Science Arts & Métiers (SAM)
is an open access repository that collects the work of Arts et Métiers Institute of Technology researchers and makes it freely available over the web where possible.

This is an author-deposited version published in: https://sam.ensam.eu
Handle ID: .http://hdl.handle.net/10985/10380

To cite this version :

Floriane LAVERNE, Nabil ANWER, Marc LE COQ, Frederic SEGONDS - Assembly Based Methods to Support Product Innovation in Design for Additive Manufacturing: An Exploratory Case Study - Journal of Mechanical Design - Vol. 137, n°12, p.8 - 2015

Any correspondence concerning this service should be sent to the repository Administrator : scienceouverte@ensam.eu

Assembly Based Methods to Support Product Innovation in Design for Additive Manufacturing: An Exploratory Case Study

Additive manufacturing (AM) is emerging as an important manufacturing process and a key technology for enabling innovative product development. Design for additive manu-facturing (DFAM) is nowadays a major challenge to exploit properly the potential of AM in product innovation and product manufacturing. However, in recent years, several DFAM methods have been developed with various design purposes. In this paper, we first present a state-of-the-art overview of the existing DFAM methods, then we introduce a classification of DFAM methods based on intermediate representations (IRs) and prod-uct's systemic level, and we make a comparison focused on the prospects for product innovation. Furthermore, we present an assembly based DFAM method using AM knowl-edge during the idea generation process in order to develop innovative architectures. A case study demonstrates the relevance of such approach. The main contribution of this paper is an early DFAM method consisting of four stages as follows: choice and develop-ment of (1) concepts, (2) working principles, (3) working structures, and (4) synthesis and conversion of the data in design features. This method will help designers to improve their design features, by taking into account the constraints of AM in the early stages.

Floriane Laverne
LCPI—Laboratoire de Conception de Produits et Innovation,
Ecole Nationale Supérieure d'Arts et Métiers,
151 bd de l'Hôpital,
Paris 75013, France
e-mail: floriane.laverne@ensam.eu

Frédéric Segonds
LCPI—Laboratoire de Conception de Produits et Innovation,
Ecole Nationale Supérieure d'Arts et Métiers,
151 bd de l'Hôpital,
Paris 75013, France
e-mail: frederic.segonds@ensam.eu

Nabil Anwer
LURPA—Laboratoire Universitaire de Recherche en Production Automatisée,
Ecole Normale Supérieure de Cachan,
61 av du Président Wilson,
Cachan Cedex 94235, France
e-mail: anwer@lurpa.ens-cachan.fr

Marc Le Coq
LCPI—Laboratoire de Conception de Produits et Innovation,
Ecole Nationale Supérieure d'Arts et Métiers,
151 bd de l'Hôpital,
Paris 75013, France
e-mail: marc.lecoq@ensam.eu

1 Introduction

As it is often confused with invention, innovation remains a difficult concept to define. Perrin [1] provided a complete definition based on three axioms:

— "No innovation without market validation." Innovation is the first commercial use of a product, process, or service that has never been used before [2,3].
— "No innovation without design stages": the design process must be the backbone of the innovation process.
— "No innovation without innovative companies." Innovation is an essential boost for companies to survive or to grow in a globalized and increasingly competitive economy.

However, among the different categories of innovation, technological innovation [4], which relates both to the process and the products, is an important driver of innovation for the industry. According to Teece [5], a process innovation results in a product innovation, i.e., the development of a product with improved performance to provide the consumer new or enhanced services.

The emergence in 1986 of an innovative manufacturing process called stereolithography and its commercialization in 1988 launched the industrial era of AM. As a technological innovation, AM upsets manufacturing practices because it allows making objects "from 3D model data, layer upon layer, as opposed to traditional manufacturing technologies," such as subtractive and formative manufacturing [6]. Due to an increased accuracy of the machines, a wider range of materials and mechanical properties similar to other manufacturing technologies, AM evolved over the years from rapid prototyping to direct manufacturing, i.e., achieving fully functional and ready to use products. AM is now mature enough to become a new standard for product manufacturing that enables product innovation at different levels [7]: incremental and radical. Indeed, it provides various opportunities, such as decreasing tool costs, increasing product's function and internal structural patterns, customized manufacturing, and production of complex shapes with multiple materials [8–10].

According to the second axiom of Perrin, product innovation is based on the design process. Among the existing design methodologies, systematic approaches are well known and widely used in the industry [11]. These methodologies divide the design process into successive stages. Pahl and Beitz [12] defined four stages: task clarification, conceptual design, embodiment design, and detail design. However, few studies focus on the breakthrough of AM into this design process [13,14] and designers do not include the AM approach in their practices. DFAM is a new developing area that impacts significantly the relationship between design and manufacturing processes. The challenges of DFAM go beyond the need to have design rules in AM. There are also new issues for the design process and product innovation stemming from the adoption of AM technologies.

The main contribution of this paper is an early DFAM method consisting of four stages that will help designers to better define the design feature, by taking into account the constraints of AM in the early stages. The outline of this paper is organized as follows: Section 2 is devoted to design for X (DFX) principles, the fundamentals of DFAM, and the classification of DFAM methods based on systemic level of product description. In Sec. 3, the DFAM categories resulting from this classification are analyzed and compared according to their ability to lead to product innovation.

Contributed by the Design for Manufacturing Committee of ASME for publication in the Journal of Mechanical Design. Manuscript received February 14, 2015; final manuscript received September 1, 2015; published online October 16, 2015. Assoc. Editor: David Rosen.

Finally, Sec. 4 defines a new DFAM method to fill in current gaps regarding radical innovation. An exploratory case study is conducted to illustrate and validate the proposed method.

2 From DFX to DFAM

2.1 DFX. Nowadays, the requirements of a product throughout its lifecycle need to be integrated by designers as early as possible: the impacted stages are named "early design stages." In a fast-changing marketplace, innovation must coexist with increasing product complexity, cost cutting, and decrease in time to market. Indeed, decisions made during those early stages determine more than 80% of the lifecycle cost even though only 10% of the expenses are incurred at this stage [15–17]. Therefore, it is crucial to provide the designers with methods and tools to take into account all the business constraints and integrated within the eco-informational and human system deployed in the companies (known as product lifecycle management systems or PLM [18,19]). This approach is called DFX [11,20] and is intended to explicit all the required knowledge of the product, process, and material in the early design. However, implementing a DFX implies the management of knowledge as well as the management of various product abstractions called IR [21,22] and the use of tools for integration of design constraints [23]. This is possible in the PLM environment where all relevant data are stored and accessible via product data management systems [18,19]. The expected contribution of DFX on product design is to improve competitiveness (quality, time to market, etc.), to rationalize decisions, and to increase the operational efficiency of the designers. Therefore, similarly to design for assembly and design for manufacturing, Bourell et al. [24] recommend the development of new design methods dedicated to AM paradigm, called DFAM.

2.2 Fundamentals of DFAM. DFAM is a set of methods and tools that help designers take into account the specificities of AM (technological, geometrical, etc.) during the design stage. 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" [12]. These two categories are DFAM for design making and DFAM for design assessment.

