge (AMK) on design ideation in the early conceptual design stage. The general flow of such studies is to model or categorize AMK first and then demonstrates the effectiveness of captured AMK in stimulating design creativity. These AMK are usually presented in the form of design heuristics [4], general design process [5], computational tools [6], and feature repositories [7] with detailed figures, physical prototypes, CAD models, descriptions, or any combination thereof. Prior studies have proven the usefulness of such AMK in stimulating design innovation via observing that novice designers with AMK assistance generate a higher quantity and quality of ideas. However, these studies failed to differentiate the types of design innovation in the result analysis; therefore, the correlation between AMK and both radical and architectural innovation is not established. Radical and architectural innovation differ in that the former requires a change of working principles (WP) while the latter does not [8]. More specifically, architectural innovation is the reconfiguration of an established system to link

existing (or adaptive) components in a new way, while radical innovation is based on different engineering and scientific principles. For example, switching a ceiling-mounted fan to a portable fan belongs to architectural innovation as only the product layout and scale of components (e.g. the blades) are altered, while the concept of a motor-driven fan to circulate airflow remains unchanged. In contrast, achieving the same goal through the development of an air conditioner belongs to radical innovation. In accordance with the general product development process [9], determination of WP precedes determining product layouts. As such, it is critical to investigate whether AMK affects the synthesis of novel WPs. In other words, if AMK has positive effects on WP, AMK assistance should be provided as early as possible in the ideation process to enlarge design solution space; however, if AMK has no or even negative effects on WP, provision of AMK may cause cognitive burden [10]. Moreover, studies [10, 11] have indicated that far-domain or even noise (irrelevant design analogy) impose a negative effect on creativeness.

To characterize the effects of AMK on design innovation with further goals of improving AMK modeling and providing insight to integrating AMK into a general design process, a design experiment is conducted with two design scenarios: original design and redesign. Two hypotheses are made.

- (1) **H1: AMK has no effect on stimulating radical innovation.**
- (2) **H2: AMK has no effect on stimulating architectural innovation.**

The structure of this paper is organised as follows. AMK modeling studies, AMK-stimulated creativity studies, and computational tools to leverage AMK are summarized in Section 2. To enhance effective comprehension of AMK within the limited experiment time, three strategies are introduced to reduce noise resulting from not fully understanding the presented AMK in Section 3. Detailed experiment procedure and evaluation metrics are presented in Section 4. Result analysis is detailed in Section 5 to validate the hypotheses. Lastly, implications and limitations of this study are discussed.

2. Literature review

2.1 AMK modeling and categorization

Various methods have been reported to categorize and model AMK, which in turn allows for better delivery to designers. A broad understanding of AMK should cover the whole spectrum that relates to AM including process knowledge (e.g. working principles and process planning), machine attributes (e.g. volume, speed, resolution), product design (e.g. AM potentials, restrictions, optimization tools, design process, and geometry modeling), supply chain configuration, and business model. Dinar and Rosen [12] proposed a formal and structured web ontology language (OWL) to formalize DfAM knowledge with a focus on documenting prismatic design features and process parameters. Similarly, Hagedorn et al. [13] extended their work to include manufacturing knowledge, business model, and design ontology. Booth et al. [14] developed a DfAM worksheet which aimed at assisting novice AM designers in creating effective prototypes which have higher rates of success. However, these works are highly concentrated on documenting the restrictive side of AM to secure manufacturability, which falls short in supporting innovative ideation.

A narrow understanding of AMK is more confined to the product design aspect. This AMK is usually presented in the form of design heuristics [4], general design process [5], computational tools [6], and feature repository [7] with detailed exemplified figures, physical prototype, CAD models, descriptions, or a mix. AMK in these studies is generally categorized by AM potentials. For example, Maidin et al. [7] classified 113 AM features into 4 groups as “user fit requirement”, “improve functionality”, “part consolidation”, and “aesthetic”. Two typical drawbacks may occur in these studies. First, intake of such massive new information may be challenging for novice designers. Second, successful interpretation and mapping of design requirements to specific AM potentials is difficult especially when examples that bear

the AM potential is irrelevant. As revealed by study [10], far-domain analogy requires intensive knowledge to extract high-level principles which can then be used to draw similarities.

2.2 AMK-related design creativity study

On the basis of successfully-captured AMK, various studies have been conducted to understand the effects of such AMK on design creativity. Richter et al. [15] found that many of these potentials remain obscure because designers lack knowledge, become fixated on already established solutions, and consider AM too late in the design process, all of which contribute to reduced creativity and innovation in the concept generation stage. Similar concerns were echoed in literature [16]. Floriane et al. [17] emphasized the importance of delivering AMK in a timely manner. In general, opportunistic AMK is significantly useful in early design stages while restrictive knowledge is relatively useless; as one progresses throughout the design process, the usefulness of [opportunistic and restrictive AMK](#) [26] is reversed. Opportunistic AMK refers to the practice of helping designers explore all degrees of freedom of AM, such as complex shapes and topologies. In contrast, restrictive AMK emphasizes consideration of AM limitations to ensure a successful build.

Experimental design studies were widely used to examine the effectiveness of AMK in various forms [7, 18-20]. The work of Maidin et al. [7] in developing an AM feature database indicated the value of providing primarily opportunistic AMK in the early design stages. Another approach [18] to facilitating creativity amongst designers is to examine the motivations of the designers in developing AM-specific concepts, assuming that there is an ideal state in which to one is able to generate creative concepts. To reach such a state, examples from other domains are drawn. An exploratory study lead by Barclift et al. [21] set out to understand what attributes impact a designer's creativity in DfAM, and what attributes impact a designer's performance in DfAM throughout the processes of AM, i.e. sketching, modelling, printing, and assembling. It was found that participants' novelty of ideas, engineering program, and "risk seeking preference" were statistically significant in predicting the performance of their ideas in AM. All the aforementioned work has the same goal in mind that creating an environment of AMK is conducive in all aspects. However, studies of Sinha et al. [19] and Abdelall et al. [20] may not agree. As revealed by literature [19], designers exposed to AM potentials produced less feasible concepts when compared to designers who were only trained in design for conventional manufacturing. Design fixation issue that designers trained in AM showed residual influences even when instructed to design for conventional manufacturing, was observed in the work [20].

Additional theoretical analysis of the effective zone of AMK in a general design process is also reported. Yang et al. [22] tactically decomposed the ideation process into sub-processes as functional analysis and design synthesis. By borrowing the framework of function-behavior-structure (FBS) modeling, it was established that AMK had no influence on functional analysis and recognition of desired behavior, but it took rather a role in mapping behavior to physical structures. The work of this paper can be seen as the extension of the theoretical study via refining the mapping as "behavior to working principle" and "working principles to product layouts".

