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DESIGN FOR ADDITIVE MANUFACTURING: A CREATIVE APPROACH

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1. Introduction

Our research object is focused on Design For Additive Manufacturing (DFAM) methods, from a creative design point of view. It appears that some existing methods already integrate some creative approaches but they guide to generate only partially creative concepts, while AM is recognized to have a great potential in new designs. We thus propose a framework of a creative DFAM method in this paper.
AM allows to introduce complexity in products at four levels: in their shape, material distribution, structure hierarchy and functionality [Rosen 2007], [Gibson et al. 2010]. To exploit this potential, several Design for Additive Manufacturing (DFAM) methods have been developed, with various design purposes. This paper aims first at presenting an overview of current DFAM methods, focusing on the input data and the initial Intermediate Representation (IR) they allow to define [Bouchard et al. 2005]. We identified that these methods impact differently the product definition and we propose to categorize them in 3 levels of changes, formal newness, functional reconfiguration and AM form & function implementation. However, among these methods, a very few are oriented to the generation of creative concepts i.e AM concepts whose features are new, realistic and useful [Bonnardel 2000]. In order to support the generation of creative concepts in AM, this paper aims at proposing a 5 stages creative approach to be integrated in early stages of DFAM methods. This approach intends to foster designers to explore new design features, by taking into account both intra-domain and far-domain sources of inspiration as input data.

2. Overview and limits of current DFAM methods

2.1 DFAM principles

As the specific orientation of Design For X (DFX) for the AM paradigm, DFAM groups methods that are intented to manage the required knowledge about product, process and material as soon as the beginning of the product lifecycle i.e the so-called *early stages* of the design process [Segonds et al. 2014]. *Opportunistic* DFAM methods guide designers to take into account AM specificities, such as the geometrical and material distribution freedoms, from the beginning and during the design process. These methods lead them to the creation of IRs [Hague et al. 2003], [Doubrovski et al. 2011]. Other methods, called *Restrictive* consider AM limits and define criteria, such as manufacturability and cost, to evaluate the IR regarding AM specificities [Alimardani et al. 2007], [Rafi et al. 2013]. They guide designers to progress from an ideal IR to realistic ones by embodying variations due to the manufacturing constraints. The 3rd category *Dual DFAM* groups methods combining the two previous approaches [Laverne et al. 2015]. These authors assert that *Dual DFAM* is more suitable for product innovation since it guides designers to exploit AM potential in a realistic way. Indeed, by conducting as soon as early stages both IR creation and IR evaluation, these methods help avoiding late design changes which cause extra cost and longer development time. However according to this author, *Dual DFAM* represents less than 30% of existing DFAM methods. It highlights the need of more researches in this category of early stages of *Dual DFAM* methods.

2.2 Dual DFAM methods: input data and impact on product's definition

From the above categorization, we analyzed *Dual DFAM* methods by focusing on the required input data and the initial IR they allow to define. Previously to the analysis, it is necessary to define some terms related to the product. A product can be generally described by its features i.e its main functions and forms, where function means *what* the product does and form *how* it is accomplished. Form means any aspect of physical properties, shape, geometry, construction, material or dimensions [Ullman 2010]. Functions and forms are embodied during the design process in different IR i.e 2D or 3D graphical, textual or artifacts that described the product to designers and stakeholders [Bouchard et al. 2005], [Pei et al. 2011]. The output of the conceptual design stage is embodied in an IR called the *initial IR*. It should be also pointed out that there may be several forms to achieve a single function [Ullman 2010]. Being more nuanced, some authors use the terms of inner and outer features [Rodrigue and Rivette 2010] or internal and external features [Maidin et al. 2011] to distinguish which forms and functions define the product boundaries (outer) from those that are not situated at the interface with an environment or with an other component in case of an assembly. Finally, function and behavior can be differentiated. The function that the product will achieve is known as the design process starts with a design brief, even if the form is still not defined. Function is then the *desired output* of the process, or the theoretical *what*. The behavior can be known if the forms of the product are defined, it is the *actual output* of the process, or the physical *how* [Ullman 2010].

