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Additive Creativity: An Innovative Way to Enhance Manufacturing Engineering Education*

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The present paper considers two pedagogical approaches that are mixing creativity tools and Additive Manufacturing (AM) knowledge and evaluates them through the originality and feasibility of the ideas generated as well as the satisfaction of the students. This experimentation was conducted in an engineering school with two groups of postgraduate students during a one-day Project-Based Learning module (PBL). This study points out that closely mixing creativity tools and AM knowledge all along the module gives better results in term of originality, feasibility, and student satisfaction than a more traditional approach disconnecting them. We believe this work can improve existing teaching activities enabling students to gain hands-on experience with additive creativity to better face tomorrow's challenges.

Keywords: additive manufacturing; creativity; innovation; additive creativity

1. Introduction

Innovation is a crucial issue for companies to succeed in a globalized and competitive world. With the increasing democratization of additive manufacturing technologies and the digitalization of information, companies can now design new products with original features/shapes/textures, deeply customize them, work with geographically dispersed teams and speed-up their time-to-market. Therefore, companies can use them to improve their core processes of design, production, and distribution to get or maintain a competitive advantage and to create value.

For that reason, one of the critical issues for companies lies in hiring young engineers understanding the full technique and process of Additive Manufacturing (AM). Formal AM education has already been integrated into curricula at different levels [1]. To enrich the teaching community this paper presents and compares two pedagogical approaches mixing creativity tools and AM knowledge and evaluates them through the originality and feasibility of the ideas generated as well as the satisfaction of the students.

The research objective of this paper is to propose and validate a new pedagogical approach to foster the use of AM knowledge in creativity session for Engineering Education. Section 2 addresses a literature review on design for and with additive manufacturing, creativity, and challenges for engineering education. Section 3 gives an overview of the research design approach. Section 4 presents the results. Finally, in section 5, we provide a discussion.

2. State of the art

2.1 *Design for and with additive manufacturing*

Until 1990's, "manufacturing techniques could be classified in two sets, according to the way the product's shape was generated: forming processes and material removal processes" [2]. The industrial era of Additive Manufacturing (AM) started in 1986 and enabled to make objects "from 3D model data, layer upon layer, as opposed to conventional manufacturing technologies" [3]. AM brings many changes: tooling is no longer needed, products' functionalities can be improved, customized, and manufacturing on demand is available. Furthermore, AM now allows the achievement of fully operational products. Thus, AM is no longer restricted to rapid prototyping which was until now its main use but also introduces the possibility of rapid manufacturing. It is also necessary to promote this new technology coming from advances in science and R&D research, from early education to Ph.D. degree. Among the three innovation strategies defined by Jaruzelski and Dehoff [4], the techno-push one best fits the current situation of AM: product innovation can arise from an appropriate use of AM and provide new insights into the product development. However, facing these new possibilities, it is necessary to provide students a new set of tools and methods considering AM specificities to foster the AM techno-push strategy: Design with Additive Manufacturing (DWAM) and Design for Additive Manufacturing (DFAM) [5] are representatives of these methods.

DFAM is a set of methods and tools that help designers to take into account the specificities of AM such as the technological, geometrical, and functional complexities during the design stages.

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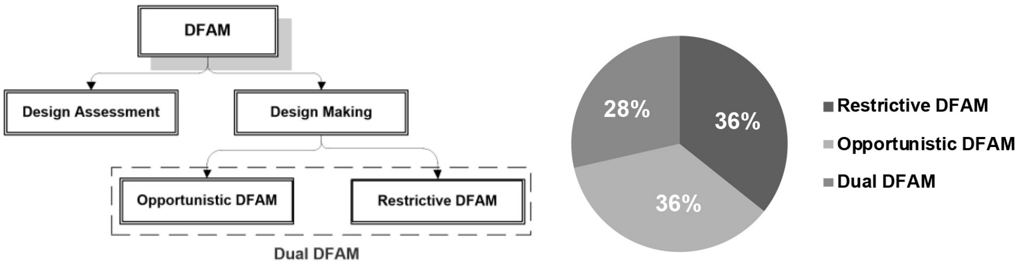


Fig. 1. Synthesis and distribution of the DFAM practices, extracted from Laverne [21].