DFAM methods for design making are intended to guide designers during the design process. They lead to the development of IRs [25–28] and mainly consist in guidelines [29] or design features [30]. DFAM methods for design assessment deploy acceptability criteria (cost, time, manufacturability, etc.) to evaluate IR created during the design making stage [31–38]. 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 important design stages, i.e., the early stages.

To refine this classification, we conducted a study on 27 peer-reviewed publications related to DFAM for decision making [8,9,13,25–30,39–56]. Three different ways to assist designers were identified. We propose to name these methods opportunistic DFAM, restrictive DFAM, and dual DFAM [57]. Figure 1 (right) shows their distribution within these 27 references.

Opportunistic DFAM methods are useful to help designers explore the geometric and/or material complexity offered by AM. Their goal is to propose new shapes or new concepts with a creative approach based on the following premise [8,40]: in AM, there is no limit on feasible shapes and on materials distribution. We classify in this category methods based on optimization techniques (parametric and topological) [25,26], those using elementary shapes like lattices structures [41], cellular structures [39], or bionic structures [28] and those defining design features produced by specific AM technologies [30].

Restrictive DFAM methods aim to take into account the limits of AM, such as usable materials and their properties [45,51,54], the performance and characteristics of AM machines [53], or product manufacturability [42]. They seek a convergence between the nominal geometric model corresponding to an ideal representation of IR, i.e., one without defects; and the skin model [58] including the expected or predicted geometric variations due to the manufacturing process and thus corresponding to a realistic representation of the IRs.

Finally, dual DFAM refers to methods that combine the two approaches described above. We believe that these methods which focus on product innovation are more suitable for designers. Indeed, they use the potential of AM in a realistic way. However, despite their significance for innovation, dual DFAM methods only account for 30% of existing DFAM methods.

This classification based on the designers' findings when using DFAM method and summarized in Fig. 1 (left) do not take into consideration the key element for innovation: the "product."

A product can be defined as a technical artifact, tangible, countable, whose ownership can be transferred [12,59]. But according to Savransky [60], a product "participates in technological processes in order to satisfy the needs of human beings or another technical system." From this definition, it appears necessary to analyze different types of products. Thus, we consider the definition of Henderson and Clark [61], who established a "distinction between the product as a whole—the system—and the product in its parts—the components—"We therefore accept that:

— A component, also called a part, is a basic element of a product that "embodies a core design concept" [61].
— An assembly or system is a set of components. It "possesses behaviors and properties that cannot be reduced to the behaviors and properties of its separate subsystems" [60].

Based on these findings, we studied dual DFAM according to the systemic level targeted for a product: component and assembly. Among these two categories, we emphasized that methods proposed for the design of assemblies (assembly based DFAM or A-DFAM) are less developed than those for the design of components (component-based DFAM or C-DFAM): 12% A-DFAM and 88% C-DFAM in the examined publications. In Sec. 3, we successively study C-DFAM and A-DFAM and then we highlight their implications on product innovation.

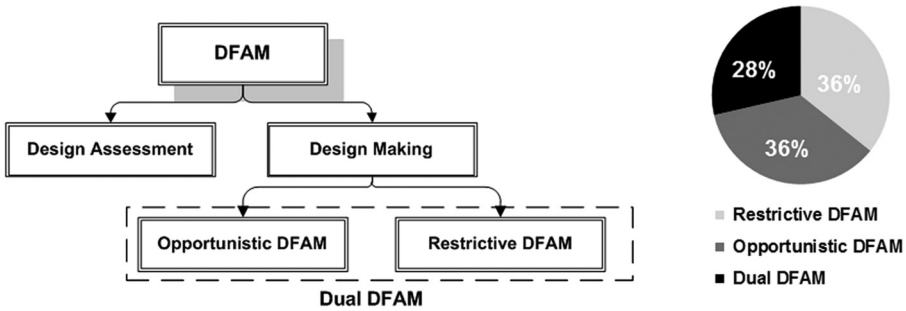

Fig. 1 Synthesis and distribution of the DFAM practices

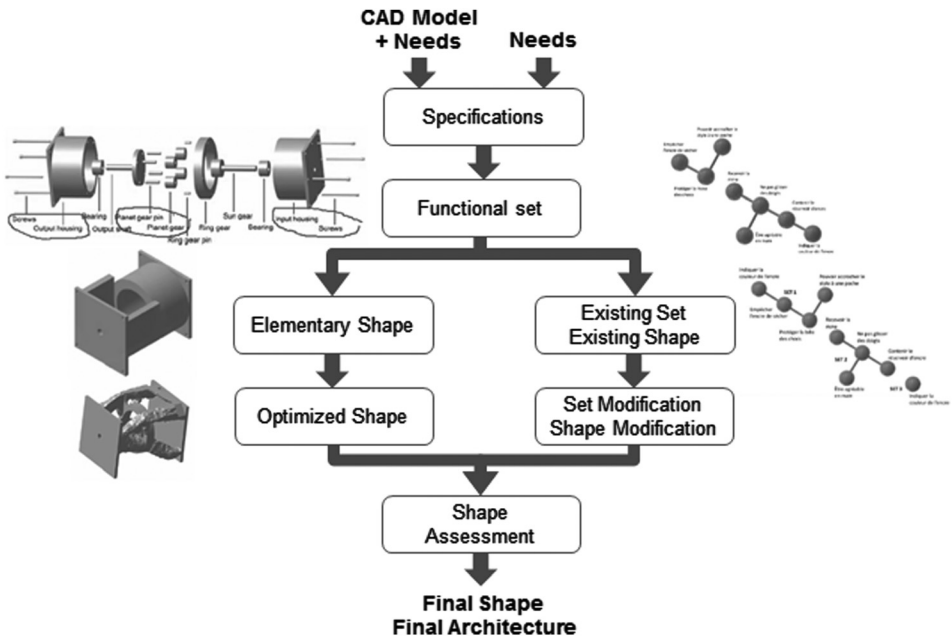

Fig. 2 Workflow of A-DFAM, adapted from Refs. [47] and [48]

3 Dual DFAM: Principles and Impact on Product Innovation

3.1 C-DFAM. The purpose of C-DFAM is the design of components which are suitable and optimized for AM. As shown in Fig. 2, C-DFAM can be categorized into two classes based on their input data.

In the first class of C-DFAM (Fig. 2, left), input data refer to all the functional features and the assembly constraints of an existing component. These features are obtained from specifications established beforehand and combined to define the design area. From these input data, the methods proposed by Ponche et al. [50] or Vayre et al. [13] seek to help designers overcome psychological barriers [60] related to their usual approach. To create an initial shape, the authors suggest the use of feature-based modeling with the concepts of "skin" and "skeleton" [62] or a topological optimization of the specifications in the design area. A manufacturing direction is also determined according to the key attributes of the machine. Moreover, Vayre et al. [13] recommended the generation of a "dimensionless" shape. This means that this elementary shape is intended to provide a preliminary topology of the IR. An opportunistic approach is then used to adapt the initial shape. It mainly deploys a topological optimization and sometimes a parametric optimization. The result is an optimized and dimensioned shape that satisfies product and process constraints. A new restrictive stage enables to turn the shape into a manufacturable shape. It involves geometric changes related to the planned manufacturing strategy and is achieved through a multiphysics process modeling [50], the integration of postprocessing tasks (removal of supports, polishing), and the estimation of the manufacturing costs [13]. A final test is performed to check whether the final IR fulfills the performance stated by the specification or not.

