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A design methodology for parts using additive manufacturing

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ABSTRACT: Additive Manufacturing (AM) allows designer to sidestep several design requirements and to create free forms, hollow parts or direct assemblies. This process also allows direct recycling of plastic into new parts, which eases the raw material supply. However, although several methodologies are used to redesign products and parts, none is dedicated to a real design of parts and products in AM. At first, we will suggest the base of a new design methodology for an end-user who wants to create a product or a part in AM. Then, we will show an example of using our methodology. Finally, we will conclude on the limits of this methodology and on our next work to validate our methodology.

1 INTRODUCTION

Additive manufacturing (AM) is a very promising manufacturing process in terms of possibilities of shapes and complexity of parts (Vayre & Villeneuve 2012), (Boyard et al. 2012). It is possible to perform multi-material parts (Muller et al. 2010), hollow parts (Vayre & Villeneuve 2012), large-scale parts (Lim et al. 2012) and ready-for-use parts (Cooper et al. 2012).

From an ecological point of view, AM also allows the recycling of certain materials. For example, Fused Deposition Modelling (FDM), which is a method to construct a part from hot wire deposition, allows reuse of certain plastics such as acrylonitrile butadiene styrene (ABS).

However, to design a product, it is necessary to adopt a precise and consistent methodology (Segonds 2011). Currently there are many methods whose relevance varies with the design goals: assembly, machining, cost, quality... (Tomiyaama 2009). Among all these methods, there is a recurrent pattern (Figure 1).

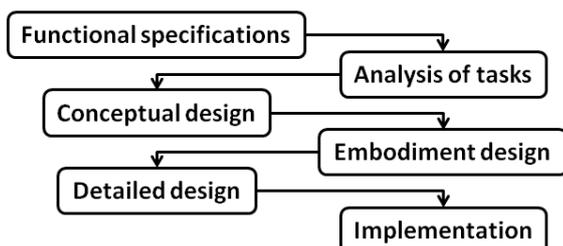


Figure 1 : Standard schema of a design methodology (Segonds 2011)

However, although various redesign methodologies have been proposed (Rodrigue 2010; Vayre & Villeneuve 2012), no design methodology has been developed specifically for AM.

Rodrigue (2010) reveal two design methodologies that may relate to the AM: The Design For Assembly (DFA), which aims to design a product in order to validate and facilitate assembly, and the Design For Manufacturing (DFM), whose goal is to design workable parts using one or more specific process(es) (Boothroyd 1994). In the case of AM, the geometry of the part is almost no longer constrained by the manufacturing process. To optimize the parts of the product with respect to the assembly and manufacturing, DFM and DFA can be performed directly in the design without generating additional constraints or changes in the initial request of the end-user. Rodrigue (2010) also offers a redesign methodology (Figure 2).

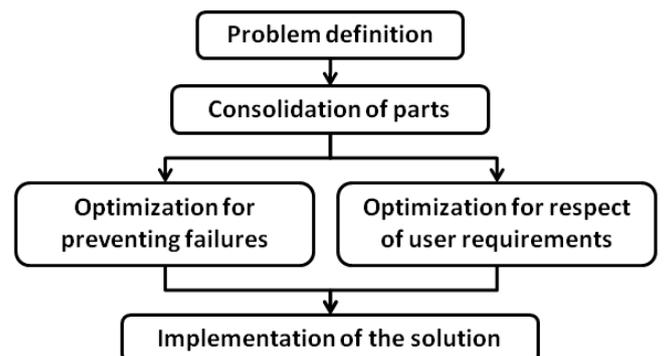


Figure 2 : Redesign methodology for AM (Rodrigue 2011)

The resulting model is then optimized in two different directions: preventing failures and respect for user requirements. Prevention of failures is based on FMECA (Failure Modes, Effects and Criticality Analysis). It aims to optimize the product to increase its reliability to meet the specifications. Compliance with user constraints aims to improve the design of each part to meet the design constraints with minimal compromise. The final purpose is to meet end-user's needs as accurately as possible. Finally, the results of these optimizations are confronted to decide the structure and shape of the final product.

