AM knowledge integration to foster innovation process: a methodological proposal.

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Short Abstract: In a few years, Additive Manufacturing (AM) has become a promising technology and opened up new prospects for the product development. Nevertheless, design methods remain predominantly based on conventional manufacturing processes and AM capabilities need to be better mastered and integrated in the design team. The methodology presented in this article seek to foster the product innovation process by avoiding these weaknesses through a contribution of AM knowledge. This AM knowledge is tailored, i.e. delivered to the right user at the right time and in the right format, in order to be useful and usable during the creative stages of the design process.

Key words: Additive Manufacturing (AM), knowledge, preliminary design, innovation.

1- Introduction

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" [1]. 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" [2]. Nowadays, seven families of AM processes exist and provide new insights into the product development. Indeed, in AM, tools are not needed, product's functionality can be improved, customized manufacturing and complex shapes with multi materials are possible [3]. Furthermore, AM now allows the achievement of fully functional products.
But facing these new possibilities, it is necessary to provide designers a new set of tools and methods taking into account AM specificities.

2- DFAM in the innovation process

2.1 – Definition and classification of the DFAM methodologies

In a highly competitive marketplace, the reduction of time to market and the decrease of the production costs are major concerns while the number of product requirements are increasing. Design has become a team work where each stakeholder must bring and share his knowledge and expertise during the preliminary design and also helps to reduce iterations between the product design stage and the downstream stages. This approach, called integrated design, is the purpose of the Design For X (DFX) methodologies which are the "natural response to improve profitability" [4]. They enable the improvement of the "design product as well as design process from a particular perspective which is represented by X" [5]. DFX also revolutionizes the practice of design because all product lifecycle considerations are taken into account through the introduction of comprehensive knowledge, procedures or metrics. Thus, DFAM methodologies are dedicated to the AM paradigm. They are intended to facilitate the consideration of the AM specificities and they provide "an opportunity to rethink [Design For Manufacturing] to take advantage of the unique capabilities of these technologies" [3].
According to Laverne, et al. [6], DFAM methodologies can be classified according to the systemic level they are focusing for a product: component level and assembly level.
Component-based DFAM (C-DFAM) are dedicated to an AM suitable and AM optimized component design from a given product architecture. Assembly-based DFAM (A-DFAM) are intended to the improvement of a product architecture through the decrease of the components number or to design new product architecture using databases.

2.2 – Limits of current DFAM methods in an innovative context

There are, in the literature, various kinds and types of innovation: product or process innovations and organizational innovations designed to amend the company's structure and business processes. This article questions how a new technology (i.e. AM) can enable product innovation. Indeed, according to Nelson [7], innovation does not always comply with a request of a clearly identified market, but may be intended to the enhancement of technological know-how: this is techno-push. Currently, AM leads to such concerns.

As Perrin [8] declares, there is “no innovation without design stages”: design is the backbone of an innovation process. To succeed in it, early design stages, starting from the research of concepts to the delivery of a preliminary layout [9], are crucial. Indeed, during these stages, creativity plays a major role “in the production of novel and useful ideas by an individual or a small group of individual working together” [10].
In the current C-DFAM and A-DFAM methodologies, the integration of AM Knowledge (AMK) is not used for challenging the specifications obtained during the preliminary studies or for defining new ideas or concepts. Thus deliverables in these methodologies are mostly redesigned products; that also means an incremental innovation at the assembly level. These methodologies are not adequate to produce "creative outputs" [11] i.e outputs satisfying two essential criteria for the development of radical innovation : originality and appropriateness. Therefore the methodology presented in this article, is intended to fill this gap through an intake of AM knowledge, suitable to the early design process.

3- Presentation of the methodology

3.1 – Methodological objectives

We showed in the previous section that the major limit of the current DFAM to develop innovative products is the difficulty for designers to break free of their architectural knowledge. An appropriate methodological response can be based on the improvement of the Design With X (DWX) methods. Indeed, DWX objective is “to inspire designers and supports them in creating products [because DWX focuses] on innovations so the product design solutions have always an innovative character” [12]. As opposed to the DFX approaches, a DWX method is not intended to focus the design on a specific purpose but to widen the space solution with special attention to an innovative aspect X and its characteristics. In an innovative process, DWX can also assist early design activities and is carried out before a DFX method in order to enhance design creativity (Figure 1).