The other class of C-DFAM (Fig. 2, right) differs in the required input data and in their processing methods during the creation of the initial shape. The starting point is a geometric model (i.e., a computer-aided design (CAD) model) rather than a feature-based model of the component [9,27,56]. The opportunity stage relies on the choice of a parametric lattice structure deployed in the CAD model. The new shape is then optimized to validate the size and distribution of the truss structure and to ensure compliance with the product constraints. The IR created with this restrictive stage is validated by using finite-element analysis. Then, similarly to previous C-DFAM methods, the optimized shape is faced with the manufacturing constraints of the AM processes. The dimensions of each elementary structure are compared with the minimum built size requirements, leading to adapt the shape to make it more realistic. Finally, the IR is validated according to initial requirements.

3.2 A-DFAM. A-DFAM methods are devoted to assemblies, i.e., set of components. Even for A-DFAM, two different approaches are developed.

The first approach (Fig. 3, left) aims to consolidate an existing assembly, i.e., to reduce the number of its components. Methods provided by Vitse et al. [48] and Rodrigue and Rivette [49] can be summarized into five steps. First, designers have to define new specifications from current product features and additional targeted features. Once the specifications are established, functions are gathered into functional sets. Suitable groupings are identified through flow-force diagrams [63], failure modes and effects analysis (FMEA) [49], or analysis of incompatibilities between selected

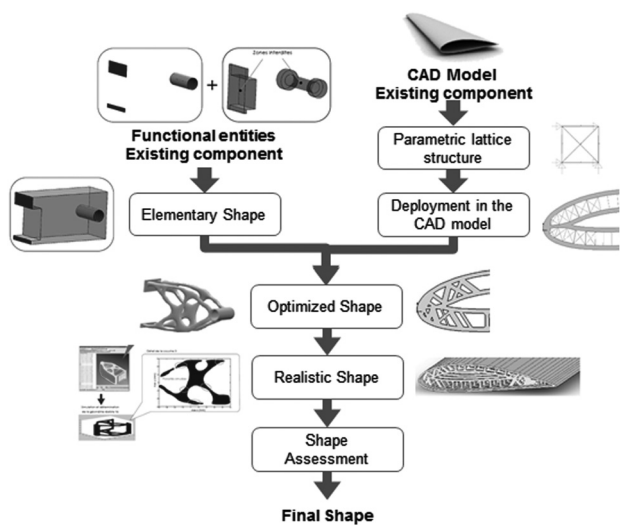

Fig. 3 Workflow of C-DFAM, adapted from Refs. [64] and [56]

materials and loads to be applied to the product [48]. This stage is also used to define a working structure through a product layout and to set the specifications of the components associated to each geometrical set. Then, the design of each component is performed. In the same way as in C-DFAM, an initial shape is first defined for each functional set. Then, the shape is improved by using topological optimization methods [48] or failure prevention tools [49]. Finally, the shape is validated according to economic and manufacturing criteria.

An alternative approach can be illustrated by the method developed by Boyard et al. [47] (Fig. 3, right). Its objectives are both the design of new products and the redesign of existing ones. Indeed, the single source of input data are customer needs. The first two steps are similar to the previous approach: drafting of the product specifications and search of functional groups in sets. At this step, the designer is able to determine different product architectures, i.e., the "arrangement of functional elements, the mapping from functional elements to physical components, and the specification of the interfaces among interacting physical components" [65,66].To assign a geometry to each functional set, authors use case-based reasoning and identify similar sets in a database. For each functional set, CAD models are associated and their spatial configurations can be modified according to requirements. The working structure and the product layout are defined by the whole sets while reusing or adapting the geometry so that an initial shape is created. Changes made on the components and on the layout depend on process, assembly, material, and manufacturing constraints. This may involve iterations on the CAD model. Finally, a design validation related to the assemblability of the components is performed.

3.3 Limits of Current Methodologies for Product Innovation. Beyond our classification, we emphasize that attention for the early design stages depends on the purpose of the DFAM method employed. C-DFAM relies on an approach that leads to a new and accurate shape of the manufactured component. However, functional analysis and technical requirement stages are not included within the framework of these methods. The achievement of an initial component shape and its improvement for manufacturability are the main concerns while A-DFAM methods focus on the preliminary stages (from the analysis of requirements to the proposal of a working structure) and do not ensure manufacturability. Hence, the challenge is to take into account the advantages provided by AM in order to develop new products at both the assembly and component levels (more specifically at the geometric level). Indeed, studying a product as a system involves to foster in its architecture [65].

The opportunities provided by dual DFAM approach in radical product innovation cannot be explored since AM techno-push innovation is partially used. C-DFAM assumes that multiview analysis, which was previously performed, resulting in the clarification of specifications, is a reliable method. It means that these methods focus on component redesign since the input data are not questioned. However, the models and specifications on which they are based are mainly performed using traditional approaches. We believe that keeping the working principles unchanged in C-DFAM methods does not lead to a radical innovation at a system level but only to a sum of components incremental innovations. This raises the following research questions: Can AM innovation be reduced to a component level innovation? Should the functional entities that determine initial shape be questioned and redefined in order to upset the assembly innovation, or should they not? We argue that the existing working principles must be reconsidered especially when constraints on components are various and too restrictive to easily use the geometric freedom of AM. Indeed, working principles underline the arrangement of the components and consequently they condition the innovation's opportunities. Moreover, even if the search of new product architectures is central in A-DFAM, current methods are more dedicated to architectural innovation, where "the core design concept behind each component remains the same" [61], than to radical innovation. Indeed, despite they force designers to rethink their technical requirements, they restrain innovation at a low level because the initial shape of the created components depends on:

— A product layout that designer tries to consolidate and in which the functions gathered specifically those not related to AM is never questioned. Product innovation also seems to be a reconfiguration of the existing system.
— A selection of working structures based on analogical reasoning also reuses existing product without proposing new solutions.

The effective use of AM in radical innovation has to go through the establishment of a "new dominant design and, hence, a new set of core design concepts embodied in components that are linked together in a new architecture" [61]. Furthermore, current A-DFAM methods only study the static aspects of a product and have little consideration about kinematics or dynamics of the components. It also refutes the definition of a system. Yet, one of the major assets of AM is to allow manufacturing of parts that are already assembled, ready to use, and to work. Taking into account kinematics and dynamics should allow the exploration of new functions, new product working structures, and could enable radical innovation.