This paper aims to establish the basis of a design methodology that can take into account the specificities of the AM. It doesn't deal with innovation methodologies. In this paper, we deal only with the design of products which does not contain any internal relative movement during use. These will be integrated in future developments dedicated to optimize, test and then assess our method.

2 A MORE COMPLETE METHODOLOGY

2.1 General overview

In the following sections, referring to our state of the art above, we present the fundamental keys to operationalize our methodology (Figure 3).

Our method includes the six steps of a standard design methodology:

- Functional specification (1) ;
- Conceptual design (2) ;
- Architectural design (3) ;
- Detailed design (4) ;
- Implementation (5).

Phases 3 and 4, corresponding to loops of DFM and DFA, are performed in parallel.

The framework of our research regards points 3 to 5 of this methodology. We will assume that the work relating to the collection of needs and the planning tasks have already been made. In addition, we will not deal the implementation phase in its entirety. These two steps are necessary for any design methodology and do not participate in the design itself. We also will assume that our methodology is consistent from the moment the designer is able to produce a manufacturable digital mock-up, corresponding to a prototype or to the finished product.

One of the difficulties in product design lies in the association of manufacturing and assembly with respect to the functional specifications. In our methodology, we propose to keep these two types of design. But rather than to perform them separately and at different times, we try here to make them complementary and simultaneous.