Unlike the popular heuristic approach of presenting AMK, a new trend of AMK application is to support intelligent recommendations where designers are provided with the most pertinent information. Yao et al. [23] introduced a hybrid machine learning recommendation system based on a design feature database. The hybrid approach relies on the output of unsupervised clustering of examples as the input to a supervised learning problem, this introduces an additional level in which error propagation is possible by assuming the clustering produces effective communities. Another progress was made by Yang et al. [24] with a special focus on identifying part consolidation candidates by using embedded AMK of candidacy rules.

From the review of prior research, we know that AMK do have positive influence over design creativity but none of these studies clearly confirmed whether AMK affect the synthesis process of working principles. Meanwhile, how to properly model and intelligently recommend AMK in a general design process needs to be improved.

3 AMK specifics

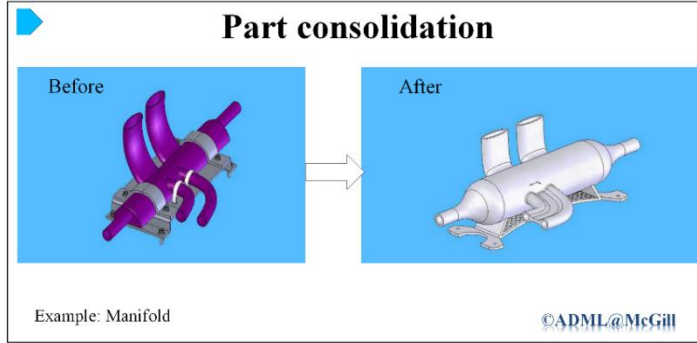
To examine the hypotheses, AMK is introduced in the form of design heuristics with a focus on AM potentials. AMK specifics are derived from reported literature and applications [2, 4, 7, 25]. In this experiment, ten types of AM potentials are presented: part consolidation, embedded foreign components, multi-material AM, articulated mechanism, multi-color AM, lattice structure, aesthetics, internal freeform channel, topology optimization, and customization. These selected AM potentials roughly cover all the reported design freedoms AM technologies allow. *Other benefits, such as simplifying supply chain management and reducing the amount of tooling required, are not included in this experiment. This is because participants involved in this study are novice designers and they are instructed without cost limit.* Moreover, these AMK specifics are a collection of AM aids used in reported studies [4, 7, 26]; therefore, they should have equal efficacy to current practices of AMK modeling and categorization in supporting design innovation. However, to avoid the deficits of prior approaches, including intake of massive information and unsuccessful mapping from design requirements to AM potentials, three measures are taken to improve understanding of these AMK specifics.

- First, the AMK specifics are sequenced in order. According to the general product design process [9], assembly configuration always needs to be considered prior to component design, especially in a redesign process. AM potentials should be organised accordingly to realize “delivered as needed”. Therefore, assembly-level AM potentials such as part consolidation and embedded foreign components come before part-level applications (e.g. lattice design). All AMK specifics are designed in the form of business card as shown in Figure 1 (a). The front is exemplified with a simple figure for visualization while the back gives detailed context. All cards are organised in sequence and chained as a booklet (Figure 1 (b)). This strategy helps novice designers quickly browse AM potentials as the design process proceeds from layout design to component design.
- Second, a catalogue is created to associate general design requirements/objectives with various AM potentials, as shown in Table 1. The mappings between objective and potential AM solutions are established in reported literatures [7, 16] and from design experience of the authors’ research group. This catalogue is presented on the first page of the booklet, which helps to quickly locate possible AM opportunities and avoids random reading in such a limited amount of time.
- Third, disturbance from existing examples that illustrate AMK should be functionally irrelevant to the design projects being tested. Otherwise, it is difficult to distinguish whether it is the example or knowledge of AM potentials that inspire the novel idea.

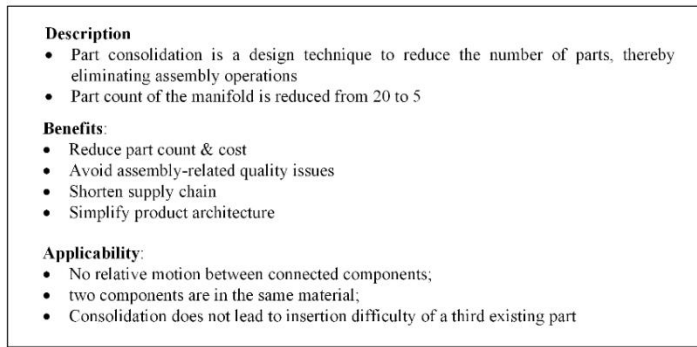
Table 1 Objective-oriented catalogue of AMK specifics

Design objectives	Possible AM solutions	
Lightweight	Part count reduction (PCR)	(1) part consolidation (2) multi-material AM (3) embedded components (4) articulated mechanism
	Reduce material usage	(1) lattice structure (2) topology optimization
Performance improvement	(1) complex freeform shape (2) internal freeform channel (3) lattice structure (4) multiple-material AM	
Customization	Property customization	(1) multi-material AM (2) multi-color AM (3) texture
	Personalization	(1) human body feature (2) customization
Value-added	(1) aesthetics (2) personalization (3) lattice design (4) topology optimization (5) multi-color AM	

Complexity for free	(1) lattice structure (2) internal freeform channel (3) topology optimization
Compactness	(1) part consolidation (2) multi-material AM (3) embedded components (4) articulated mechanism
Cost reduction	(1) PCR (2) lightweight

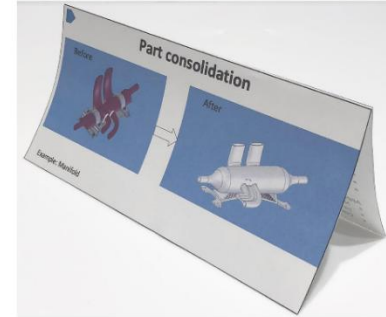


Front view



Back View

(a) Front and back views of a single card



(b) Physical AM booklet

Figure 1 AMK specifics cards.