Based on these definitions we identified that *Dual DFAM* methods, which exploit some AM specificities, have different approaches to process from input data to the creation of an initial IR. We propose to categorize them in 3 levels as we noticed, through the qualities of the generated initial IR, 3 levels of changes. We described them in the figure below: Level 1 – Formal newness, Level 2 – Functional reconfiguration, Level 3 – Form & Function implementation.

Level 1: Formal newness – DFAM methods of this category are oriented to the redesign of existing products. Designers start the process knowing most of the product's data: they know what are its inner and outer functions, how are its inner and outer forms and the product behavior. The purpose of these methods is to redesign in order to make the product suitable and optimized for AM. As shown in Figure 1 (left), the used input data refers to the existing product forms, functions and assembly constraints. Some methods propose to represent them as a CAD model [Rosen 2007], [Maheshwaraa et al. 2007] and [Chu et al. 2008] or a 3D scan file [Tang et al. 2014]. This initial IR describes the physical formal and functional boundaries of the product to be designed. Then, exploiting the opportunities brought by AM to manufacture shape and hierarchy complexity, a parametric lattice structure is chosen among different patterns inspired by nature, cellular, crystalline, orthogonal and others. The lattice is then deployed into the CAD model. This stage results in a new inner form regarding the existing product. Parametric optimization method is then applied on the resulting geometry according to the product constraints. The behavior of the optimized form is simulated in order to evaluate how well this new inner form performs the initial requirements.

In order to help designers to not limit themselves to their usual approach [Gerber and Barnard 2007], other DFAM methods propose to first automatically generate a 3d model from the functions, representing only component *skin* and *skeleton* [Vayre et al. 2012], [Ponche 2013]. When combined, the resulting initial IR is an *elementary* shape i.e the theoretical formal and functional boundaries of the product to be designed. According to Ullman's definition, it can be named an elementary form. As AM allows to manufacture any complex shapes, topological optimization methods are then used to generate an optimized form, within the theoretical boundaries, that realizes the functions while satisfying the constraints. This generated form is new regarding the existing product in both its inner and outer definitions. The behavior of this new optimized form is simulated with the integration of a manufacturing strategy, the process and post-process constraints and a manufacturing costs estimation to obtain a realistic form, which is guaranteed to be additively manufacturable. This form is finally evaluated to check how well it performs the initial requirements. To sum up, in this category, AM specificities are exploited with methods which consider as input data existing form and functions. The firstly described methods conduct to define an initial IR which embodies the existing features in a manner that the available design space, where changes can be made, is reduced to the inner form of the product. The secondly described methods conduct to create an initial IR which also represents existing features. But by considering it theoretical, the available design space allows changes in both inner and outer form definition of the product.