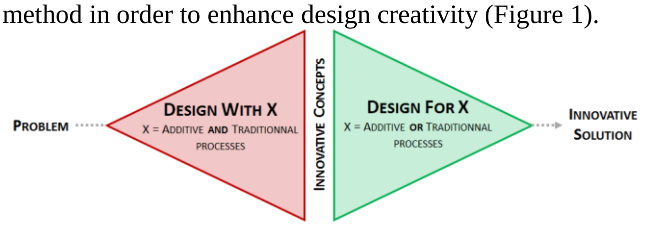

Figure 1 DWX and DFX in the innovation process

Since AM opportunities and restrictions are poorly known whereas those related to traditional processes are mastered by designers, we can see the interest of a DWX methodology enriched with AM paradigm. We call it Design With AM (DWAM). It aims to increase the creative potential by introducing a suitable AM knowledge in order to enable the undermining of the architectural knowledge and the development of original and appropriate concepts (also called working structures). Thus, when innovative concepts are created, the use of DFAM methodologies become possible.

3.2 – Importance of AM knowledge for creativity.

Among Popadiuk and Choo [13] one of the difference between incremental and radical innovation is the resource and skill requirement: for radical innovation, “additional expertise from outside might be required”. Moreover, in their C-K theory, Hatchuel and Weil [14] highlight the importance of a reasoning focused, on the one hand on the knowledge space ("K" space) and, on the other hand, on the concepts space ("C" space) to succeed in an innovative design. The methodology presented in this article is specifically focused on the transition from K to C, called disjunction. It aims to improve the generation of alternative by extending the C space “with elements coming from the space K”. These elements are AM knowledge. The relationship between creativity and knowledge has been formalized by several researchers [15]; nevertheless, there is no data available to specify how AM knowledge, which is the innovative aspect of the methodology, should be introduced to designers.
In a previous study [6], the creative potential of design groups with expert or guided AMK was compared with an inexperienced group in the AM field. We showed that a huge intake of AMK was not suitable to develop innovative and manufacturable working structures. It is more appropriate to split this knowledge to make it more understandable and immediately usable. This requires to identify the appropriate AMK (i.e. founding the “what”) designers need for each of their design activities. This tailored AMK is depending from three parameters: who, when, how.

- Who is the target i.e. the stakeholder (industrial designer, ergonomist or engineer) or the pluridisciplinary group who will use the AMK
- When corresponds to the most adequate moment to introduce the AMK.
- How is the best form that embodies and transmits the AMK.

3.3 – Initial model of the methodology

To succeed in the objectives presented in section 3.1, the first model of our methodology is adapted from stage based with iterative activities models of the design process where we highlight some key elements that identify a temporality in the design progression. These elements are the product representations created during a design stage and called Intermediate Representation (IR). For a design stage, divergent activities (called ideation) are dedicated to IR generation and convergent activities (called selection) provide a ranking of these IR following specific criteria.
As triggers for the supply of AMK, we select IR related to three major stages of the early design: the search of ideas, the concepts development and the arrangement of the architecture. These IR are the possible function, the ideas sheets, the drawing of concepts and the preliminary layout (Figure 2).

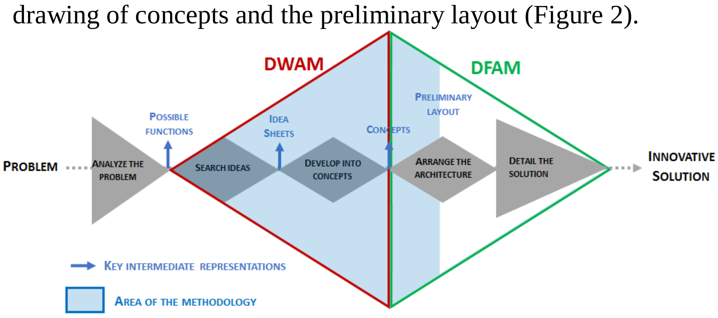

Figure 2 Key IR and activities of the methodology

In order to define the tailored KAM needed for each stage of our methodology, we conducted several experimentations whose protocol and results are detailed in section 4.

4- Formalization of the "just need" knowledge

4.1 – Experimentation 1

4.1.1 Protocol

This experiment is dedicated to the identification of the tailored AMK i.e. the useful knowledge to enhance the design creativity. It is based on an analysis of the cognitive and informational process followed by designers working on the early stages of innovative industrial projects.
The study was carried out in two phases. First, participants have to describe their current design practices; especially what kind ok knowledge about traditional processes is retrieved and applied during. Then they have to fulfill a questionnaire dealing with the relationship between the product-level characteristics of innovative products [16] and their possible ways of improvement thanks to AM.
The interview focuses on the following topics:

- Listing of the IR usually created and illustration in the selected project,
- Description of the design activities, design considerations and design stages followed to produce IR or to take decision,
- Presentation of the inspirational and informational sources,
- Description of the AM role in the daily work

At the end of the interview, the participant is asked to fulfill the survey.