4. Design experiment

4.1 Participants

Voluntary participants were recruited from the undergraduate mechanical engineering course “Principles of Manufacturing” led by one of the authors at McGill University; participants were offered extra credits as an incentive. Registered students are from Year 2 or 3. These students were chosen because they shared similar elementary design education and experience, acquired from design courses, projects, and internships, which assure that the students have the basic drawing skills and understanding of product design process. Moreover, the experiment is set in the very beginning of the course to make sure that participants are not exposed to the design thinking of design for manufacturing. This measure avoids the influence of manufacturing constraints on design creativity. A background information survey was also conducted to evaluate individual’s level of AMK and drawing skills. The survey queried participant’s “gender”, “available time slots”, “design course already taken”, “familiarity of 3D printing processes”, “experience of design something for 3D printing”, and “sketching skills”. In total, 34 students were chosen from the 60 volunteers, then divided into groups of 17 (6 females, 11 males); one group without knowledge of AM (G1), and one with (G2). However, three more students (male) without AM knowledge were able to participate because of solved time conflicts, resulting in groups of 20 and 17. The detailed grouping information and conditions are presented in Table 2. All individuals in both groups (G1 and G2)

are to complete two design problems individually; however, only the students with prior AM knowledge (G2) are provided with AMK specific cards. It should be mentioned that students in G2 have very limited knowledge (mainly in restrictive aspect) of AM and most of them only use AM as a rapid prototyping tool. The purpose of presenting AMK to G2 is to make them more knowledgeable so that the beneficial effects of AM on stimulating design creativity can be maximized. Details of the design projects are enclosed in Section 4.2.

Table 2 summary of grouping of participants and conditions

#	# of students	Attributes of participants				Design variables		Design project	
		Gender (F/M)	Education (Year)	AMK level	Design exp. (years)	AMK specifics		Mixer	Hairdryer
						0	1		
G1	20	6/14	2, 3	null	1.5				
G2	17	6/11	2, 3	entry	1.5				
Hypothesis								H1	H2

4.2 Design problems

Two separate design problems are presented to examine the hypotheses. Radical innovation requires a breakthrough from the WP perspective. Therefore, the design problem to examine H1 needed to allow for multiple solutions in a limited time period. To meet this goal, design of a mixer was chosen. In contrast, H2 requires that variants of WP are limited so that students will be focused on new architectures. Therefore, redesign of a typical hairdryer was chosen. The mixer problem was presented first to stimulate divergent thinking.

4.2.1 Mixer design

The mixer design problem was stated as follows: “*Design a mixer to mix two type of liquid as uniform as possible. There is no cost limit and be creative. The function to be fulfilled is to mix liquid.*” To avoid design fixation [27], no physical form of any mixer was released to the participants. Participants were encouraged to consider three strategies to expand their set of operating principles: “recall existing examples in life”, “use case-based analogy sharing the same principle”, “think from the perspective of bio-mimics”, all of which have been deemed effective in prior research [28]. This problem was designed to be meaningful and challenging with moderate complexity to avoid frustration, but still facilitate unique solutions that are attainable by novice designers.

4.2.2 Hairdryer redesign

The hairdryer design problem was stated as such: “*Redesign a heating coil-based hairdryer to make it more compact and lightweight. There is no cost limit and be more creative. Functional requirements include a) circulate airflow; b) convert electricity energy to heat; and c) regulate intensity. Other requirements to be fulfilled: a) compactness; and b) lightweight.*” Exemplified stereotype hairdryer design and corresponding functional diagram is shown in Figure 2.

Participants were encouraged to consider four possible strategies in rethinking the hair dryer’s layout: “function allocation” [29], “function integration” [30], “spatial rearrangement”, and “scaling”. This design problem is highly bounded by its well-developed working principles which have already been optimized over decades. Therefore, participants are less likely to spend time altering the operating principles and the design changes are likely to occur in architectural innovation.

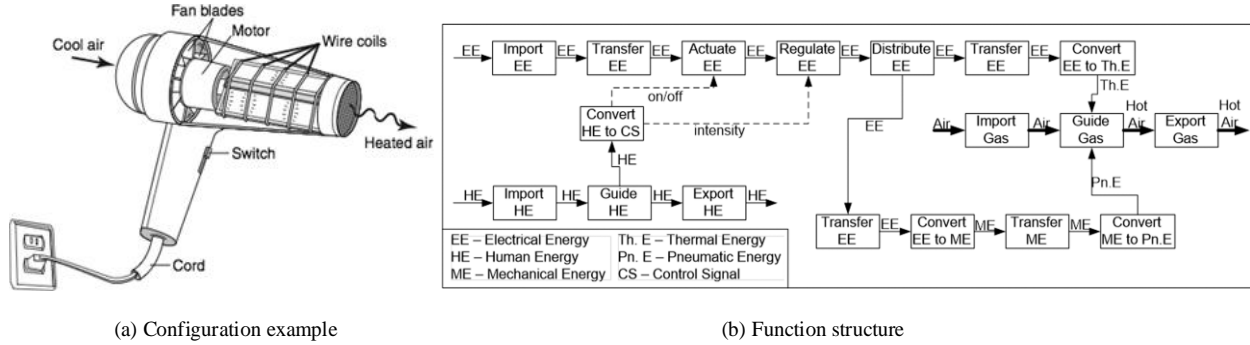


Figure 2 A typical device to dry hair.

4.3 Design protocol

4.3.1 Experiment procedure

The experiment consisted of three phases: Experiment Brief, Project 1, and Project 2; designed to last approximately 110 minutes. The detailed procedure is presented in Table 3.

First, participants were briefed with experiment procedure, session rules, design project explanation, and deliverables. The two groups were seated separately with space in between. Discussion and external information (e.g. internet) were not allowed. A general design process with ideation strategies was reviewed to assist in recalling training from past design courses. Participants were required to record all concepts using words and sketches, even for seemingly ridiculous ideas. The brief stage took around 15 minutes and 5 additional minutes were reserved for Q&A.

The first design project (mixer design problem) was then presented to both groups. Note that the problem description and functional requirements were listed in the heading of the sketch sheet to serve as a constant reminder; a technique advocated in the Brainwriting approach [31]. The process was divided into two sub-stages: ideation (15 min) and sketching (20 min). During the ideation stage, both groups are encouraged to come up with as many solutions as possible, but no extra materials were assigned. In the sketching stage, students were asked to do schematic sketching and AMK specifics cards were distributed only to group G2. Students were then given a short break (10 min).

The second design project (hair dryer design problem) was then presented and consisted of the same two stages in the first design project. Participants received a copy of the hairdryer example and its functional structure (see Figure 2). The focus of this example was emphasized to be innovative layouts and features.

When the whole experiment was finished, a post-experiment survey was conducted in terms of difficulty of the two design projects, usefulness of the AMK cards, and strategies taken for finding new product layouts.

Table 3 experiment procedure.