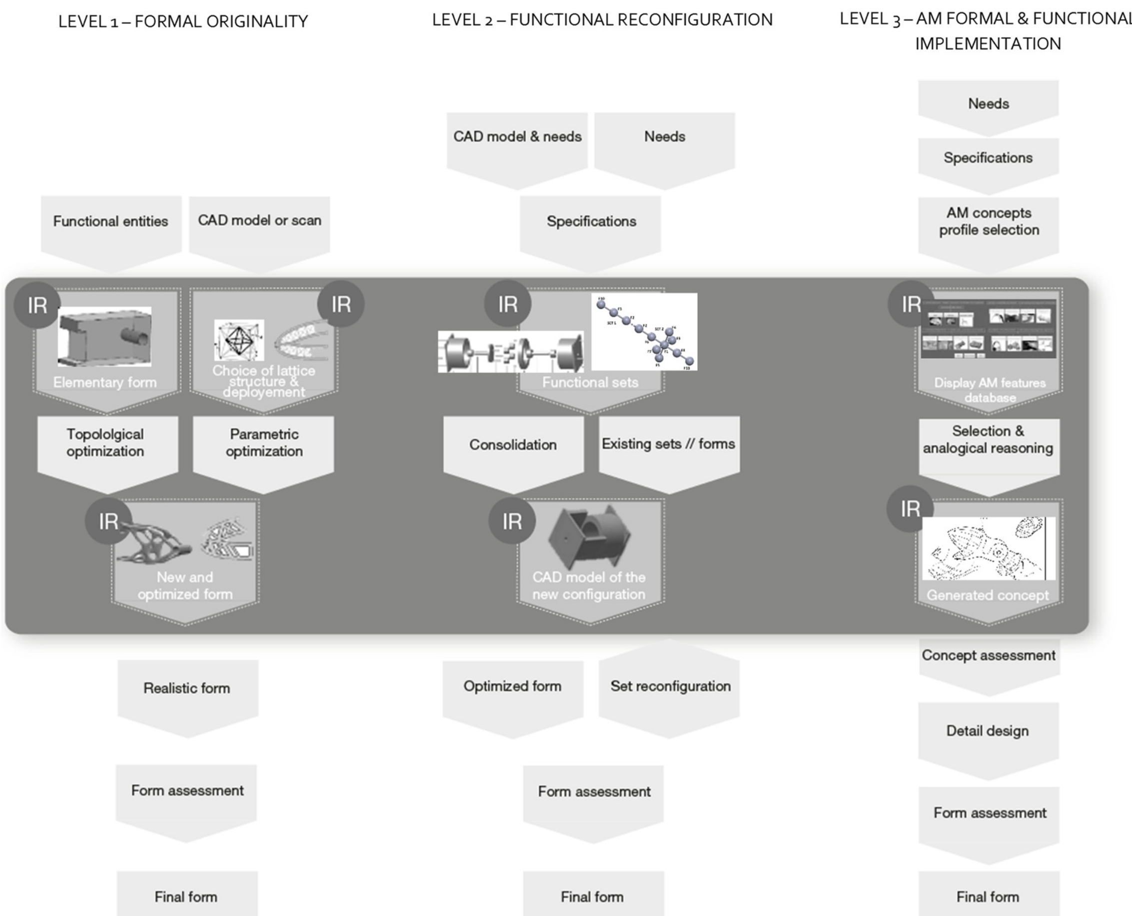

Figure 1. Workflows of current DFAM methods, adapted from [Maheshwaraa et al. 2007], [Rodrigue and Rivette 2010], [Maidin et al. 2011], [Ponche 2013], [Boyard et al. 2013]

Level 2: Functional reconfiguration - Methods of this category are dedicated to the re/design of existing products that embody assemblies i.e the definition of the relation between multiple component, since AM allows to produce several components in one build. The purpose of the method proposed by [Rodrigue and Rivette 2010] is the consolidation i.e to reduce the number of components of existing assemblies or of existing whole products [Munguia et al. 2007]. In order to define the initial IR of the assemblies, all the existing features are first mapped in functional sets visually represented by a CAD model (see Figure 1 – center). Two criteria are applied to identify which components of the assembly can be eliminated or grouped with other ones: the need to be separated for maintenance and the need to move relatively to the connected components. Once the candidates are eliminated this step results in a reconfiguration of the existing assembly i.e changes in the relation between components while keeping functions identical to the mapped assembly. The new configuration groups functional sets represented by a redesigned CAD model. This CAD model is considered as being the initial IR. Then, flow-force diagrams are used to identify new technical specifications (example: minimize the amount of heat transfer to the motor) to optimize the functions. A creative problem solving tool based on TRIZ methodology is used to find the action levers (change material or modify geometry) [Savransky 2002]. The resulting product representation is finally optimized through finite elements analysis and materials are selected.

Developing his DFAM method, [Boyard et al. 2013] (Figure 1 – center) proposed a similar approach. This method is oriented both to the design of new assemblies or redesign of existing ones as the author determines the input data only from customer needs, translated into specifications. The first step is grouping functions to define functional sets. The resulting product's representation is a 3D graph where dots represent functions and segments connections between functions. The forms which embody each set of functions are defined by case-base reasoning. Practically, each set of functions is compared to a use-case database to identify similar sets. When similar sets exist, their CAD representation are extracted and applied or adapted to the set to be designed, depending on the process, assembly, material and manufacturing constraints. The 3D graph which embodies both the functions and their forms is the initial IR of the assembly. According to the author, the 3D graph is made modular so it can be reconfigured along to the discussions with the stakeholders. This may cause a new database search to define the forms which achieve the functions and therefore involve modifications on the CAD model. When the configuration of the assembly is considered defined, the whole design is evaluated according to assemblability criteria to obtain the final product representation. We retain that in the described methods product features are mapped in functional sets, which are therefore the initial IR. These approaches allow to reconfigure the relations between the components of the assemblies while they consider as input data existing functions, which are not specific to AM, and/or the ones asked by the customer. The reconfiguration impacts the product definition at its formal level, indeed both the inner and outer forms of the sets have to be redesigned as soon as the functions configuration is changed.