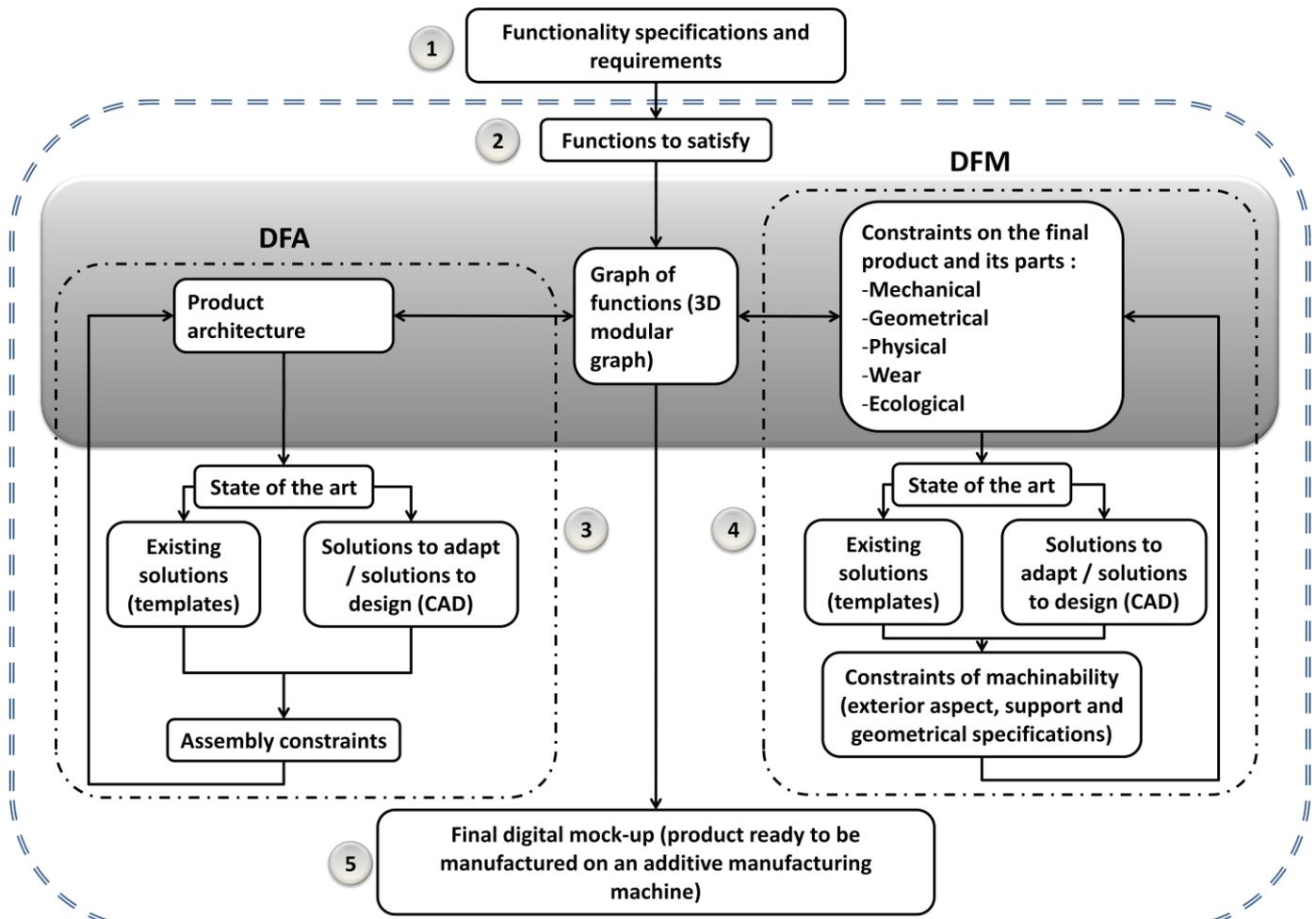


Figure 3 : Design methodology for Rapid Manufacturing (DFRM, Design for Rapid Manufacturing)

In addition, the democratization of the AM (Anderson 2012) and the setting up of co-design phases in companies (phases with all stakeholders concerned with the whole product design: engineering, stylists, end-user, designer ...) implies to develop a methodology that can be used by any person without any prerequisites.

2.2 Conceptual design

The conceptual design phase (Figure 3, step 2), which is the real starting point of our research, aims to take each function and constraint of the functional specifications.

However, changes from the client occur frequently throughout the product design. This is why the extraction of functions from the functional specifications should be flexible and modular to allow of new functions and constraints.

Once the features extracted, they will be arranged in a graph of functions by the actors of the design in order to provide a first iteration of the architecture of the final product. The first proposal is based on a simple set of rules that we need to define. Some of these rules concern, for example, the geometric appearance. Thus a function requiring the holding in position of a part will be disposed downward, whereas a function requiring fast access to a part of the product is preferably placed on an outer surface... Similarly, the graph will be able to integrate new functions as and when the changes of the client.

This graph is a modular three-dimensional graph to be drawn in CAD software and then to provide support to the digital mock-up (Figure 4).

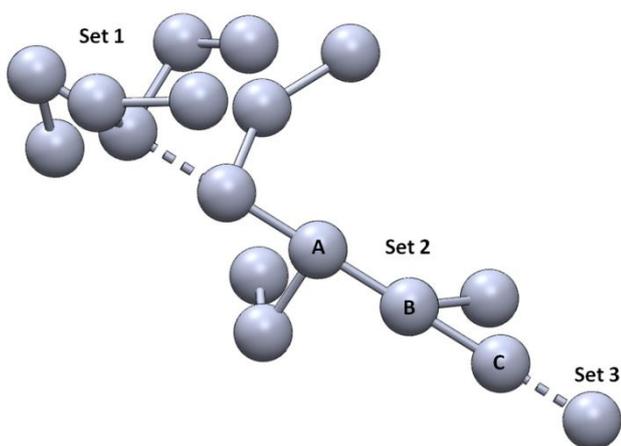


Figure 4 : Graph of functions

The graph is a global representation of the product. As stated earlier, our methodology concerns only products containing no internal movement in functioning. However, these products can be composed of several parts. We therefore decompose the graph into several sets, each set representing a part of the product.

Since AM can manufacture any type of mechanical part, we assume that for any set of functions there is at least one piece that meets all the functions of this set. A part is defined here as a unitary physical body.