Finally, we emphasize the role of assessment. Regardless of the systemic level that is considered, assessment of the product architecture often occurs too late in the design process: it is performed when each component design is frozen. Thus, the consequences on costs and lead-time if modifications on architecture are needed can quickly become prohibitive.

All these findings lead us to consider a new A-DFAM method intended to overcome the limitations mentioned above. In Sec. 4, the purpose of this new A-DFAM is detailed and a case study dedicated to the validation of the first stage of this methodology is presented.

4 Early A-DFAM (eA-DFAM)

4.1 Purpose. C-DFAM methods use the potential of AM to design innovative parts and ensure their manufacturability but let the product architecture unchanged. Meanwhile, current A-DFAM methods allow simplification of the working structures of existing products and the design of individual components but they are not efficient because the manufacturability assessment is not taken into account. In a radical innovation context for product, the scope of A-DFAM methods seems too large. Thus, we have developed a methodology called eA-DFAM, focused on the preliminary stages, and intended to foster designers' creativity on AM optimized working structures (Fig. 4). This eA-DFAM starts when product requirements are available and enabling to convert the working structures in design entities suitable for the C-DFAM methods. Howard et al. [67] demonstrated that conceptual design results in creative design outputs, i.e., a "design output containing at least one creative output at the systems' level under study." Therefore, we assume that our methodology must rely on a creative approach in order to develop innovative working structures. Indeed logical methods "involve the use of past solutions" or "develop ideas […] by systematically analyzing basic relations, causal chains, and desirable/undesirable attributes" [68] but current background in AM is not sufficient to provide a robust approach with these methods.

4.2 Case Study. The developed case study focuses on the idea generation stage of the eA-DFAM (gray area in Fig. 5). Its aim is the proposal of innovative solutions for designing an educational robot for high school (i.e., an assembly). We analyzed the contribution of AM knowledge given, in the eA-DFAM when considering a design group during the convergent stage of their

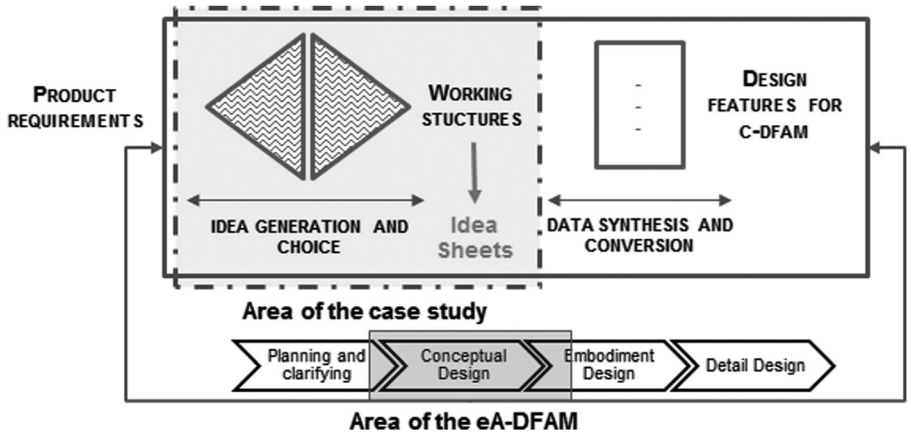

Fig. 4 Details of the eA-DFAM method and position of the case study

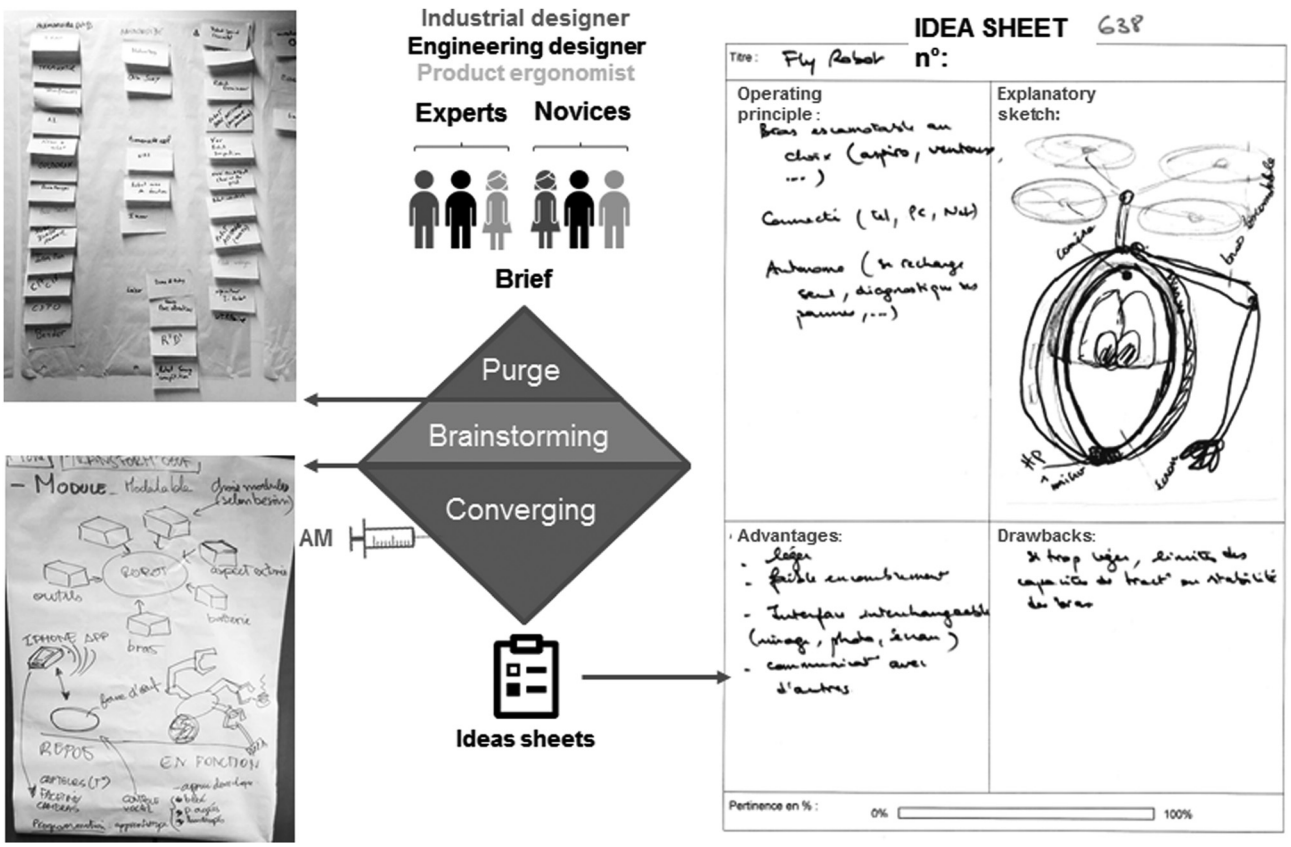

Fig. 5 Protocol and productions of the case study

creative work; with a particular interest in the originality and manufacturability of the developed solutions.