Level 3: AM Form & Function implementation – Methods of this category are intended to the design or redesign of products. The purpose of the methods developed by [Burton 2005] and in the following [Maidin et al. 2011] (see Figure 1- right) is to globally emphasize the use of AM capabilites in product design. From the design specifications, the product desired features are assessed regarding AM specificities through a questionnaire [Burton 2005]. This stage intends first to evaluate if AM is recommended regarding major specificities (production volume, desired surface finish, mechanical property and accuracy). Secondly it intends to identify which are the most important features required for the product. Based on the answers, a "concept profile is determined" among four [Maidin et al. 2011 p.183]. The concept profile selection opens to a cases base of existing features represented by pictures of existing products made with AM and keywords describing their functions. Similarly to the method proposed by [Boyard et al. 2013], the concept is defined by analogical reasoning. In this case, designers are suggested to implement specific AM functions and forms which are relevant for their product to be designed. The generated concept, which is the initial IR, is evaluated according to the initial requirements and further detailed until the final design. Finally, in this category, the methods consider as input data features that have already been already realized in AM. With these methods AM impacts the product definition at both its formal and functional levels.

2.3. Limits of current DFAM methods regarding creative concepts generation

Through the presented 3 levels classification, we note that the ability to generate creative concepts with DFAM methods depends on the main purpose of the employed method, on the nature of the input data and on the integration of a creative approach.

As described in section 2.2, *Dual DFAM* methods follow 3 strategies which already integrate some creative approaches and creativity tools, and thus generate some creative outputs. We compare the 3 strategies and the qualities of the generated concepts (represented by the initial IR) in a summary table (see table 1 below). The main result of this comparison is that the existing *Dual DFAM* methods guide designers to generate only partially creative concepts while fully creative concepts are suitable for a more radical innovation than incremental innovation [Garcia and Calantone 2002].

Table 1. Summary table comparing the DFAM strategies and their generated concepts qualities of the 3 identified levels (X = No newness, O = Newness)

Generated concepts qualities		Level 1: Formal newness	Level 2: Functional reconfiguration	Level 3: AM F & F implementation
DFAM methods authors		[Rosen 2007], [Maheshwaraa et al. 2007], [Chu et al. 2008], [Vayre et al. 2012], [Ponche 2013], [Tang et al. 2014]	[Munguia et al. 2007], [Rodrigue and Rivette 2010], [Boyard et al. 2013]	[Burton 2005], [Maidin et al. 2011]
New what	Functions (25%)	X	X	O
	Forms (25%)	O	O	O
New to	AM industry (25%)	O	X	X
	Conventional industry (25%)	O	X	O
Level of newness allowed by the methods (max. 100%)		75%	25%	75%
Realistic to AM capabilities		O	X	O