Steps	Brief	Q&A	Project 1		Break	Project 2		Feedback
	Procedure deliverables		Ideation	G1		Ideation	G1	
				G2 + AMK			G2 + AMK	
Time (min)	15	5	15	20	10	15	20	10

4.3.2 Deliverables

The final deliverables include the sketches (see Figure 3 (a)) and feedback questionnaires (see Figure 3 (b)). The participants' perception of the project difficulty, AMK booklet helpfulness, strategies employed for generating solutions, and suggestions for improving the experiment design were collected and analyzed.

Concept List Worksheet			
Problem description	Project 1: design a mixer to mix two types of chemical liquid. No cost limit and be more creative.	Group #	1
	Functional requirements: to mix liquid	Name	

(a) Concept list sheet

Post-test feedback				
Questions	Specify your opinion with 3, 1, -1, or -3			
Is Project 1- mixer problem difficult?				
Is AM booklet helpful in Project 1 to help you find new working principles				
How do you find new working principles?	Existing example	Bio-inspiration	Experience	Imagination
Is Project 2- hairdryer problem difficult?				
Is AM booklet helpful in Project 2 to help you find new product layout?				
How do you find new product layout?	Function allocation	Function integration	Rearrange spatial location	Scaling
Open questions	Answer			
What is the most difficult part in conceptualization?				
What is the takeaway of this test?				
Any suggestion of improvement of experiment design?				

Strongly agree (3), agree (1), disagree (-1), strongly disagree (-3)

(b) Feedback questionnaire

Figure 3 concept list worksheet and feedback questionnaire design.

4.4 Evaluation metrics

Two sets of quantitative metrics were used to evaluate the impacts of AMK on design innovation. One is focused on measuring the quality of working principles and the other is to characterize the effects of AMK on creativity in layouts and features.

4.4.1 Quantity and novelty of working principles

Quantity of ideas is often used as a measure to assess the effectiveness of ideation, as more ideas results in a higher chance of producing high-quality and novel ideas [10]. Ideation quality of each participant was reflected by their number of unique solutions and the novelty of these solutions. Each metric is defined below.

- (1) **Number of solutions:** The quantity of design concepts is recorded by counting all solutions proposed by each participant.
- (2) **Number of unique solutions:** The number of less duplicated solutions can be used to gain insight on the creativity of each participant. Duplication is assessed by whether two design concepts share similar operation principles.
- (3) **Novelty of solutions:** Novelty, which can be characterized by rareness [32], is the most important measure to reflect creativity. To be more specific, novelty of a solution is an inverse function of its occurrence [33] as shown in Equation (1).

$$S_i = 1 - \frac{Occ_i}{\sum Occ_i} \quad (1)$$

Where S_i is the novelty score of the i th solution and Occ_i is the occurrence of the i th solution.

4.4.2 Quantity and novelty of layouts and features

Architectural innovation comes from novel changes in layouts and features. Four metrics are adopted to measure the effectiveness of AMK in promoting design creativity.

- (1) **Number of layouts:** Product layout is the spatial arrangement of components. Theoretically, AM-enabled freedoms of geometric and material complexity should free designers from stereotype layout design. The number of layouts is an important indicator of such a trend.
- (2) **Number of unique layouts:** To avoid influence of duplicate layouts, the number of unique layouts is counted.
- (3) **Novelty of layouts:** Novelty of a layout is scored by the occurrence of the same concept. If the layout is enumerated by multiple designers, the novelty value decreases.
- (4) **Number of novel features:** To account for the changes of features (color, geometry, texture, etc.) that are frequently investigated in the prior studies [7, 16, 19], a similar approach of counting the number of novel features is taken in this paper. Novel features are those different from the existing design.

4.5 Data analysis strategy

Concept list sheets and feedback questionnaires are collected and labelled with numbers for easy identification. Two raters for this study are experts in the DfAM domain with good understanding and abundant experience in optimization and prototyping. They also have more than 3 years of product design experience acquired from coursework and industrial projects. This level of expertise is comparable to other studies of ideation quality assessment [34, 35]. These two raters counted the number of solutions on each concept sheet and collaborated to decide if a given solution is unique in its WP. One WP reused several times by the same participant is only counted once when the number of unique solutions is studied. A consensus must be reached before proceeding to the next solution. As such, the total list of unique WPs can be drawn, and the novelty score of each solution can be determined based on Equation (1). Then, novelty scores of each participant are calculated by adding up the novelty score of the unique solutions. A similar strategy is applied for the evaluation of hairdryer redesign project.

5 Result analysis

This study examines how AMK affects design ideation outcomes in terms of working principles, layouts and features. The experiment results are analyzed to gain a better understanding of the correlation between AMK and radical innovation or architectural innovation. The mixer design project is studied for the purpose of radical innovation, while the hairdryer redesign project is investigated for architectural innovation. IBM SPSS software is used for statistical analysis of the result.

5.1 AMK and working principles correlation

In total, control group G1 proposed 113 design concepts with 92 of them being unique, while the AMK group G2 generated 92 ideas with 70 of them being unique. To obtain the novelty score of each design solution, all distinctive WP occurrences are tracked (as summarized in Table 4). From the table, we can see that the top three most frequently-used ideas are rotation of spinner, rotation of container, and gravity; however, there are some more innovative ideas spotted such as “polarize liquid”, “use sponge to absorb and mix”, and “soft container”. Sketches of some novel principles are displayed in Figure 4. One interesting observation is that layouts from control group G1 sometimes displayed attributes in line with DfAM. This may stem from novice designers being unfamiliar with the principle of design for (conventional) manufacturing. An example of this is shown in Figure 4 (e) and (f). A next-step in this research is planned to investigate if this occurs with design experts.

Table 4 summary of obtained working principles from both groups.