The rules for establishing a set are:

- Is the part corresponding to this set a wear part?
- Can functions be grouped on the same part, or should they be separated?
- Are parts movable relative to each other?
- ...

A set of functions is a collection of functions connected by links. A set must contain at least one function. If all functions of the functional specifications are interconnected to others, then the graph will contain only one set. Sets are interconnected by dotted line representing a fixed joint between two parts.

Each function is represented as a sphere. The spheres are the nodes of the graph. The functions are then linked to each other by segments. These segments represent both direct connections between functions and spatial organization of the functions with each other. Thus, different interconnected functions belong to the same part. In addition, a function A connected to a function B itself connected to a function C indicates that the function B will be found between or will separate functions A and C (Figure 4).

This representation allows the user of the methodology to spatially reorganize functions with each other. The advantage is, without conducting discussions of technical solutions, to begin to propose architecture of the final product based only on the functions and constraints to be addressed.

Moreover, this graph is modifiable: each function can be reorganized with respect to each other and connections can be changed. This has two advantages: the first is to provide a modular basis for discussion with stakeholders of the design, the second is to allow stakeholders to easily review the results of the conceptual design.

2.3 Detailed design

The detailed design phase, which analyzes each set of functions present in the global graph of functions, corresponds to a DFM phase (Figure 3, Step 4).

Firstly, all the constraints that the part will support are added to the set of this part. These constraints can be mechanical, geometrical, physical, of wear, ecological...

Constraints are layered on geometry proposed by the global graph of functions.

In a first step, the CAD software will compare to a database the set corresponding to the part. This database contains all the graphs of functions already

designed by the design team and all the associated 3D models. It can be mutualised with other design teams. This corresponds to the state of the art step. Three alternatives are possible: either the proposed graph already exists and a piece is proposed. Otherwise, if a variant of the proposed graph (dependent on a minimum number of common functions) exists, it can serve as a basis for the design of the part. Either there is no corresponding or similar graph, the part has to be fully designed.

In the last two cases, the stakeholders will detail the geometry of the part and propose a combination of one or more materials to satisfy the constraints and functions imposed.

Finally, designers should specify an AM machine. The geometry of the part will be confronted with manufacturing capabilities of the AM machine and assembly constraints with other parts.

If the part does not meet these criteria, the stakeholders will then optimize part by adjusting the following parameters: part geometry, materials, functions of to the part.

If the part is valid, it is locked in the graph. If a function is added or removed to a part (which could be validated or not), it must again validate the detailed design phase.

2.4 Architectural design

The architectural design phase, or embodiment design phase, is realized in parallel of the detailed design phase (figure 3, step 3). Thanks to the modularity of the graph, the structure of the product may be modified whenever.

Each time a set is created or each time a part is validated during the detailed design, the architecture of the product must also be re-validated.

To proceed, as in the detailed design phase, the CAD software compare the entirely graph (and not a specific set) with the models of products of a database. This comparison could provide existing products which give a model for the structure of the product and for the connections between the sets. This is particularly helpful to design a range of products or for mass customization (Zarb, F. 2012).

Otherwise, either an existing product may be fit, or, if there is no existing similar product, the architecture is to be entirely designed.

Once the architecture of the product is designed, it is faced to the assembly constraints (removable or irremovable parts, accessibility to parts, steps of assembly/disassembly...). If the product fits the constraints, it is validated. Else, the software indicates that the architecture has to be redesigned, which may lead to the transfer of one function from a set to another or to the internal reorganization of a set.

2.5 Co-design

Another purpose of this methodology is to allow the co-design of the product, involving all the stakeholders of design (end users, designers ...) at every moment of the design process.

Thus, if parts of the detailed design and the architectural design are outsourced to CAD software for the searching of existing solutions, most of the design is a result of subjective decisions of the stakeholders, especially those of end-users. This is why the co-design phase - including the conceptual, architectural and detailed design - should allow adding some constraints of appreciation:

- Physical (textures, distribution and perception of product weight);
- Mechanical (flexibility, elasticity);
- Geometric (grip, aesthetic);
- Architecture (type of mobile connection, disassembly);
- ...