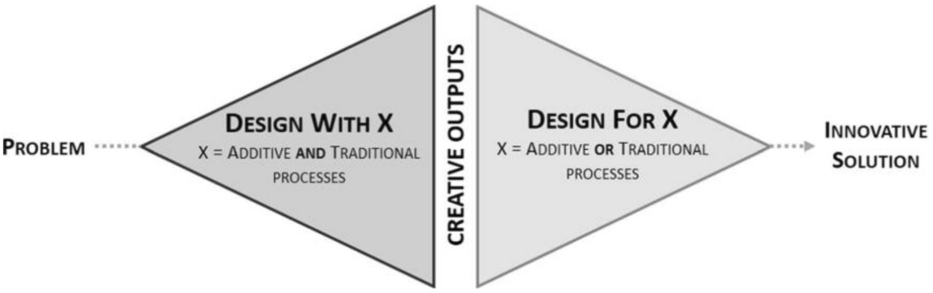


Fig. 2. DWX and DFX in the innovation process, extracted from Laverne [5].

Current DFAM methods can be divided into two related categories because "each step of the design process must be evaluated [and] evaluation serves as a check on progress towards the overall objective" [6]. These two categories are DFAM for design making and DFAM for design assessment (Fig. 1 left). DFAM methods for design making are intended to guide designers during the design process. They lead to the development of Intermediate Representations (IR) [7–10] and mainly consist of guidelines [11] or design features [12]. DFAM methods for design assessment deploy acceptability criteria such as cost, time and manufacturability to evaluate IR created during the design making stage [13–20]. Due to the extra costs of late design changes, DFAM methodologies for new product development must encompass IR creation and IR evaluation while focusing on the most crucial design stages, i.e., the early stages. Laverne et al. [21] surveyed 27 peer-reviewed publications related to DFAM for decision making. They identified three different ways to assist designers and propose to name these methods opportunistic DFAM, restrictive DFAM, and dual DFAM. Fig. 1 right shows their distribution within these 27 references.

An appropriate methodological approach in the early stages of design can be based on the improvement of the Design With X (DWX) approach and its linkage with DFAM. Indeed, DWX objective is "to inspire designers and support them in creating products [because DWX focuses] on innovations so the product design solutions have always an innovative character" [22]. The primary use of DWX is Design With User in user-centered design because it increases users' involvement compared with Design For Users. Thus, as opposed to DFX, DWX approaches are not intended to focus the design on a specific purpose but to widen the solution space with particular attention to an item. DWX is also a cumulative approach. In an innovative process, DWX assists early design activities and has to be carried out before DFX method to enhance design creativity (Fig. 2). Since AM opportunities and restrictions are poorly mastered by students and designers compared with those about traditional processes, we can confirm the interest of a DWX methodology enriched with AM paradigm. Laverne et al. [5] call it Design With AM (DWAM). DWAM will use AM as an additional way to increase the creative potential of designers.

2.2 Creativity

Creativity is a term appeared in the 70's to express the creative faculty of man. It can be defined as "the ability to transcend traditional ideas, rules, patterns, relationships, or the like, and to create meaningful new ideas, forms, methods and interpretations" [29]. It is considered as crucial for designing products and enabling innovation [30]. Plenty of technique exists to foster the creativity such as analogical thinking, brainstorming, mind mapping, forced relation or connection [31]. For example, when a project manager needs to find an innovative solution to a generic problem identified in one of the phases of the design process, it is usual to organize a creative session. This session usually takes place outside the workplace, with a multidisciplinary team of participants that is not necessarily composed of specialists unlike the participants of a session of technical creativity. The moderator uses a series of tools and games (previously organized according to the objectives). He manages the group ensuring that there is no censorship of participants among themselves. To do this, he must consider all the ideas generated by participants as interesting. The moderator should encourage participants to be as creative as possible, in particular promoting the diversion or bouncing on the ideas of others. The structure of an overall creativity session consists of four steps as presented in Fig. 3, structured in double diamond approach [32]. Step 1 allows participants to become familiar with this type of exercise. For group cohesion, games are organized. Objectives and expectations of the session are defined. During the second step, tools such as brainstorming, or mind map are used to enlarge the space solutions to maximize the amount of idea generated. Then in the third step, the group converges, working on specific ideas sheets to identify concepts. Those concepts are evaluated by the whole group via a multi-criteria matrix in the fourth step. The session ends with a summary of the moderator and a presentation of the next project tasks.