	Principles	Occurrence	Working principle	Novelty
	Rotate/shake spinner			
1		46	Motor-driven rotation of spinner/whisk	0.72
2		5	Magnetic driven spinner	0.97
3		4	Bubbles	0.98
	Rotate/shake container			
4		34	Motor-driven rotation/shaking of container	0.79
5		2	Soft container (punch)	0.99
	Oscillate			
6		7	Spring	0.96
7		7	(sound/water) wave energy/ vibration	0.96
8		10	Slide & crank	0.94
	Distribute: Distribute liquid into smaller drops			
9		3	Porous pipe/funnel	0.98
10		4	Vaporization & liquidation	0.98
	Absorb & squeeze			
11		1	Use sponge to absorb two types of liquid first and squeeze	0.99
	Accelerate liquid speed			
12		22	Use gravity	0.86
13		16	Use pump/piston to compress liquid to accelerate mixing	0.90
	Polarize liquid			
14		1	Using magnetic principle to polarize liquid	0.99

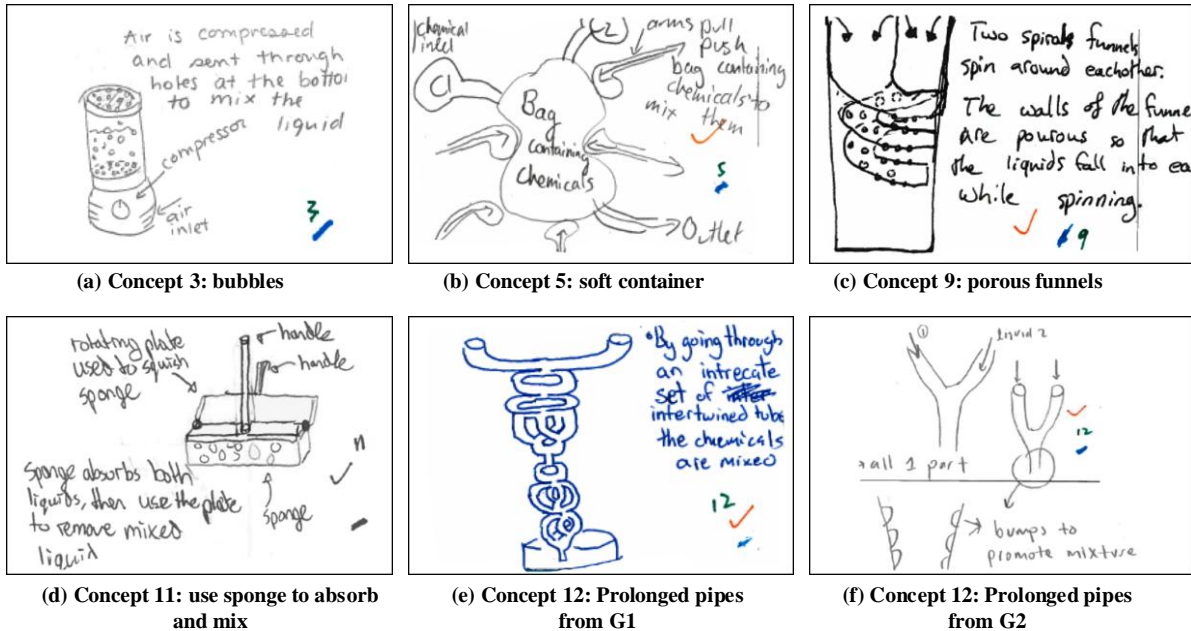


Figure 4 exemplified sketches of working principles from both groups.

To test hypothesis H1, the equality of means is tested in terms of “number of solutions”, “number of unique solutions”, and “novelty of solutions”. As shown in Figure 5, the control group G1 outperforms G2 in all three categories; however, the standard errors are all larger than those of the AMK group (G2). In order to conduct T-test, Shapiro–Wilk’s test of normality is performed first. As shown in Table 5, all datasets except “number of solutions from G1” ($P=0.019$) and “number of unique solutions from G2” ($P=0.007$) passed the normality test. However, ANOVA is robust even if the normality criterion is not met because the homogeneity principle is fulfilled [36]. One participant in the control group (G1) only generated one solution, which is much lower than the average performance of the rest group (more than

two standard deviations of the mean). Therefore, this participant should be considered as an outlier. Two-sample T-Test is conducted for both the original dataset and the refined dataset. From Table 5, it is observed that there is no significant difference ($P > 0.05$) between the mean performance of both groups in all proposed metrics. Additionally, Cohen's D test is conducted to calculate the effect size (ES) for each dataset. The results in Table 5 indicate that the effect sizes are either small or medium (0.5) for each dataset. Therefore, [the null hypothesis of the H1 cannot be rejected](#). In other words, there is no statistical significance showing that group G2 with AMK aid performs better than the group G1 in terms of quantity and novelty of working principles.

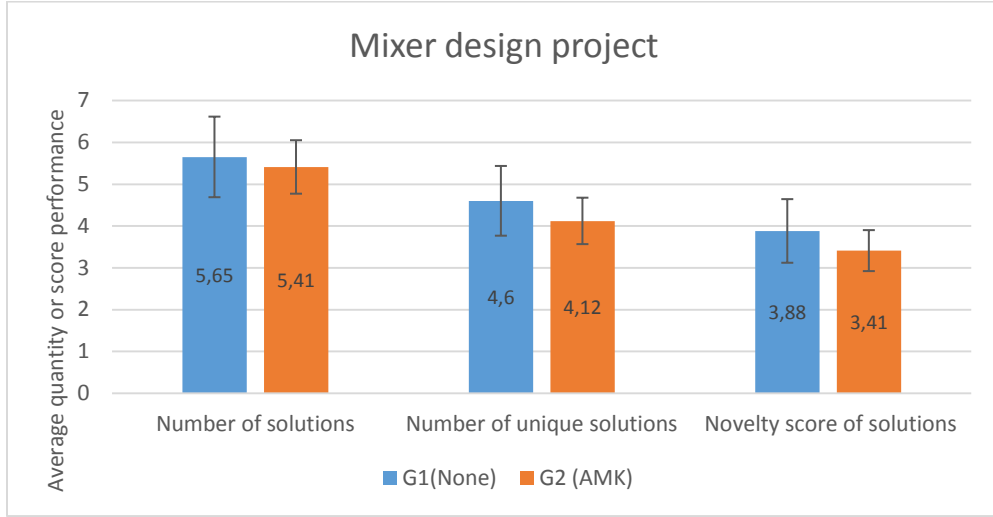


Figure 5 average number of concepts generated and novelty score of solutions for the mixer design project.

Table 5 Shapiro–Wilk's test of normality of different data sets and T-test for equality of means in the mixer design project

	<i>Shapiro–Wilk’s test</i>								<i>T-test</i>			
	G1		G2		Original dataset			Refined dataset				
	<i>df</i>	<i>P</i>	<i>df</i>	<i>P</i>	<i>df</i>	<i>t</i>	<i>P</i>	<i>ES</i>	<i>df</i>	<i>t</i>	<i>P</i>	<i>ES</i>
Number of solutions	17	0.019 ^a	20	0.57	35	0.435	0.667	0.146	34	0.981	0.333	0.223
Number of unique solutions	17	0.142	20	0.007 ^a	35	1.015	0.317	0.333	34	1.529	0.136	0.407
Average Novelty score of solution	17	0.37	20	0.062	35	1.106	0.276	0.367	34	1.605	0.118	0.438

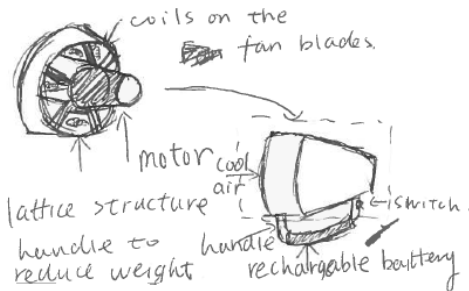
^a Failure of normal distribution assumption.