2.6 Deliverable

The purpose of our design methodology is to allow the user to manufacture his "own" product.

Once the product has been approved by all the stakeholders and the software no longer requires modification, parts resulting of the design will be post-processed by the CAD software to convert digital files parts in a machine readable code.

This post-treatment has been validated during the detailed design phase. Indeed, at this stage, each part was confronted with the characteristics of the machine which will manufacture them. The notions of surface quality, material manufacturing cost, machinability, manufacturing strategy and precision are thus validated.

Once the manufacturing strategy has been validated by stakeholders, the code is generated and the part is ready to be manufactured.

3 CASE STUDY: THE SALTCELLAR

To illustrate our methodology, we propose a simple case study: the saltcellar.

For this, we use a simplified functional specification including the following nine functions:

- F1: Contain condiments;
- F2: Can be filled;
- F3: Distribute the content;
- F4: Protect condiments in case of fall;
- F5: Indicates type of contained condiments;
- F6: Indicates quantity of contained condiments;
- F7: Do not slide;
- F8: Hold on a table;
- F9: Being comfortable in hand.

The first task of the design stakeholders will be to establish a graph of the functions.

We will consider that the result of the discussion between the stakeholders, according to the rules of designed we will define, leads to a graph of two sets. The first one contains the functions F2 and F3. The second one contains the other functions (Figure 5).

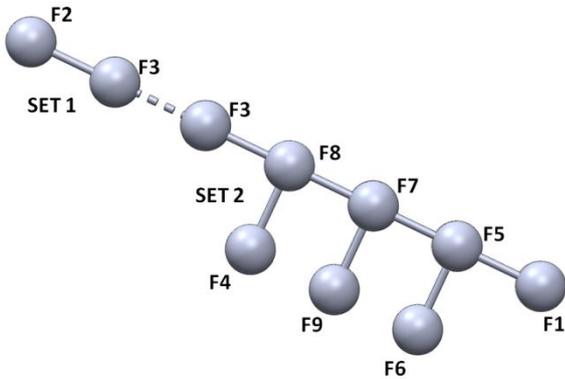


Figure 5 : Graph of functions of the saltcellar

Then, the CAD software compares this graph to those which are contained in the database (functions and structure). An approaching solution is the saltcellar with a metallic screwtop (Figure 6) which is a product also composed by two sets (Figure 7) which includes two other functions:

- F10: Limit the flow when distributing (set 1);
- F11: Be washable (set 2).



Figure 6 : Saltcellar with metallic cap

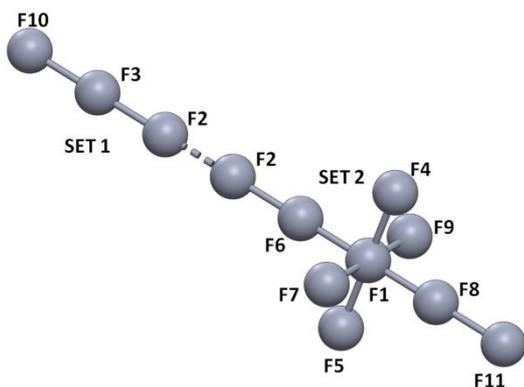


Figure 7 : Graph of function of the saltcellar with screwtop

Function F3 « Distribute the content » is only contained in the first set. However, function F2 « Can be filled » is contained by both set 1 and set 2 and links them. Indeed, if the final product fits to the functional specifications, it is possible to duplicate a function, even it is redundant. In our case, this corresponds to the fact that the screwtop is screwed to the body of the saltcellar when used and unscrewed when filled: there is a relative movement only during the filling step. This matches with our methodology: when used; the screwtop is related to the body of the saltcellar by a rigid joint.