4.2.2 Results

The interviews were used to map design process within the framework of innovative projects. The analysis of these maps shows that there is a shift, for a given design activity, between the use of knowledge dealing with traditional processes and the AMK (if held by the designer): either it is not used or it is later. But for a specific activity, it is conceivable that the availability of an AMK is necessarily performed in conjunction with the first instantiation of this same content referring to traditional knowledge.
Although designers say they are aware of the AM working principle and particularly of its usefulness for concepts prototyping, 86% of them (Figure 3) answer in the survey that a better knowledge would bring them new opportunities for product innovation during the ideation stages.

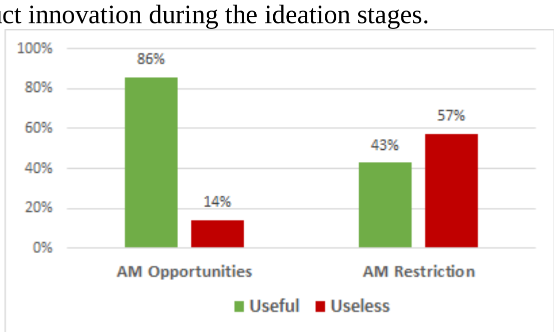

Figure 3 Evaluation of the usefulness of AMK in early design stages

Moreover, when they are more precisely questioned on the product-level characteristics that could be affected by this AMK, we notice that the possible ways of innovation highlighted in the literature are poorly known (Figure 4). This also gives us indications on the AMK contents we need to give to the designer to improve its exploration of innovative concepts.

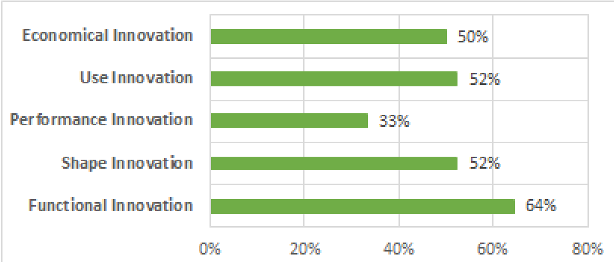

Figure 4 Perceived utility of AMK for different categories of innovation

At last, 57% of the participants (Figure 3) feel that the contribution of knowledge dealing with AM restriction will not help them. It put forward an idealized view of AM in which the AM has no impact on converging activities. It is therefore necessary to bring AMK also during these phases in order to assess IR according to criteria such as certification, development time of the solution…

4.2 – Experimentation 2

4.2.1 Protocol

The purpose of this experiment is to identify the adequate knowledge forms usable in the methodology and more particularly those which are not suitable for conveying the knowledge.
The study was conducted with different business profile of designers (engineers, industrial designers and ergonomist). Each participant had to evaluate a transcription of knowledge predominantly based on: a text, a video, a picture, an artifact. The appreciation of each format was marked on a 5 levels Likert scale (1 = dislike and 5 = appreciate)

4.2.2 Results

Among the proposed forms, only three of them have an average score higher than 4 (Figure 5), which means they are appreciated by users. Using only text to bring a knowledge is not adequate.

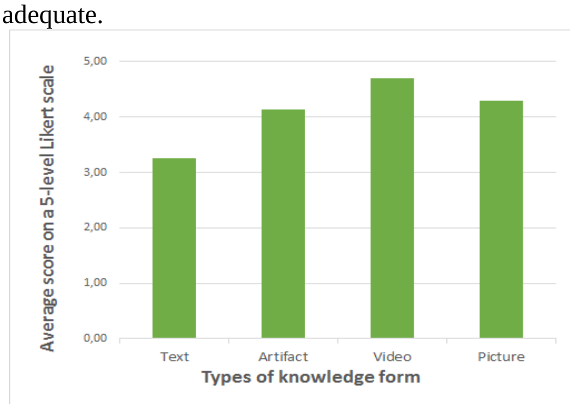

Figure 5 Appreciation of knowledge forms

Secondly, a knowledge transferred with an artifact is admittedly appreciated but is poorly compatible with a need to regularly and quickly update the knowledge contents because of the current developments in the AM field. It is also a necessity to set up a AMK form, compatible with the data management enabled by a PLM environment.