5.2 AMK and novelty of layouts and features correlation

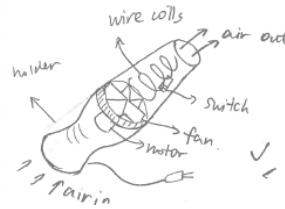
In this hairdryer redesign project, there were overall 141 layouts (73 from G1 and 69 from G2), within which 128 layouts are distinctive. The AMK group (G2) outperforms the controlled group (G1) by 12 more kinds of unique layouts. To characterize the novelty of each layout, all the adopted layouts are summarized and the novelty score is calculated on the basis of occurrence. There are 23 different concepts (see Table 6) which are distributed in three categories in terms of innovative strategies, including “function integration”, “spatial rearrangement”, and “scale”. However, none of generated solutions use the “function allocation” strategy. Among these strategies, “function integration” is the most cited one. Exemplified sketches are shown in Figure 6. To further investigate the influence of AMK on feature design innovation, the number of novel features is also counted. In this paper, feature is referred to shape or architecture and a novel feature is justified by whether it is different from the provisional concept. For example, Figure 6 (c) presents an innovative concept with 5 novel features: “lattice handle”, “rechargeable battery”, “foldable handle”, “back-positioned heater”, and “new casing”.

Table 6 summary of novel hairdryer layouts from both groups.

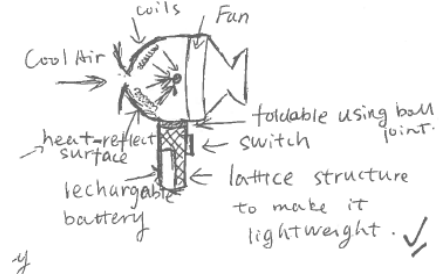
#	Layouts	Occu.	Novelty
Strategy I: function integration			
Change of coil			
1	Integrate fan with coil	24	0.81
2	Integrate coil with outer casing	10	0.92
3	Change of coil shape (spiral or grid)	9	0.93
4	Coil-less design	10	0.92
5	Foldable handle	5	0.96
Change of handle			
6	Integrate handle with casing	17	0.87
7	Lattice handle	10	0.92
Change of fan			
8	Fan-less hairdryer	3	0.98
9	Change of fan shape	2	0.98
Change of casing			
10	Porous airflow inlet	4	0.97
11	Side air inlet	2	0.98
12	Helmet-shape hairdryer	2	0.98
13	Comb-like hairdryer	3	0.98
14	Straightener-like hairdryer	1	0.99
15	Soft/foldable casing	1	0.99
16	Retractable casing	3	0.98
17	Change material of casing (carbon fiber)	2	0.98
18	Change shape of casing	3	0.98
Change of cord			
19	Cord-less design	1	0.99
20	Retractable cord	2	0.98
Strategy II: spatial rearrangement			
21	Rearrange fan & heater	11	0.91
22	Motor inserted in fan blade housing	1	0.99
Strategy III: scale			
23	Scale and redesign of fan blade	2	0.98



(a) Concept 1:
integrated fan with coil



(b) Concept 6: integrate
handle with casing



(c) Concept 21: rearrange
heater and fan

Figure 6 exemplified sketches of redesigned hairdryers.

The statistical average performance of both groups is presented in Figure 7. Clearly, the AMK group (G2) developed more layouts, and the uniqueness and novelty of these layouts was also greater. More importantly, the mean number of novel features of the AMK group (G2) is almost 1.5 times higher than that of the controlled group. Due to the inequality and large standard errors, ANOVA is conducted. As shown in Table 7, Shapiro–Wilk’s test of normality indicated the failure of the dataset of “number of unique layouts” and “number of novel features”. However, as ANOVA is robust even if the normality criterion is not met because of homogeneity principle is fulfilled. Two participants of the control group G1 generated only one unique layout, which is more than two standard deviations from the mean; therefore, they are considered outliers. Two-sample T-Test is conducted for both the original dataset and the refined dataset. The results reveal that the mean performance of AMK group (G2) is better in “number of unique layouts”, “novelty of layouts”, and “number of novel features”. Exception occurs in the index of “number of layouts”. Like in the mixer project, Cohen’s D test is conducted to calculate the effect size (ES) for each dataset. The results in Table 7 indicate the effect sizes are large (>0.8) for each dataset except “number of layouts”. As such, we can conclude that AMK can effectively stimulate innovation of layouts and features.

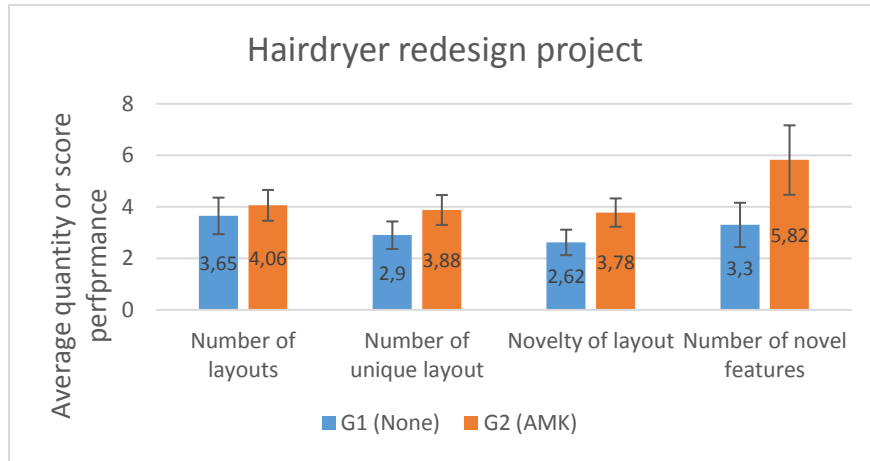


Figure 7 Average performance of both groups and corresponding standard errors.