As seen in chapter 2.1, DWAM is a way to improve the creative potential of designers. We think that mixing creativity sessions and AM knowledge, especially in the divergent phases, will provide more feasible and original concepts. We call this mixing approach Additive creativity (Fig. 3).

2.3 *Challenges for engineering education*

Engineering education is the activity of teaching knowledge and principles related to the professional practice of engineering. Its main challenges are to answer to the rising need for companies to get advanced and talented engineers, and to attract and retain students in that field [33]. Companies work now in a globalized and competitive world, and basic engineering skills can be provided by lower cost engineers in developing countries. Therefore, engineering education should provide to companies advanced workforce that can boost their positions. Today, engineers should get the ability to innovate, to work in multicultural environments, to understand the business context, to adapt to changing conditions, and to know how to use advanced technologies like AM. However, there is a worldwide declining number of students enrolled in engineering degrees and finishing their degrees [34]. Many persons do not have a clear perception of the nature of engineering, and there is a lack of attractiveness due to the perceived difficulty of the curriculum.

To answer these challenges, Smith et al. propose some solutions [35] such as introducing students to the excitement and relevance of engineering early in the educational experience, and exposing students to research early on. They also suggest placing engineering in a social or business context, inviting practitioners and other engineers to speak, and changing the way to teach engineering. For this last point, to better engaging students, some pedagogical approaches have been used: active and cooperative learning, learning communities, service learning, cooperative education, inquiry and problem-based learning, team projects and serious game [36, 37]. One of the currently most-favored pedagogical models for teaching design is project-based learning (PBL) [38].

Concerning AM teaching, there is a growing number of courses both at the undergraduate and the postgraduate levels [1]. Traditional instruction, as well as problem-based and project-based pedagogies, have already been tried [39]. To enrich the teaching community, this paper provides an example of a project-based learning (PBL) mixing creativity session and AM with two different approaches and compare them.

3. Research design approach

This part presents the experiment conducted with postgraduate engineering students (in their fifth year at university). The objectives of this experiment are to compare two pedagogical approaches mixing