4.3 – Experimentation 3

4.3.1 Protocol

This last experiment focuses on the couple knowledge content – timing. It was performed with 18 design students in research master. These students are formed in the design and innovation processes and have basic knowledge in AM. The V0 model methodology is presented and explained to each participant beforehand. Next, different typologies of AMK are introduced and detailed. Then each participant have to place among the 3 stages of the model where this knowledge could be useful and usable for their design activities.

4.3.2 Results

The graph below (Figure 6) shows the first, the average and the last occurrence for each typology of knowledge.

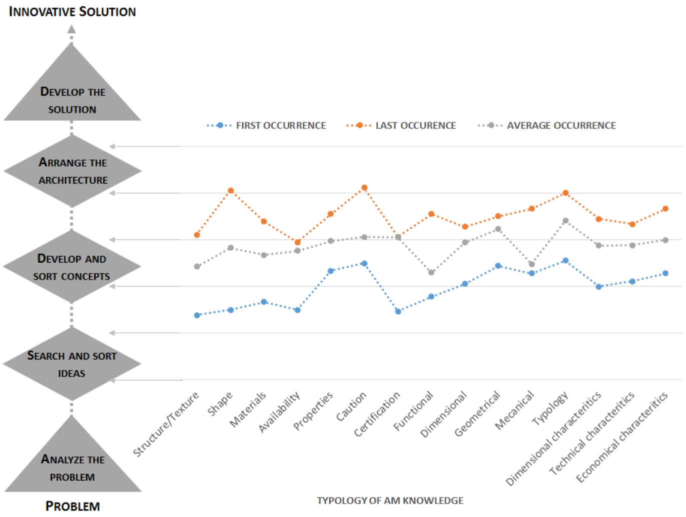

Figure 6 Preferred time for the introduction of different AMK

We notice the misuse of several AMK in the design process. Indeed, the study shows that all typologies of AMK are required during the concepts development and its sorting. Creativity tools such as TRIZ or brainstorming encourage the research of ideas in various fields, without restriction. Therefore it may be necessary to provide knowledge (e.g. on AM application areas) in order to avoid missing out some ideas or eliminating others just because they seem unrealistic.
AMK dealing with of the complexity for free seems required during the development of concepts, i.e. the combination of ideas (functions and working principles) into a solution.
Finally, it is surprising that knowledge on the characteristics of AM machines are perceived as useful for selecting concepts while dimensions or mechanical behavior have not been specified. It is therefore necessary to indicate designers to integrate this knowledge does not at this stage but later

5- Proposition of an enriched with AM knowledge model (final model)

The model, resulting from the compilation of the experimental studies, defines five specific contributions of AM knowledge, during the early design (Figure 7). Three of them are intended to improve the ideation stages (AMK 2, AMK 3 and AMK 5) and the two others to improve the selection stages (AMK 1 and AMK 4).
At this point of our study we cannot distinguish content dedicated to a particular expert skill, we also propose a "universal" model which must be refined with other experiments.
A demonstration tool was created jointly with the development of the V1 model. Based on results from experiment 2, AMK contents are mainly presented using pictures, but some short comments are also added to facilitate the understanding.

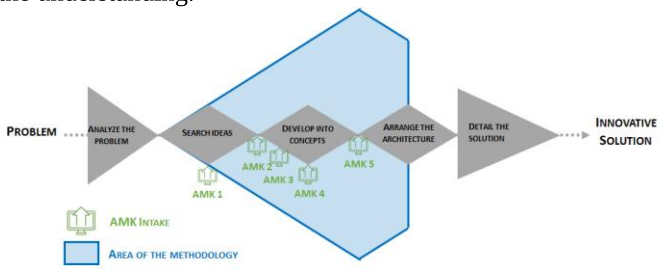

Figure 7 Final model with AM knowledge

6- Conclusions and perspectives.

The methodology have to be tested both in its content but also in its usefulness in the innovation process.
The assessment of the contents will be achieved with user test in a context of industrial innovation projects. It aims to improve the AMK contents but more specifically the three associated parameters who, what, and when. Thereby, a robust V2 model will be obtain.
The validation of its usefulness for the creation of innovative architecture will be performed through a comparative analysis of two workshop carried out on the same project. The first one will have to work with the methodology (V2 model and tool), the other will be free to use its own approach. The comparison will be based on qualitative (expert evaluation) and quantitative results (number of ideas, number of components or functions …)

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