Concepts qualities are defined according to criteria of [Garcia and Calantone 2002 p.113] who specifies that *newness* should be evaluated from both the perspectives of *what* is new and *who* is it new to. Based on the definition of [Bonnardel 2000], we define that, in our study, creative concepts are concepts whose features are fully new i.e never realized in traditional industry nor AM industry, and are realistic and useful. Methods of Level 1 (see left column on Table 1 above), based on optimization techniques, use analogical reasoning from various examples of lightweight and resistant structures like bones, crystals or cells development, to generate AM lattice structures. This bionic approach leads to new forms which can be produced only by AM. However, these methods do not include a functional analysis. Indeed, product's functions are considered as fixed input data, they are not questioned regarding AM capabilities. More oriented to the achievement of an initial form and its improvement for manufacturability, these methods guide to the definition of concepts which can be realistic but only partially new, i.e their forms are new regarding both existing AM and conventional industries (see left column – Lines 3 and 4) while their functions are not new regarding these worlds (see left column – Line 1). On the contrary, the main concern of Level 2 methods (see center column on Table 1) is the definition of functional assemblies, via focusing on the arrangement of the components. Case-based reasoning is used to define component's features, applied from a database of precedents i.e previously designed artifacts showing existing technical solutions that are not specific to AM. The creative tool TRIZ is used in downstream stages, when features are already defined, to target which of them can be optimized. Finally, these methods do not ensure manufacturability. They thus guide to the generation of concepts that may be useful but not new regarding conventional industry nor AM industry (see center column – Lines 3 and 4) The realism of the generated concepts regarding AM feasibility is not evaluated then considered uncertain. Similarly, in methods of Level 3, analogical reasoning from precedents is used to define rather components or whole systems, and both at their functional and formal levels. In this case, the considered precedents are specific to AM. These methods guide designers to the generation of concepts which can be new regarding existing conventional products and realistic regarding AM capabilities. However, by using only AM precedents they condition creative opportunities without looking for new solutions. Moreover, restricting designers to some *existing solutions* seems to be a not robust approach since current AM background is quite reduced, due to the relative newness of AM processes compared to others industrial processes [Ponche 2013]. This background is also expected to be expanded along to AM processes improvements [Wohlers 2013].

This overview of current *Dual DFAM* methods emphasized that the adopted creative approaches, do not guide to the generation of creative concepts but restrain designers to partially new concepts (a maximum of 75% of newness). We believe that to unlimit input data only to existing features could enhance the generation of creative concepts. We thus propose a creative model to be integrated in early stages of DFAM methods, to support creative concepts generation in AM. The proposed framework is described in the following section 4.

4. A creative approach for early stages of DFAM

4.1 Purpose

Creative designers use sources of inspiration as input data in order to stimulate ideas production. They gather visual and textual information to get inspiration about features that could be, by analogical or case-based reasoning, implemented in the product to be designed [Ansburg and Hill 2003], [Goldschmidt and Smolkov 2006]. In the same way, they also use precedents. By being examples of existing solutions, artifacts, graphical and textual information embody design knowledge which activates the designer's personal knowledge. Recently activated knowledge is used to generate ideas [Pasman 2003]. According to [Bonnardel and Marmèche 2005] inspirational examples can be found within the product domain (i.e *intra-domain*), in this case within mechanical design, AM processes and AM products background. They also can be found far from these domains. DFAM methods of Levels 2 and 3 showed that inspiration from intra-domain leads to partially creative concepts while Level 1 methods inspired by far-domain sources (Nature in this case) also guide to partially creative concepts. Therefore, we assume that our method must rely on associations between intra-domain examples and far-domain examples. Thus, our method intends to foster designers' creativity by crossing AM examples with other domains examples. The goal of this forced association is to extend the design space to new possible concepts. Based on this approach, we propose a framework called Creative-DFAM.

4.2 Framework of the proposed Creative-DFAM method

This 5 stages Creative-DFAM method is rooted in [Maidin et al. 2011]'s approach but with the integration of other domains examples inspiration such as in the Level 1 methods. The forced and systematic association of 2 different domains examples is inspired by the work of [Yoon and Park 2005] on morphology analysis to forecast R&D opportunities. The method can be used by both engineers and industrial designers who already have some knowledge about AM processes. It is intended to impulse R&D collaborations between designers and industrial stakeholders interested in emphasizing the use of AM in the industrial sector they work for. We specify that this framework is dedicated to AM design projects only, not to projects where the choice between AM or conventional processes is not yet done. The method starts when general design specifications are available. The framework of our Creative-DFAM method is represented in Figure 3 below. To illustrate our method, we propose an example: the generation of a creative AM concept of a turbine blade (Figure 4).