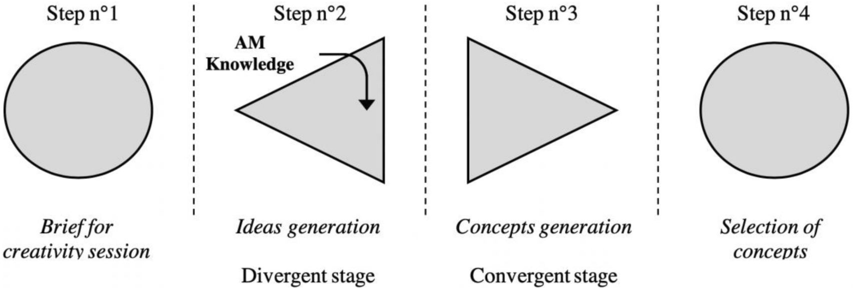
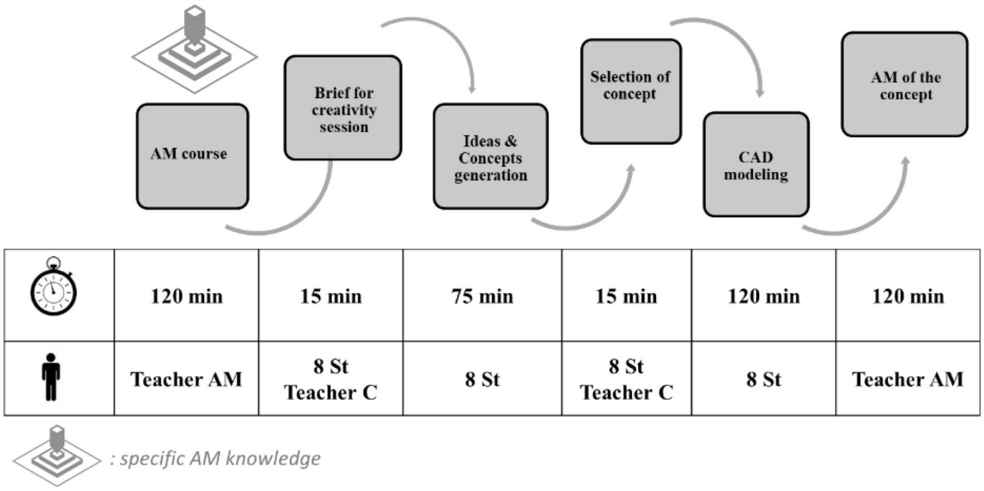


Fig. 3. The generic structure of an additive creativity session adapted from [32].



⏱	120 min	15 min	75 min	15 min	120 min	120 min
🧍	Teacher AM	8 St Teacher C	8 St	8 St Teacher C	8 St	Teacher AM

Fig. 4. Pedagogical approach for panel A.

Additive Manufacturing Knowledge and creativity, and to evaluate the interest of students. This part presents these two pedagogical approaches and the way they are evaluated.

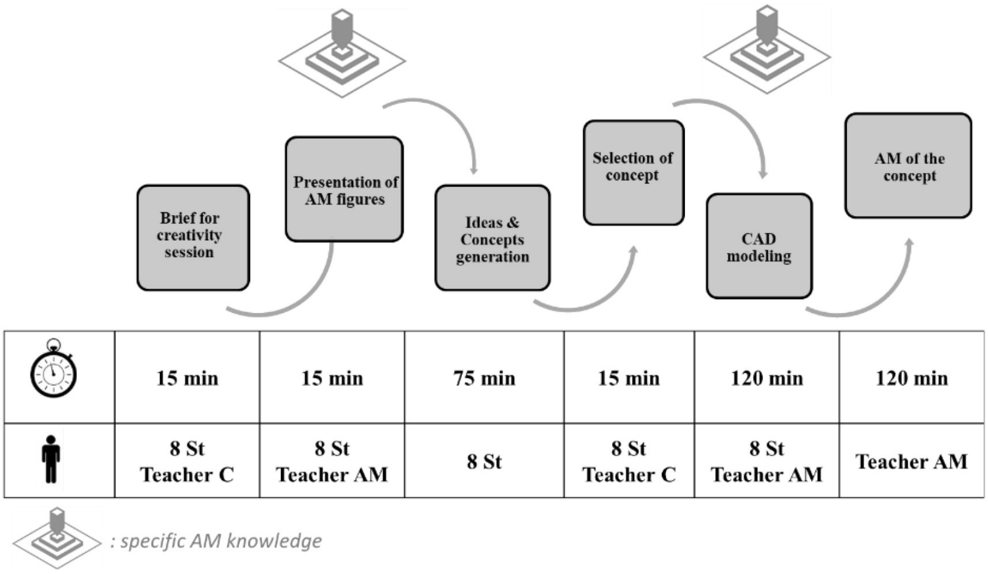
3.1 Pedagogical approaches

Figure 4 describes the first one named "panel A". The participants are a teacher in AM (Teacher AM), a teacher in Creativity (Teacher C) and eight students (St).