To fit exactly with the graph deduced from the functional specifications, the graph presented on the figure 6 may be modified and adapted.

Either functions F10 and F11 may be deleted respectively from set 1 and set 2, or the graph presented on the figure 5 may include these functions (only if the end-user agree this modification of the functional specifications). Only the stakeholders of the design can make this choice.

Nevertheless, to fit the graph, it is necessary that every other function is satisfied. This involves the step of constraint of machinability from the DFM loop (Figure 3, step 4). According to the machine which will be used, stakeholders may have the possibility to produce the body of the saltcellar in an entirely transparent material or to produce it in multi-material, at least one of them is transparent.

Once the graph is validated, stakeholders will be able to modify the position of the functions inside the sets to start to create the geometry of the parts.

In our case, since the software proposed an existing solution, it is possible to base on the existing numerical model of this solution to design the geometry of the parts. In every case, stakeholders will have to design the parts on the CAD software which allows the use of the graph of functions.

Here, the first set corresponds to the screwtop. The second corresponds to the body of the saltcellar.

By adding constraints on the sets, stakeholders will be able to design step by step the final geometry of the product and assign materials to the parts. Indeed, geometry and material must answer to the functional requirements. This will give the cost of raw material of the product.

In the case of imposed external parts, like an electric motor-reducer, stakeholders have to know the exact geometry of these parts. They must have, at least, sharp diagrams to redesign and include these parts in the mock-up based on the graph in order to create the geometry of the product.

In our case, the body of the saltcellar may be made in transparent glass, to allow the end-user see the type and the remaining quantity of contained condiment. More, a glass saltcellar is easily washable. The type of glass and the geometry of the body

have to fit functions F4 « Protect condiments in case of fall », F7 « Do not slide », F8 « Hold on a table » and F9 « Being comfortable in hand ». These choices are delegated to the stakeholders. However, it is not possible to add a stick on the saltcellar to indicate the type of condiment. Otherwise, the graph would have been composed by three sets: one for the body, one for the screwtop and one for the stick.

As one goes along the design, the software verifies the respect of assembly and machinability constraints, indicating the possible mistakes or incompatibility. In this way, the mock-up resulting of the design is ready to be converted in a file which can be read by the additive manufacturing machines chosen to manufacture the product.

4 LIMITS

The methodology presented in this article is the subject of a thesis, which can explain why some points have not yet been tested. Thus, the overall methodology remains to be validated in an experiment involving different stakeholders (ergonomists, engineers, manufacturers, designers, end users...).

Moreover, it is difficult to estimate the cost of some developments which have to be done on the CAD software. If the technical feasibility of our methodology has been validated through the use of SolidWorks software (Kou X. 2005), which allows the addition of features such as the integration of a comparative database, the length and complexity of these developments has not yet been quantified.

Thus, the methodology proposed in this paper is still at an ideal level. However, it can make a precise statement of requirements and necessary developments. These are all avenues of research to explore.

Another point to develop is how stakeholders will interact with to the function graph. There are different technologies for multiuser interaction (Kadri 2007). However, the challenge is to propose a suitable solution for all stakeholders, for their vision of the design vision, their vocabulary or to their field of competence (Segonds 2011).

5 CONCLUSION

The methodology we propose will therefore allow to design parts made using AM, with the most accurate respect of the functional specifications.

More, it differs from other methodologies (Hascoet et al. 2011) by the use of the graph of function which transcribes the will of designing the geometry of the product the later as possible.

In addition, this methodology allows the design of parts with complex geometries by abstracting a large number of manufacturing constraints associated with conventional methods (cutting angles, ac-

cess to cutting tool, lubrication, tool wear...). It also allows the design of parts satisfying both DFA and DFM in the earliest phase early of the design. This possibility will limit a priori costly late changes.

Finally, this methodology falls within the scope of environmental concerns by providing, for certain processes, the ability to produce parts by using only the amount of material necessary to the final volume (Boyard et al. 2012).

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