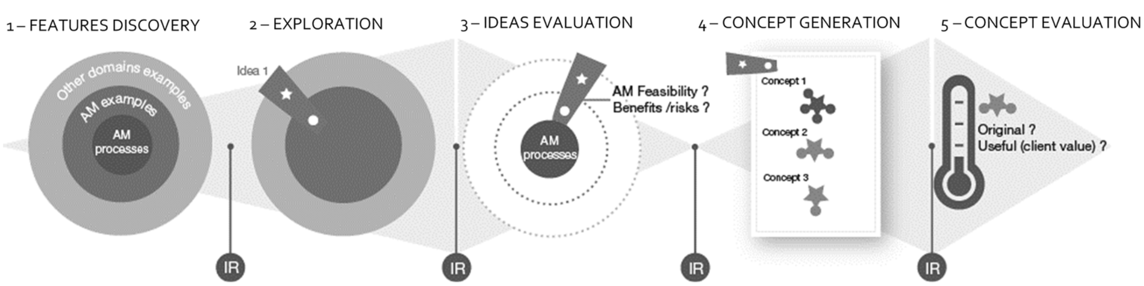

Figure 3. Framework of the proposed Creative-DFAM method

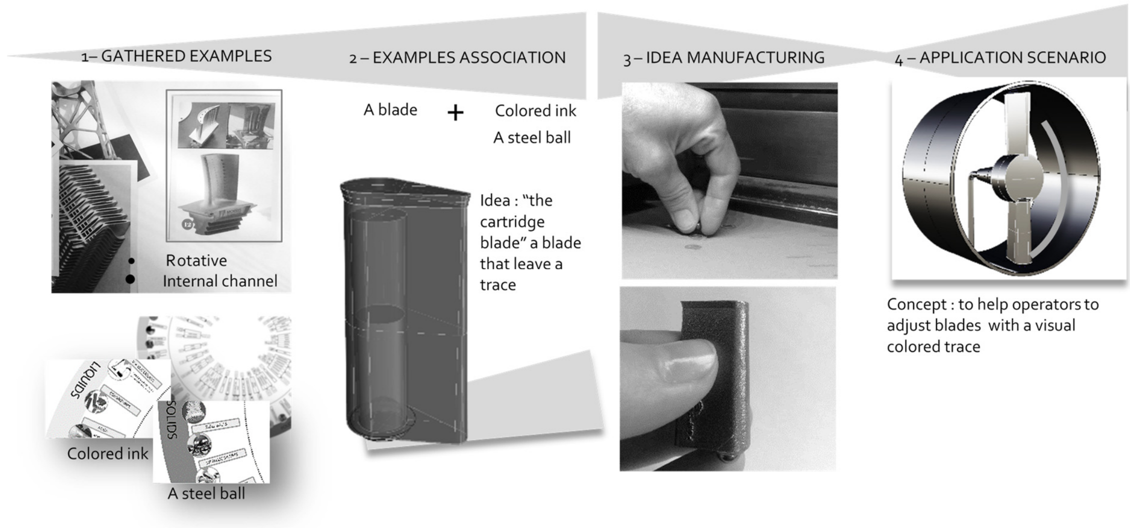

Figure 4. Example of a generation of a creative AM concept following the Creative-DFAM steps

1/ Features Discovery (Figure 3 stage 1) – The first task for R&D designers is to gather examples of AM products (i.e features already realized in AM) and other domains examples (i.e features not yet realized in AM). The examples can be represented by pictures, words or artifacts. The purpose of this stage is to have a great view of what has been done and what can still be created. The survey has to be regularly enriched to update the two taxonomies. Then, designers name the examples' features with keywords and 3D model these features in a simplified and editable manner. In the showed illustration (Figure 4 stage 1) a turbine blade is identified among others as a product already realized in AM. It is described by two keywords: ROTATIVE and INTERNAL CHANNEL. Two others domains examples COLORED INK and A STEEL BALL have been identified, among others, as not yet linked to AM. Their features are named LEAVE A TRACE and ROLL. As an output, designers form an extended portfolio of examples.