Six steps compose this approach:

- Step 1: The teacher expert in AM teaches two hours on the various AM technologies and manufacturing constraints to consider when making the CAD (Computer-aided design), and on faults to avoid during design.
- Step 2: The teacher in charge of the creativity session presents the brief: "design one innovative goody for a young company."
- Step 3: During 75 minutes, the eight students realize a creative session using brainstorming to offer a maximum of Idea Sheets (IS).
- Step 4: The creativity teacher is refocusing the work and ask students to select by vote their favorite concept.
- Step 5: The students realize their concept with CAD software (Catia, from Dassault Systèmes) during two hours.
- Step 6: The Additive Manufacturing teacher begins the manufacturing and performs the post-processing of the parts. They are realized on a Stratasys Object Connex 260V machine with ultraviolet curing resins.

Figure 5 describes the second approach named



⏱	15 min	15 min	75 min	15 min	120 min	120 min
🧍	8 St Teacher C	8 St Teacher AM	8 St	8 St Teacher C	8 St Teacher AM	Teacher AM

Fig. 5. Pedagogical approach for panel A.

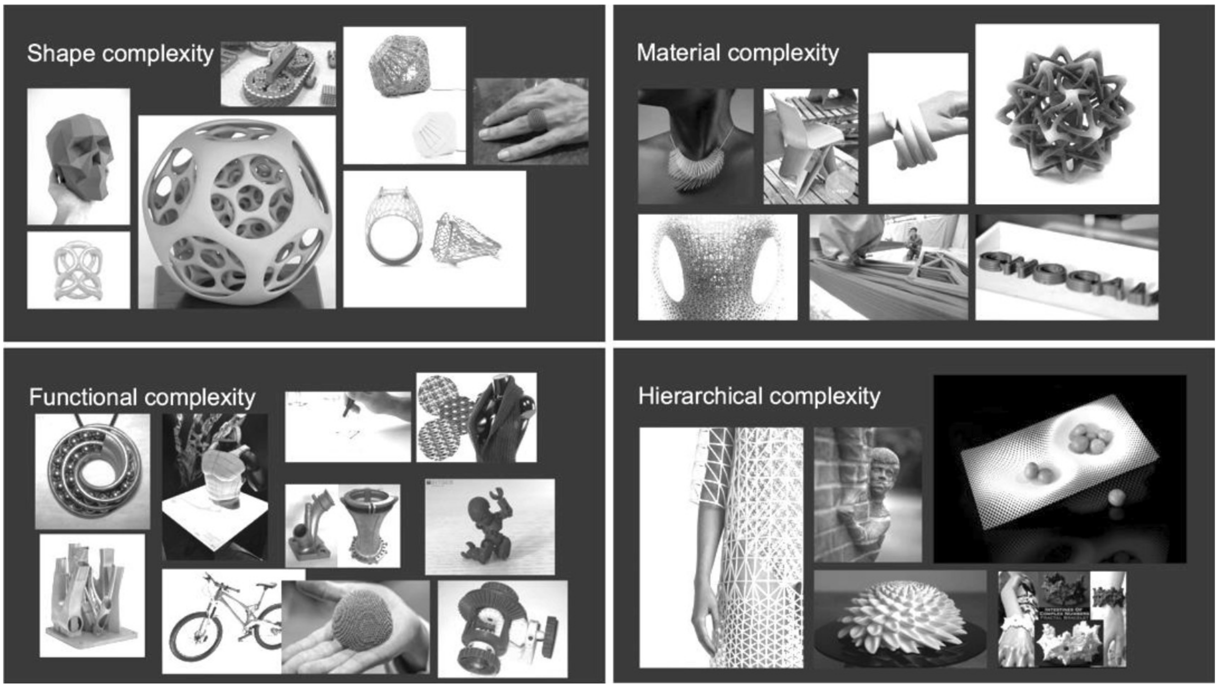
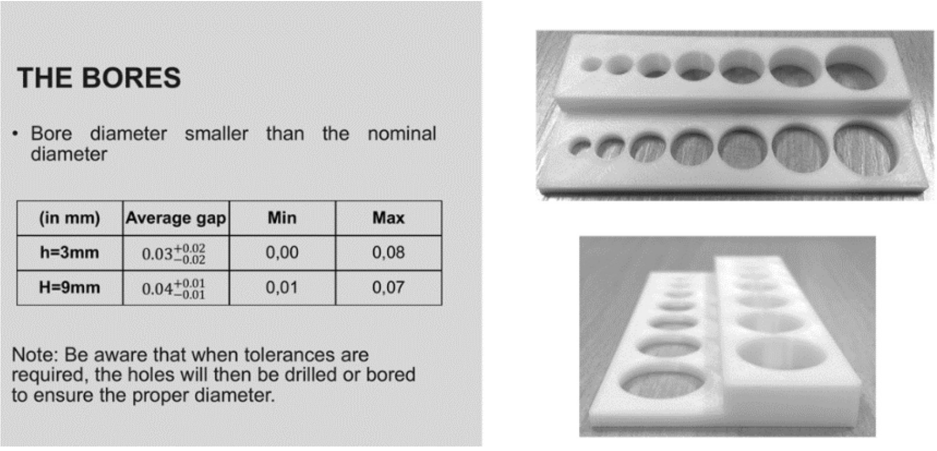