4.2.1 Population. Pahl and Beitz [12] underlined the significance of multidisciplinary work in early design stages in order to enable innovative products. At these stages, "engineering science, practical knowledge, production, and commercial aspects need to be brought together" [69]. Thus, to comply with this requirement, we introduce three different key skills of the innovation process: engineering design, industrial design, and product ergonomics [70]. Ergonomists provide their skills about the products use because nowadays designing a nice and technically efficient product is not sufficient. These profiles are also key profile for product design. Each of the three groups is composed of six members, in adequacy with Curral et al. [71] and Moreland et al. [72]. The independent variable in this case study is the group's knowledge in AM:

— Group 1 is a control group. No member knows AM.
— In group 2, none of the members has knowledge of AM. Yet during the experiment, technical memos that describe advantages (material, shapes, etc.) and drawbacks (staircase effect, dimensions, etc.) of AM are given to each member. Moreover, technical objects are distributed to illustrate notions presented in the memos.
— Group 3 has knowledge of AM through the expert skills of three members.

Furthermore, in order to avoid differences during the experiment, all groups are equivalent with four males and two females, two members in each skill: one expert and one novice.

Due to the diversity of the participants' profiles, 18 professionals participated in the experimentation. This rather small sample represents the main limitation of this case study. We think that, in spite of this, the early DFAM method we posit is of scientific interest and provides scientific orientations for further studies.

4.2.2 Protocol. The experiment lasted 3 hrs for each group and was divided into three stages. Figure 5 summarizes the protocol and the main results of this case study.

First, the workshop started with a 10-min oral brief and a presentation. The context of the study, the requirements, the session rules [73], and the expected deliverables were defined.

Then groups started the ideas generation process with a purge (20 min) introduced by the two following questions: "What robots do you know? Can you rank your answers in specific categories?" The objective is to list the group's ideas on the topic and to release the participants from their preconceived ideas. Once the purge is completed and the families of robots are listed, began a brainstorming session (40 min) based on biologically inspired reasoning [74], i.e., an analogical reasoning in order to enable group members to offer many ideas. Participants had to justify their proposal by associating an attribute, a function, a shape, or a use to an interesting working principle for their robot. The stage ended with a 10-min selection of functional or physical principles consistent with the requirements, followed by a 10-min break.

The last stage lasted 1.5 hrs and involved convergent thinking work. Before starting, designers were asked to ensure that their concepts would be manufacturable. To facilitate the work, a list of stimulus words was distributed. Studies have shown their deep impact on the evocation process of participants having more or less of expertise in design [75]. Finally, the use of AM knowledge was specified verbally after 45 min in order to influence the inspirational process when formalizing the ideas [75,76]. Memos and objects were distributed to provide a support of AM knowledge to group 2.

At the end of the stage, members were invited to describe their solutions on idea sheets (ISs) which are IRs of the product at the end of this workshop. These ISs are intended to explicit the ideas developed during the divergent stage, especially through sketching.

ISs use the following structured template:

— A short text explains the operating principle of the concept and describes the functionality, materials, or texture required for their concept.
— Sketches show the spatial arrangement of the working principles and illustrate the proposed concept.
— Advantages and drawbacks of the solution are listed.

An example of IS is provided on Fig. 5 (right) with these three main parts rounded. We can note that sketching is an important part of this early design delivery. Indeed, sketching is an important part of design (practice and education) and there has been a large amount of research investigations on the sketching activity by designers [76]. As Schon [77] defines it, design can be seen as a "reflective conversation" based on a generation-visualization loop, made possible by the production of handmade drawings.

Finally, at the end of this empirical study, participants were asked to fill in a survey on their individual performance during the session.

4.2.3 Evaluation. The case study outputs are numerous (317 ideas and 36 ISs were generated), which is necessary in innovation phases. First, ideas proposed during the divergent stage and ISs produced during the convergent stage were counted for each group. Then, all the ISs were formatted and anonymized by a same person. To identify whether, after a divergent stage, the contribution of AM knowledge can significantly impact the created IRs, all the ISs were evaluated by six experts whose skills were in product innovation or product manufacturing (traditional and additive). Each IS was analyzed with qualitative criteria:

— Adequacy with initial requirements was measured on a binary scale: 1 means that the concept fulfilled the objectives, 0 that it did not.
— Technical feasibility and originality of the concepts were assessed using a Likert scale with five levels: 1 means a very bad result and 5 an excellent one.

Table 1 presents a summary of the quantitative results and qualitative evaluation of this case study.

4.3 Results and Discussion. The first result of our case study is that during the divergent thinking stage, groups 1 and 2 proposed more ideas and more unique ideas than group 3 (uniqueness is defined using the statistical rarity). Consequently, they provide a higher number of ISs. AM knowledge in the experimental conditions also does not affect the quantity of ISs in a group.

The second result deals with originality of the ISs developed by groups with AM knowledge. More ISs were assessed as original (i.e., with a mean grade above 3) than those offered by the control group (48% and 50% against 22%). In this study, setting up creativity groups who have knowledge in AM fosters the originality of the ISs when AM is specified as an explicit research track. Indeed, evaluators found that the ISs of these groups sketched and described concepts with more functionalities and with textures and materials in line with the AM possibilities. It also corroborates the findings of Bin Maidin et al. [30], who demonstrated that their AM feature database was "inspirational, useful, relevant, and helpful to support the conceptual design of parts and products." However, the analysis of the individual surveys shows that 10 out of 18 participants perceived the requirement for using AM during the convergence phase as a barrier more than as a facilitator when they had to produce ISs.

Another result is that fewer ISs developed by groups with AM knowledge were assessed as manufacturable, i.e., with a mean mark above 3 (17% and 38% against 44%). For this case study, knowledge in AM restriction also does not foster the manufacturability when AM is specified as an explicit research track.

While this study was performed on a rather small panel, these results bring us a first prospect, highlighting the significance of AM knowledge during the idea generation process. It also helps us to refine our eA-DFAM because the contribution of AM knowledge without distinction between restrictions and opportunities is

Table 1 Analysis of the ideas sheets

		Group		
		G1 (AM novices)	G2 (AM novices + memos)	G3 (AM experts)
Divergent stage	Number of ideas	113	122	82
	Number of unique ideas (ratio)	47/113 (42%)	49/122 (40%)	26/82 (32%)
Convergent stage	Total of ISs	9	21	6
	ISs meeting initial requirements	7/9 (78%)	12/21 (57%)	4/6 (67%)
	ISs judged as original (mean mark > 3)	2/9 (22%)	10/21 (48%)	3/6 (50%)
	ISs judged as manufacturable (mean mark > 3)	4/9 (44%)	8/21 (38%)	1/6 (17%)
	ISs consistent with all assessment criteria	1/9 (11%)	2/21 (9%)	0/6 (0%)