Table 7 Shapiro–Wilk’s test of normality of different data sets and T-test for equality of means in the hairdryer redesign project

	<i>Shapiro–Wilk’s test</i>						<i>T-test</i>					
	G1		G2 with AMK		<i>Original dataset</i>				<i>Refined dataset</i>			
	<i>df</i>	<i>P</i>	<i>df</i>	<i>P</i>	<i>df</i>	<i>t</i>	<i>P</i>	<i>ES</i>	<i>df</i>	<i>t</i>	<i>P</i>	<i>ES</i>
Number of layouts	17	0.068	20	0.057	35	-0.935	0.356	0.312	33	-0.627	0.535	0.211
Number of unique layouts	17	0.045 ^a	20	0.128	35	-2.669	0.011	0.878	33	-2.197	0.035	0.739
Novelty of layout	17	0.479	20	0.437	35	-3.359	0.002	1.108	33	-2.919	0.006	0.983
Number of novel features	17	0.044 ^a	20	0.101	35	-3.444	0.003	1.114	33	-3.021	0.007	1.012

^a Failure of normal distribution assumption.

5.3 Feedback questionnaire analysis

Thirty-seven feedback questionnaires were collected and analyzed in terms of participants’ subjective perception of the difficulty level of projects, AMK booklet helpfulness, and ideation strategies. Suggestions are also encouraged for improving experiment design. The results of which are presented as follows.

First, project difficulty level is studied. As shown in Figure 8, the majority (over 50%) of both groups agreed that the mixer project was not difficult but expressed the inverse opinion of the hairdryer project. The potential reason is that compared to the open-ended mixer project, the hairdryer redesign project was

proved to be more difficult for them to think out of box. Moreover, novice designers may feel pressured when asked to work independently, especially within a limited amount of time, although the hairdryer project was carefully selected with moderate complexity (considering their knowledge level). When comparing the two groups, it is observed that G2 (with AMK) had 10% more participants encounter hardship in the mixer project, but again the hairdryer redesign project yielded inverse results. This observation was echoed by G1 generating 20 more solutions than the G2 (with AMK) in the mixer project; further investigation may be valuable to determine if the provided AMK booklet forms negative influence (i.e. noise) in the WP synthesis process. In contrast, the provision of the AMK booklet in the second project appeared to ease the pressure of ideation of new layout and features for G2. Second, the statistical results of AMK helpfulness for the two projects are shown in Figure 9. Most participants in G2 thought the provided material was not helpful in mixer design, but agreed that it was valuable for inspiration of new layout and features. This finding also agrees with the two hypotheses. Third, the ideation strategies of WPs and layouts are studied with the aim of improving experiment design for future studies. For the WP proposal, knowledge of existing products and being creative (i.e. imagination) are the most significant source of inspiration for novice designers. As such, the selected projects must be within the scope of scientific and engineering knowledge of novice designers. For layout design, the most frequently-used methods in both groups include “function integration” and “rearrange spatial location”. “function allocation”, was mentioned by 2 students in the questionnaire, however, this subjective perception was wrong because according to Table 4, none of the reported solutions reflect this claim. As such, it is necessary to further improve the participants’ skills of applying such advanced design methods (e.g. function allocation) to maximize the design output. Lastly, answers to the general questions regarding to the experiment revealed that the concerns of “thinking out of box”, “trying to be creative with constraints”, and “ignoring the examples given” were very common amongst the participants. Therefore, the project selected for creativity evaluation should be very carefully handled, especially for novice designers, thereby minimizing the possibility of biased conclusions.

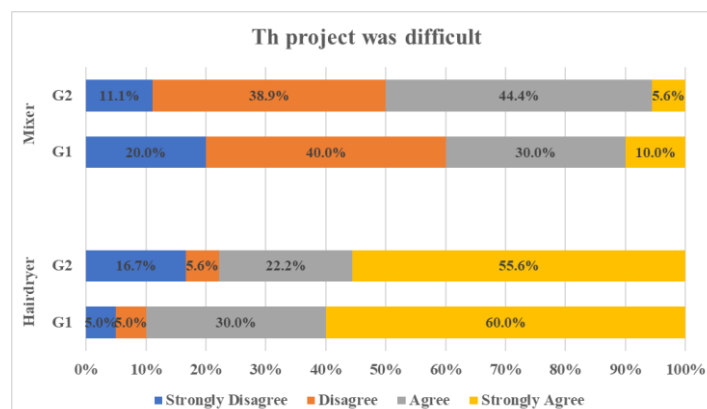


Figure 8 project difficulty evaluation by G1 and G2 in the mixer and hairdryer projects.

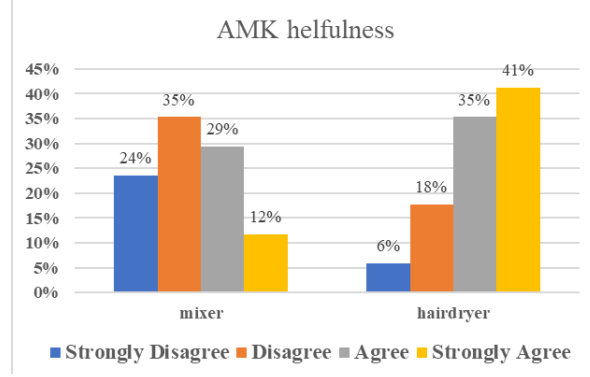


Figure 9 AMK helpfulness analysis within G2.

6. Discussion and implications

As presented in Section 5, this investigation reveals that while AMK does not impose significant influence on working principle innovation, it does have significant impacts on architectural innovation. The authors believe that the results found in this study will generalize to products of varying levels of functional and architectural complexity, but more products should be studied in the future to confirm this. Although the understanding of these effects is very preliminary, the findings have important implications for design creativity study and AMK modeling.

6.1 Implications

AMK does not contribute to radical innovation. A counter-example might be raised by researchers as shown in Figure 10. It depicts the transition from a conventional motor-driven gripper design to a heat-induced deformation-based gripper with varied stiffness [37]. Apparently, the first two concepts (Figure 8 (a)-(c)) share the same working principle of full actuation to realize “grab” motion while the last two use the principle of material deformation (under-actuation) to achieve the same goal. It seems that AMK does contribute to radical innovation. However, this example has two hidden pitfalls. First, as revealed in this study, if participants are not well exposed to the concept of design for manufacturing, their imagination is only bounded by individual cognitive scope from education and experience rather than manufacturing knowledge; therefore, the correlation between working principle and manufacturing is not strong. In other words, AM is not the only way of fabricating shape memory polymers. Second, AMK needs to kick in at the stage of concept evaluation when manufacturability is considered. This helps designers to avoid giving up “non-manufacturable concepts” in conventional manufacturing context, which is also advocated in prior research [17].