Fig. 6. Visuals representing achievable features /shapes/materials in AM.

"panel B." The participants are also a teacher in AM (Teacher AM), a teacher in Creativity (Teacher C) and eight students (St).

Six steps compose this approach:

- Step 1: The teacher in charge of the creativity session presents the brief: "design an innovative goody for a young company."
- Step 2: In only 15 minutes, the creative teacher provides students AM knowledge, represented by visuals showing the richness of features/shapes/textures achievable by these technologies classified according to Gibson [40] (Fig. 6). Thus, the creativity instructions differ from panel A by the additional use of those visuals.
- Step 3: During 75 min, the eight students realize a creative session using brainstorming and purge to offer a maximum of Idea Sheets (IS).
- Step 4: The creativity teacher is refocusing the work and ask students to select by vote their favorite concept.
- Step 5: During two hours, the students realize their concept with CAD software. During this implementation of CAD, the teacher of Additive Manufacturing shows them a series of "defect cards" and defective printed parts (Fig. 7) to show them defects they should avoid in the design of their parts.
- Step 6: The Additive Manufacturing teacher begins manufacturing and performs post-processing of the parts. The parts are realized in the same way as Panel A.



THE BORES

- Bore diameter smaller than the nominal diameter

(in mm)	Average gap	Min	Max
h=3mm	$0.03^{+0.02}_{-0.02}$	0,00	0,08
H=9mm	$0.04^{+0.01}_{-0.01}$	0,01	0,07

Note: Be aware that when tolerances are required, the holes will then be drilled or bored to ensure the proper diameter.

Fig. 7. Example of defect cards given to the panel B student, on the dimensional parts error.

Table 1. Coded table for Originality and Feasibility rating

Used scale to rate the originality (from 1 to 7)	
7	+++
6	++
5	+
4	0
3	-
2	- -
1	- - -

Used scale to rate the feasibility (from 1 to 4)		TRL scale	RD3 scale
4	Existing product	9	level 1
3	Product industrially achievable	6 to 8	level 2 to 3
2	Achievable product laboratory	1 to 5	level 4
1	Product not feasible to date		level 5

In synthesis, the main difference between panel A and B are on the way the AM knowledge is provided to the students. In panel A, there is a first AM course of 2 hours, and then the creative and design work is realized. In panel B, the AM knowledge is disseminated with visuals all along the process, in the steps of ideas and concept generation, and CAD modeling.

3.2 Evaluation

Following these sessions, ideas are evaluated by a panel of 4 experts to compare their originality and their feasibility. Experts evaluate the originality with a 7 points Likert scale (Table 1 top) and evaluate the feasibility on a 4 points scale (Table 1 bottom). The last two columns of this table indicated the correspondence with the TRL (Technology Readiness Level) and RD3 (R&D Degree of Difficulty) scales [46].