2/ Exploration (Figure 3 stage 2) – This stage consists in randomly and systematically associating an example of one wheel to an example of the other wheel. In other terms, designers conduct forced associations of AM examples with OD examples in order to generate ideas. At least one idea should be formulated for each association. For example (Figure 4 stage 2), blade's features are associated to colored ink and steel ball features to generate the idea of a blade that integrates a colored ink in its internal channel and a steel ball at the end of it in order to leave a trace when it's rolling. Similar to a cartridge the idea is called "the cartridge blade". The idea is represented by modifying the input simple 3D model. The output of this stage is a case-base of various and numerous ideas that present potential opportunities for collaborative R&D.

3/ Ideas evaluation (Figure 3 stage 3) – A first idea evaluation is conducted by AM experts. The generated ideas are faced to AM processes in order to scale the ideas at a mature level i.e they are feasible with current AM processes or an emergent level i.e potentially feasible if AM processes improve. Some associations could be evaluated as impossible due to major technical limit or technical risk. The association would be then eliminated. The proof of the ideas feasibility is established by actually additively manufacture them as shown in Figure 4 stage 3. This stage leads to a reduced portfolio of ideas embodied in artifacts.

4/ Concept generation (Figure 3 stage 4) **–** The artifacts and their manipulation stimulates analogical reasoning to translate the previous ideas into concepts which show application scenarios. As shown in our example (Figure 4 stage 4), the scenario of a "cartridge blade" used to help operators in adjusting rotative blades has been formulated. The blades should leave a constant and uniform trace on the support if they are well adjusted. This stage is conducted by designers in a co-design approach with industrial stakeholders in order to enhance the formulation of concepts with a high client value. This stage output is a base of concepts sheets describing potential products to be developed for industrial sectors.

5/ Concept evaluation (Figure 3 stage 5) – The purpose is to identify the concepts to be further detailed and optimized in downstream DFAM stages. The required profiles for the evaluation are experts of AM who have a good understanding of industrial sectors where AM is integrated, such as innovation managers, senior designers and trade engineers for example. They are asked to say how much the generated concepts are: 1/ Original (in the sense of new) regarding traditional products of the involved industrial sector and regarding AM industry, 2/ Useful regarding the involved industrial sector (client value), 3/ Realistic regarding AM capacities. For example, the "cartridge blade" is considered new since it integrates new functions and forms, and since the associated features have not been already realized in AM industry.

Table 2. Originality evaluation of the generated concept "Cartridge blade"

New what	Functions (25%)	O
	Forms (25%)	O
New to	AM industry (25%)	O
	Conventional industry (25%)	O
Level of newness of the concept		100%

5. Discussion

The proposed Creative-DFAM method is intended to increase the number of generated ideas. Indeed, as shown in the example, one forced association suggests at least one idea. As the forced associations are systematic, the method support designers in not neglecting some conceptual possibilities. Forced associations also help designers to generate creative concepts without limiting themselves or prematurely eliminating some ideas. In our example, the forced association suggests the inclusion of colored ink in an AM product. As not yet been realized in AM, this concept raises several design questions. But instead of eliminating the idea, designers are invited by the method to explore it. The generated result is an original concept, as an AM part that includes colored ink as not yet been realized in AM. Even if this method is here just illustrated with an example, it opens a prospect on the role of a creative method and tool in AM product innovation.

6. Conclusion and future work

Although creative design is a well-known approach for product innovation, only a few DFAM methods integrate one, and only partially, while AM is said to have an important product innovation potential. The purpose of this article was first to understand how creative approaches are taken into account in current DFAM methods. We propose a 3 levels classification of current *Dual DFAM* methods and a comparison of the generated concepts'qualities. The classification highlights that the existing creative approaches in *Dual DFAM* condition innovation's opportunities to already known features without supporting the search for new concepts. The cited methods don't lead to creative concepts. We thus proposed a framework called Creative-DFAM to support designers in early design stages, for the exploration and generation of new concepts in AM. It guides designers through 5 steps in order to generate creative concepts which exploit the unique AM capabilities. We illustrate the framework with an example. This study is part of a doctoral thesis, it is expected to be further evaluated through field experiments with industrial partners. As capabilities of AM are rapidly spreading and companies' needs to integrate and exploit them, this framework leads to the development of a creativity toolkit to support the practice of innovation teams in industrial companies. The use of the toolkit in industrial companies will allow to evaluate the relevance of the framework.

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