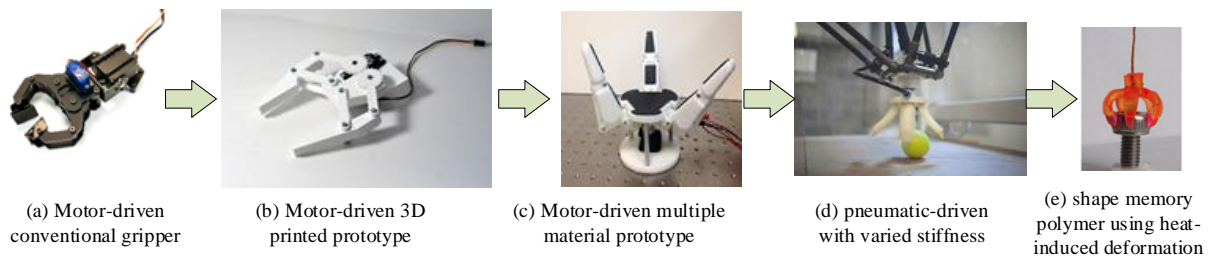


Figure 10 various gripper design concepts.

The remaining question is whether it is possible to stimulate radical innovation by only providing AMK. As revealed in this experiment, if AMK is irrelevant to the design problem itself, the effect on stimulating radical innovation is very limited. This is because novice designers may have difficulty of extracting and

migrating high-level principles of analogies to their own projects. Two alternative strategies may be useful.

- 1) Never consider manufacturability in the process of synthesizing working principles. Manufacturing knowledge may cause pre-mature convergence of design solutions, which is against the trend in current design practice in industry.
- 2) More information on previous successful instances of AM is required. If the goal of developing AMK is to help designers to achieve more radical innovation, a more effective strategy for imparting this knowledge must be developed. Such an AM instance should be analyzed for its functionality, working principles, and the AM potentials that it embraces (e.g. customization, light weighting, internal channels, functional integration, and surface structures). Once enough instances are collected, artificial intelligence may be employed to automatically provide a means for delivering AMK that is just in need for the unique application.

Revisiting the example of gripper, we can structuralize AMK by using function-behavior-structure (FBS) ontology [38] as shown in Figure 11. The function to be delivered is “grab objects” and the expected behaviors include “full actuation” and “under-actuation”; the difference between them being that the former’s degrees of freedom are equal to the number of actuators (see reference [39]). In the structure layer, detailed examples bearing the specific AMK and desired behavior can be easily retrieved in the early conceptual design stage to stimulate radical design innovation. For example, to achieve the behavior of under-actuation, two strategies are available in the existing design. In the third example [40] of Figure 10, the action of grasp is realized by rigid structures with gear train mechanisms and springs. It can exert conformal grasping performance to objects that have regular shapes (e.g. block or ball), but it encounters difficulty with irregular ones. With the aid of AM, flexible and controllable structures with adaptive stiffness are able to overcome such deficits in the fourth and fifth examples. In conclusion, an AMK database enabling radical innovation must be capable of delivering not only all degrees of freedom of AM but also enough functional information (e.g. function and behavior) of the instance that displays such AM potentials.

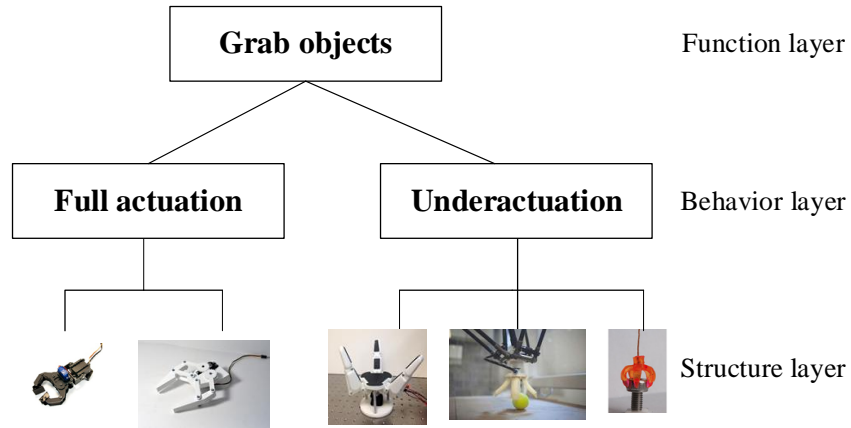


Figure 11 proposed FBS modeling of AMK.

6.2 Limitations

There are several limitations in this study which should be acknowledged. Although the AMK specifics provided in this experiment are comprehensively summarized from reported literatures, full understanding of complex concepts of AM such as conformal cooling and multi-material AM may still be challenging for these novice designers to understand in such a limited amount of time. Successful application of such AMK requires a more intimate knowledge of each topic. This incomplete understanding of AMK may

produce a biased conclusion, which needs to be validated with AM design experts in the planned research. Second, individual differences still exist especially when it comes to creativity and passion in design, although we have tried to minimize such effects in grouping. A larger group and more effective strategy to encourage more outputs from the students should be considered. Third, there is one interesting observation that participants in the control group generated 20 more ideas than the AMK group in the mixer design project. Although the larger number of participants is one important factor, the average performance of participants in G1 is higher than that of participants in G2. It is necessary to further investigate whether the presented AMK specifics impose negative impacts on ideation of working principles if these AMK specifics are irrelevant to the design problem. Lastly, participants in this study are not only relatively new to AM but also general product design methodologies. Therefore, basic constraints that may occur in design experts are not examined in this study. To simulate a real design scenario in industry, more experienced designers should be compared.

7 Conclusions

In this paper, a preliminary design experiment is conducted to understand the correlation between additive manufacturing knowledge and design innovation with a special focus on radical innovation. To reduce the influence (noise) of less comprehension of presented AMK for novice designers, three strategies including sequence of AMK, objective-oriented AMK categorization, and AMK specific cards are adopted. Through the contrasted design experiments of a mixer design project and a hairdryer redesign project, observations are summarized as: a) AMK shows no significant influence on radical innovation given that AMK is structuralized as is in most AMK studies; b) AMK has substantial impacts on architectural innovation. Based on these findings, a function-behavior-structure modeling hierarchy for capturing AMK is proposed rather than the current practice of simply presenting AM potentials without functional information. In the next planned research, we are trying to build an AMK repository to enable radical design innovation via functional, behavior, or feature similarity.

Acknowledgement

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