A questionnaire was also sent to all the 16 participants to assess their feelings about these two approaches. Four questions were asked to understand their interest, their perceived acquisition of AM knowledge, their perceived acquisition

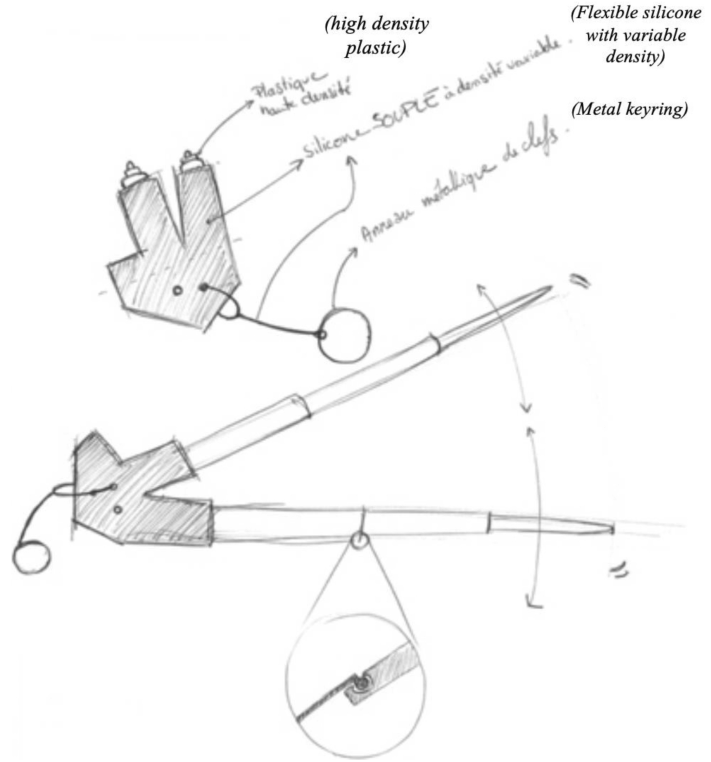


Fig. 8. Example of a spontaneous generation of an idea card "Innovative chopsticks."

of creativity tools knowledge and their global satisfaction.

4. Results

In total, 28 Idea Sheets (IS) were generated. Panel A realized 12 Idea Sheets (IS), Panel B realized 16 Ideas Sheets. Fig. 8 presents an example of one of them. It is a new concept of chopsticks for a Japanese restaurant that can be used as a "key ring."

4.1 Results on originality and feasibility

Table 2 presents the results concerning the Originality and Feasibility. This table shows that the ideas resulting from the creativity of panel B are more original and more feasible than those of panel A. Originality is increased by 12.5% and feasibility by 12.3%.

Figure 9 presents the percentage of ideas of panel A and panel B above the originality average of panel A + B. In panel A, 5 in 12 ideas (i.e., 42%) are above the overall average, in panel B, 9 in 16 (i.e., 56%) are above the overall

Figure 10 presents the percentage of ideas of panel A and panel B above the feasibility average of panel A+B. In panel A, 3 in 12 ideas (i.e., 25%) are above the overall average, in panel B, 9 in 16 ideas (i.e., 56%) are above the overall.

Therefore, these figures show that the ideas of panel B seems more original than the ideas of panel A, and much more feasible than those from panel A.

4.2 Results on the satisfaction of the students

The students were asked four yes/no questions. The first question was on their interest in this PBL. The second and third ones were if they had acquired the basics of AM knowledge and the fundamentals of creativity. The last one was if they were satisfied with the module taught. Fig. 11 presents the results.