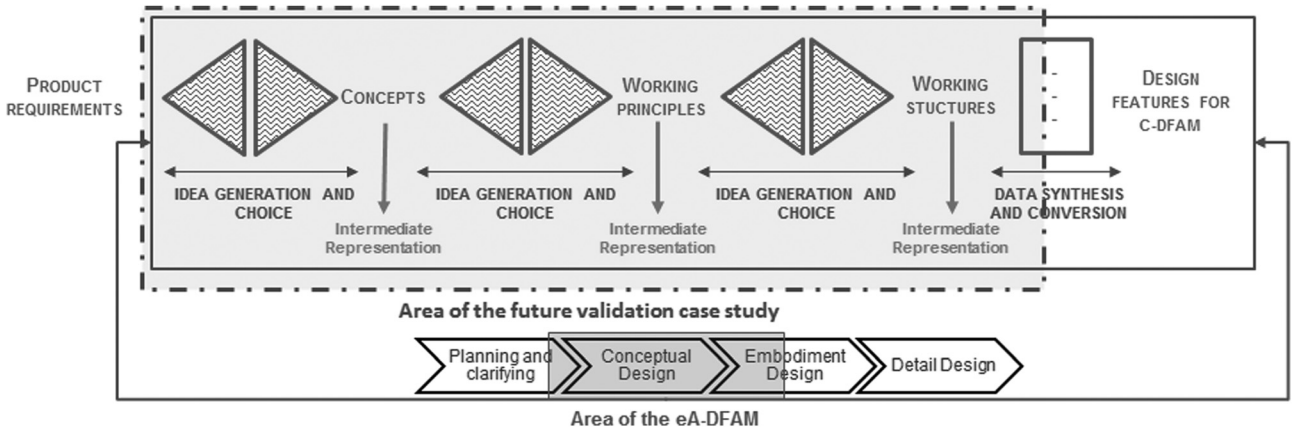

Fig. 6 Proposal of optimized eA-DFAM

not relevant during a creativity session. Indeed, even if less concepts are developed with AM knowledge, they are considered as more original but less manufacturable than the others. We cannot efficiently identify which data among the whole AM knowledge is actually used by designers and for which reason.

4.4 Future Work. Although our preliminary study covers a unique scenario, we notice that limits exist in the current sequencing of our eA-DFAM methodology. Giving designers a global knowledge in AM is not suitable for single creative stage: too much information is given at once to the designers. Consequently, we are not able to specify what AM knowledge was used or which one could have been used to imagine original or manufacturable working structures, i.e., original or manufacturable IRs on ISs.

To provide designers with the right AM knowledge at the right time, we decide to split the creative stage of the eA-DFAM into several stages. This approach is validated by Mann and Dewulf [78], who declared that "there is currently no single creativity entity that will satisfy every individual desire." This new proposed sequencing relies on three successive creative stages using cognitive processes and dedicated to the creation of three different IR: concepts, working principles, and working structures (Fig. 6). For each stage, a specific AM knowledge rather than an overall one must be delivered. We posit that this AM knowledge can be used in the convergent or divergent activities and may influence more strongly the produced IR.

The validation of this sequencing is currently carried out using individual semidirected interviews conducted with key actors of the early design stages (engineering designers, industrial designers, and ergonomists). To do this, participants are introduced beforehand to the taxonomy of IR developed by Pei et al. [22] and to the sequencing of the methodology. They are asked to prepare a data set related to a representative project of their work as an early designer. During the interview, each participant has to:

— describe the activities, reasoning, and tools he uses
— specify the criteria he has adopted for selecting the ideas to develop
— indicate when manufacturability and assemblability are evaluated and with what criteria

At the end of this experiment, we will be able to correctly identify the needs in AM knowledge in the early design process. Then, we will have all the relevant data to test and validate this eA-DFAM in an experiment based on a higher number of groups.

5 Conclusion

In this paper, we have analyzed several DFAM methods and proposed a classification depending on the type of aid they provide to the designer during the design making or design assessment phases. Then, we highlighted that, among DFAM for decision making, two major directions stand out: using of opportunities allowed by AM or integrating the restriction inherent in AM. We emphasized that in an innovation context, dual DFAM methods are the most suitable and that they are linked to a systemic level of product description. We developed new approaches C-DFAM and A-DFAM intended to apply to components and assemblies and we demonstrated that product innovation prospects essentially remain on the redesign area, i.e., incremental innovation. The main contribution of this paper is a new A-DFAM method focused on early design stages, named eA-DFAM, first tested in a small sample size case study. We show that AM knowledge can impact a creative session. But this knowledge was not sufficiently adapted to the designers needs and also poorly exploited. We have therefore proposed a second eA-DFAM method to overcome these shortcomings, consisting of four stages as follows: choice and development of: (1) concepts, (2) working principles, (3) working structures; and (4) synthesis and conversion of the data in design features. AM knowledge suitable for each stage of this method is currently collected with professional interviews and will be used for a future validation.

References

[1] Perrin, J., 2001, *Concevoir L'innovation Industrielle: Méthodologie de Conception de L'innovation*, CNRS, Paris.
[2] Kelly, P., and Kranzberg, M., 1978, *Technological Innovation: A Critical Review of Current Knowledge*, San Francisco Press, San Francisco, CA.
[3] Schmitt, L., Buisine, S., Chaboissier, J., Aoussat, A., and Vernier, F., 2012, "Dynamic Tabletop Interfaces for Increasing Creativity," Comput. Hum. Behav., **28**(5), pp. 1892–1901.
[4] Tödtling, F., Lehner, P., and Kaufmann, A., 2009, "Do Different Types of Innovation Rely on Specific Kinds of Knowledge Interactions?" Technovation, **29**(1), pp. 59–71.
[5] Teece, D. J., 1986, "Profiting From Technological Innovation: Implications for Integration, Collaboration, Licensing and Public Policy," Res. Policy, **15**(6), pp. 285–305.
[6] ASTM, 2012, "Standard Terminology for Additive Manufacturing Technologies," ASTM F2792-12a.
[7] Culverhouse, P. F., 1995, "Constraining Designers and Their CAD Tools," Des. Stud., **16**(1), pp. 81–101.
[8] Hague, R., Campbell, I., and Dickens, P., 2003, "Implications on Design of Rapid Manufacturing," J. Mech. Eng. Sci., **217**(1), pp. 25–30.
[9] Rosen, D. W., 2007, "Computer-Aided Design for Additive Manufacturing of Cellular Structures," Comput. Aided Des. Appl., **4**(5), pp. 585–594.
[10] Gibson, I., Rosen, D. R., and Stucker, B., 2010, *Additive Manufacturing Technologies*, Springer US, New York.
[11] Tomiyama, T., Gu, P., Jin, Y., Lutters, D., Kind, C., and Kimura, F., 2009, "Design Methodologies: Industrial and Educational Applications," CIRP Ann. Manuf. Technol., **58**(2), pp. 543–565.
[12] Pahl, G., and Beitz, W., 2007, *Engineering Design—A Systematic Approach*, 3rd ed., Springer, London, UK.
[13] Vayre, B., Vignat, F., and Villeneuve, F., 2012, "Designing for Additive Manufacturing," CIRP Conference on Manufacturing Systems, pp. 632–637.
[14] Yang, S., and Zhao, Y., 2015, "Additive Manufacturing-Enabled Design Theory and Methodology: A Critical Review," Int. J. Adv. Manuf. Technol., **80**(1), pp. 327–342.