Table 2. Originality and Feasibility results

	Originality		**Feasibility**	
	Panel A	**Panel B**	**Panel A**	**Panel B**
Average	4.15	4.67	2.92	3.28
Standard deviation	1.31	1.15	0.39	0.46

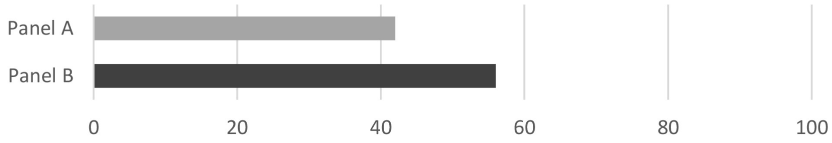


Fig. 9. Originality: Percentage of ideas above average.

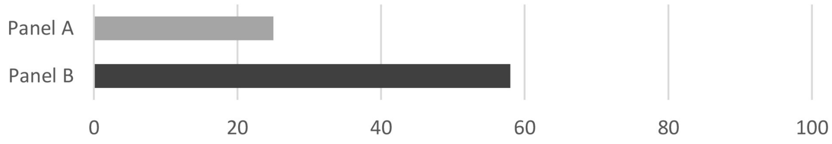


Fig. 10. Feasibility: Percentage of ideas above the average.

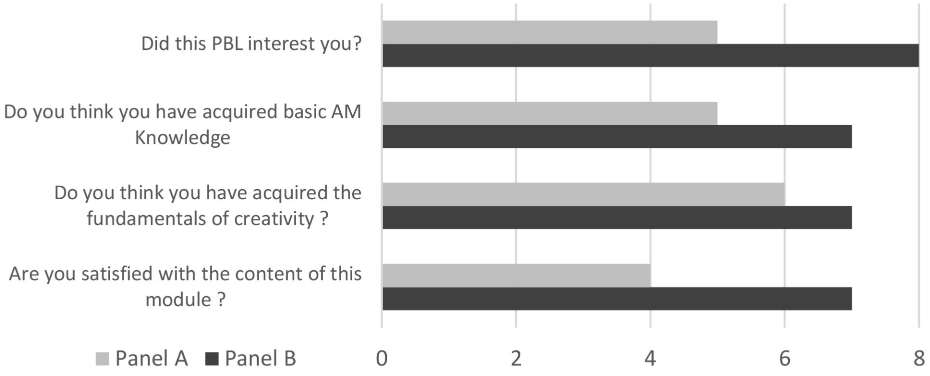


Fig. 11. Results of the satisfaction questionnaire (8 students per panel).

All the students from the panel B are interested in this PBL. A vast majority of them (7 in 8) thinks they have acquired the basics of AM Knowledge, the fundamentals of creativity, and is satisfied with the content of the additive creativity module. On the other side, students from panel A are less interested in this PBL (5 in 8) and less satisfied (4 in 8). Fewer students than those of panel B think they have acquired knowledge in AM and fundamentals of creativity. These results show that the teaching method used with panel B is better accepted by students.

5. Conclusion and future work

Can the disciplines of creativity and Additive Manufacturing be learned in a fun and effective way, through additive creativity? Linking creativity tools and AM knowledge can be challenging as it involves two distinct domains generally taught by different teachers that have to interact together. The teachers' roles are essential in the learning experience, and so guidance is required to help them use the full learning potential of creativity and AM in engineering schools. The whole learning experience has been made more effective thanks to the concerted efforts of teachers and researchers in an engineering faculty.

This study compares two different approaches of interaction and highlights that the deep integration one gives more original and feasible concepts as well as more satisfaction of the students. One of the limitations of this study is the number of students involve in it. Future works will reiterate it to confirm the results and add in the comparison new pedagogical approaches. We propose and validate a new pedagogical approach to foster the use of AM knowledge in creativity session for Engineering Education. We prove that it increases the originality and feasibility of the idea generated, as well as the satisfaction of the students.

As one of the crucial issues for competitiveness in the manufacturing sector lies in the education and training of future young engineers, we believe the presented approach will help to overcome students' declining interest in the sciences and engineering and provide to companies advanced workforce that can boost their positions.

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