[15] Ullman, D. G., and Jones, E. A., 2003, *The Mechanical Design Process*, McGraw-Hill Higher Education, New York.
[16] Ishii, K., 1995, "Life-Cycle Engineering Design," ASME J. Vib. Acoust., **117**(B), pp. 42–47.
[17] Wang, L., Shen, W., Xie, H., Neelamkavil, J., and Pardasani, A., 2002, "Collaborative Conceptual Design: State of the Art and Future Trends," Comput. Aided Des., **34**(13), pp. 981–996.
[18] Garetti, M., Terzi, S., Bertacci, N., and Brianza, M., 2005, "Organisational Change and Knowledge Management in PLM Implementation," Int. J. Prod. Lifecycle Manage., **1**(1), pp. 43–51.
[19] Sharma, A., 2005, "Collaborative Product Innovation: Integrating Elements of CPI Via PLM Framework," Comput. Aided Des., **37**(13), pp. 1425–1434.
[20] Huang, G. Q., 1996, *Design for X—Concurrent Engineering Imperatives*, Chapman & Hall, London.
[21] Bouchard, C., Camous, R., and Aoussat, A., 2005, "Nature and Role of Intermediate Representations (IR) in the Design Process: Case Studies in Car Design," Int. J. Veh. Des., **38**(1), pp. 1–25.
[22] Pei, E., Campbell, I., and Evans, M., 2011, "A Taxonomic Classification of Visual Design Representations Used by Industrial Designers and Engineering Designers," Des. J., **14**(1), pp. 64–91.
[23] Kuo, T. C., Huang, S. H., and Zhang, H. C., 2001, "Design for Manufacture and Design for 'X': Concepts, Applications, and Perspectives," Comput. Ind. Eng., **41**(3), pp. 241–260.
[24] Bourell, D. L., Leu, M. C., and Rosen, D. W., 2009, "Roadmap for Additive Manufacturing—Identifying the Future of Freeform Processing," Technical Report, The University of Texas at Austin, Austin, TX.
[25] Fey, N. P., South, B. J., Seepersad, C. C., and Neptune, R. R., 2009, "Topology Optimization and Freeform Fabrication Framework for Developing Prosthetic Feet," Solid Freeform Fabrication Symposium, pp. 607–619.
[26] Gardan, N., and Schneider, A., "Topological Optimization of Internal Patterns and Support in Additive Manufacturing," J. Manuf. Syst., (in press).
[27] Chu, C., Graf, G., and Rosen, D. W., 2008, "Design for Additive Manufacturing of Cellular Structures," Comput. Aided Des. Appl., **5**(5), pp. 686–696.
[28] Emmelmann, C., Sander, P., Kranz, J., and Wycisk, E., 2011, "Laser Additive Manufacturing and Bionics: Redefining Lightweight Design," Phys. Procedia, **12**(Pt. A), pp. 364–368.
[29] Gerber, G. F., and Barnard, L. J., 2008, "Designing for Laser Sintering," J. New Gener. Sci., **6**, pp. 47–59.
[30] Bin Maidin, S., Campbell, I., and Pei, E., 2012, "Development of a Design Feature Database to Support Design for Additive Manufacturing," Assem. Autom., **32**(3), pp. 235–244.
[31] Lokesh, K., and Jain, P. K., 2010, "Selection of Rapid Prototyping Technology," Adv. Prod. Eng. Manage., **5**(2), pp. 74–134.
[32] Byun, H., and Lee, K., 2005, "A Decision Support System for the Selection of a Rapid Prototyping Process Using the Modified TOPSIS Method," Int. J. Adv. Manuf. Technol., **26**(11), pp. 1338–1347.
[33] Alexander, P., Allen, S., and Dutta, D., 1998, "Part Orientation and Build Cost Determination in Layered Manufacturing," Comput. Aided Des., **30**(5), pp. 343–356.
[34] Ruffo, M., and Hague, R., 2007, "Cost Estimation for Rapid Manufacturing—Simultaneous Production of Mixed Components Using Laser Sintering," J. Eng. Manuf., **221**(11), pp. 1585–1591.
[35] Atzeni, E., and Salmi, A., 2012, "Economics of Additive Manufacturing for End-Usable Metal Parts," Int. J. Adv. Manuf. Technol., **62**(9), pp. 1147–1155.
[36] Childs, T. H. C., and Juster, N. P., 1994, "Linear and Geometric Accuracies From Layer Manufacturing," CIRP Ann. Manuf. Technol., **43**(1), pp. 163–166.
[37] Hopkinson, N., and Dickens, P. M., 2001, "Rapid Prototyping for Direct Manufacture," Rapid Prototyping J., **7**(4), pp. 197–202.
[38] Yim, S., and Rosen, D., 2012, "Build Time and Cost Models for Additive Manufacturing Process Selection," ASME Paper No. DETC2012-70940.
[39] Williams, C. B., Mistree, F., and Rosen, D. W., 2005, "Towards the Design of a Layer-Based Additive Manufacturing Process for the Realization of Metal Parts of Designed Mesostructure," Solid Freeform Fabrication Symposium, pp. 217–230.
[40] Doubrovski, Z., Verlinden, J. C., and Geraedts, J. M., 2011, "Optimal Design for Additive Manufacturing: Opportunities and Challenges," ASME Paper No. DETC2011-48131.
[41] Reinhart, G., and Teufelhart, S., 2011, "Load-Adapted Design of Generative Manufactured Lattice Structures," Phys. Procedia, **12**(Pt. A), pp. 385–392.
[42] Muller, P., Mognol, P., and Hascoet, J., 2013, "Modeling and Control of a Direct Laser Powder Deposition Process for Functionally Graded Materials (FGM) Parts Manufacturing," J. Mater. Process. Technol., **213**(5), pp. 685–692.
[43] Adam, G. A. O., and Zimmer, D., 2014, "Design for Additive Manufacturing—Element Transitions and Aggregated Structures," CIRP J. Manuf. Sci. Technol., **7**(1), pp. 20–28.
[44] Kilburn, P., 2012, *Overview of Additive Manufacturing and Materials*, CERN, Zurich, Switzerland, p. 76.
[45] Ahn, S. H., Montero, M., Odell, D., Roundy, S., and Wright, P. K., 2002, "Anisotropic Material Properties of Fused Deposition Modeling ABS," Rapid Prototyping J., **8**(4), pp. 248–257.
[46] Ahn, D., Kim, H., and Lee, S., 2007, "Fabrication Direction Optimization to Minimize Post-Machining in Layered Manufacturing," Int. J. Mach. Tools Manuf., **47**(3–4), pp. 593–606.
[47] Boyard, N., Rivette, M., Christmann, O., and Richir, S., 2013, "A Design Methodology for Parts Using Additive Manufacturing," International Conference on Advanced Research in Virtual and Rapid Prototyping, Leiria, Portugal, Oct. 1–5, pp. 399–404.
[48] Vitse, M., Laverne, F., Segonds, F., Ratgras, S., L. Pellat Finet, and Yantio, G., 2014, "Fabrication Additive: Integration du DFAM Pour la Conception Petites et Moyennes Séries Dans le Domaine Aerospatial," CONFERE'14, Sibenik, Croatia, p. 8.
[49] Rodrigue, H., and Rivette, M., 2010, "An Assembly-Level Design for Additive Manufacturing Methodology," IDMME—Virtual Concept 2010, Bordeaux, France, p. 9.
[50] Ponche, R., Kerbrat, O., Mognol, P., and Hascoet, J., 2014, "A Novel Methodology of Design for Additive Manufacturing Applied to Additive Laser Manufacturing Process," Rob. Comput. Integr. Manuf., **30**(4), pp. 389–398.
[51] Alimardani, M., Toyserkani, E., and Huissoon, J. P., 2007, "A 3D Dynamic Numerical Approach for Temperature and Thermal Stress Distributions in Multilayer Laser Solid Freeform Fabrication Process," Opt. Lasers Eng., **45**(12), pp. 1115–1130.
[52] Chan, C. K., and Tan, S. T., 2005, "Volume Decomposition of CAD Models for Rapid Prototyping Technology," Rapid Prototyping J., **11**(4), pp. 221–234.
[53] Choi, J., and Chang, Y., 2005, "Characteristics of Laser Aided Direct Metal/Material Deposition Process for Tool Steel," Int. J. Mach. Tools Manuf., **45**(4–5), pp. 597–607.
[54] Rafi, H. K., Starr, T. L., and Stucker, B. E., 2013, "A Comparison of the Tensile, Fatigue, and Fracture Behavior of Ti–6Al–4V and 15-5 PH Stainless Steel Parts Made by Selective Laser Melting," Int. J. Adv. Manuf. Technol., **69**(5), pp. 1299–1309.
[55] Brackett, D., Ashcroft, I., and Hague, R., 2011, "Topology Optimization for Additive Manufacturing," 24th Solid Freeform Fabrication Symposium, pp. 6–8.
[56] Maheshwaraa, U., Seepersad, C., and Bourell, D. L., 2007, "Design and Freeform Fabrication of Deployable Structures With Lattice Skins," Rapid Prototyping J., **13**(4), pp. 213–225.
[57] Laverne, F., Segonds, F., Anwer, N., and Le Coq, M., 2015, "Conception Pour la Fabrication Additive: Un état de l'art," AIP PRIMECA'15, La Plagne, France, p. 7.
[58] Anwer, N., Ballu, A., and Mathieu, L., 2013, "The Skin Model, a Comprehensive Geometric Model for Engineering Design," CIRP Ann. Manuf. Technol., **62**(1), pp. 143–146.
[59] ISO, 2009, *Systèmes de Management de la Qualité: Principes Essentiels et Vocabulaire*, AFNOR, Paris.
[60] Savransky, S. D., 2000, *Engineering of Creativity: Introduction to TRIZ Methodology of Inventive Problem Solving*, CRC Press, New York.
[61] Henderson, R. M., and Clark, K. B., 1990, "Architectural Innovation: The Reconfiguration of Existing Product Technologies and the Failure of Established Firms," Adm. Sci. Q., **35**(1), pp. 9–30.
[62] Skander, A., Roucoules, L, and Klein Meyer, J. S., 2008, "Design and Manufacturing Interface Modelling for Manufacturing Processes Selection and Knowledge Synthesis in Design," Int. J. Adv. Manuf. Technol., **37**(5), pp. 443–454.
[63] Otto, K. N., and Wood, K. L., 2003, *Product Design—Techniques in Reverse Engineering and New Product Development*, Prentice Hall, Upper Saddle River, NJ.
[64] Ponche, R., 2013, "Methodologie de Conception Pour la Fabrication Additive, Application à la Projection de Poudres," Thèse de doctorat, IRCCyN, UMR CNRS 6597, École Centrale de Nantes, Nantes, France.
[65] Ulrich, K., 1995, "The Role of Product Architecture in the Manufacturing Firm," Res. Policy, **24**(3), pp. 419–440.
[66] Kalyanasundaram, V., and Lewis, K., 2014, "A Function Based Approach for Product Integration," ASME J. Mech. Des., **136**(4), p. 041002.
[67] Howard, T. J., Culley, S. J., and Dekoninck, E., 2008, "Describing the Creative Design Process by the Integration of Engineering Design and Cognitive Psychology Literature," Des. Stud., **29**(2), pp. 160–180.
[68] Shah, J. J., Kulkarni, S. V., and Vargas-Hernandez, N., 2000, "Evaluation of Idea Generation Methods for Conceptual Design: Effectiveness Metrics and Design of Experiments," ASME J. Mech. Des., **122**(4), pp. 377–384.
[69] Cross, N., 2008, *Engineering Design Methods: Strategies for Product Design*, Wiley, Chichester, UK.
[70] Broberg, O., 1997, "Integrating Ergonomics Into the Product Development Process," Int. J. Ind. Ergonom., **19**(4), pp. 317–327.
[71] Curral, L. A., Forrester, R. H., Dawson, J. F., and West, M. A., 2001, "It's What You Do and the Way That You Do It: Team Task, Team Size, and Innovation-Related Group Processes," Eur. J. Work Organ. Psychol., **10**(2), pp. 187–204.
[72] Moreland, R. L., Levine, J. M., and Wingert, M. L., 1996, "Creating the Ideal Group: Composition Effects at Work," *Understanding Group Behavior*, Vol. 2, E. Witte and J. H. Davis, eds., pp. 11–35.
[73] Linsey, J. S., Green, M. G., Murphy, J., Wood, K. L., and Markman, A. B., 2005, "'Collaborating to Success': An Experimental Study of Group Idea Generation Techniques," ASME Paper No. DETC2005-85351.
[74] Helms, M., Vattam, S. S., and Goel, A. K., 2009, "Biologically Inspired Design: Process and Products," Des. Stud., **30**(5), pp. 606–622.
[75] Bonnardel, N., and Bouchard, C., 2014, "Design, Ergonomics and User Interfaces: Complementary and Interdisciplinary Studies to Enhance Creative Activities," Ergonomie et Informatique Avancée Conference, Bidart-Biarritz, France, ACM, New York, pp. 2–10.
[76] Mougenot, C., Watanabe, K., Bouchard, C., and Aoussat, A., 2009, "Visual Materials and Designers' Cognitive Activity: Towards In-Depth Investigations of Design Cognition," International Association of Societies of Design Research, Seoul, South Korea.
[77] Schon, D., 1992, "Designing as Reflective Conversation With the Materials of a Design Situation," Res. Eng. Des., **3**(3), pp. 131–147.
[78] Mann, D., and Dewulf, S., 2001, "Evolving the World's Systematic Creativity Methods," 7th European Association for Creativity and Innovation Conference, p. 9.