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## A new global approach to design for additive manufacturing

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## chapter eleven

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# *A new global approach to design for additive manufacturing*

*R. Ponche, J. Y. Hascoet, O. Kerbrat, and P. Mognol*

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Nowadays, due to rapid prototyping processes improvements, a functional part can be built directly through additive manufacturing (AM). It is now accepted that these new processes can increase productivity while enabling a mass and cost reduction and an increase of the parts functionality. However, in order to achieve this, new design methods have to be developed to take into account the specificities of these processes, with

the design for additive manufacturing (DFAM) concept. In this context, a methodology to obtain a suitable design of parts built through AM is proposed; both design requirements and manufacturing constraints are taken into account.

## 11.1 Introduction

Recent progress has permitted transition from rapid prototyping to AM. Indeed, today, with this kind of manufacturing process, not only prototypes can be produced but also real functional parts in current materials including metals, polymers, and ceramics can be produced [1]. Because AM for production eliminates the need of tooling and can generate free forms, many of the current restrictions of design for manufacturing (DFM) and assembly are no longer valid [2]. However, whatever the technology used [3], as in all the manufacturing processes, the AM ones have characteristics and specificities of their own which may have an impact on the manufactured parts' quality. In order to utilize the AM possibilities in the best way in terms of design and to ensure the quality of the produced parts, a global numerical chain which allows moving from functional specifications of a part to its manufacturing must be defined (Figure 11.1). The purpose of this numerical chain [4] is to reach a global process control from knowledge of process obtained from experimentations, measurements, and simulations. Among the prerequisite to achieving such numerical chain, a DFM [5] approach is required which allows the AM processes' capabilities to be taken into account and limits directly from the design stage.

### 11.1.1 Design for additive manufacturing

Several works have been carried out concerning the classical DFM approach [6] for AM. By concerning manufacturability estimation, manufacturing cost and time have been analyzed [7,8] according to the manufacturing sequence. Similarly, the relationship between parts surfaces quality and manufacturing sequence has been studied [9,10]. From these different specific works, [11] proposed a methodology to map parts in relation to its manufacturability. Based only on geometrical analysis, these studies are limited because they do not take into account the physical phenomena that occur during the manufacturing

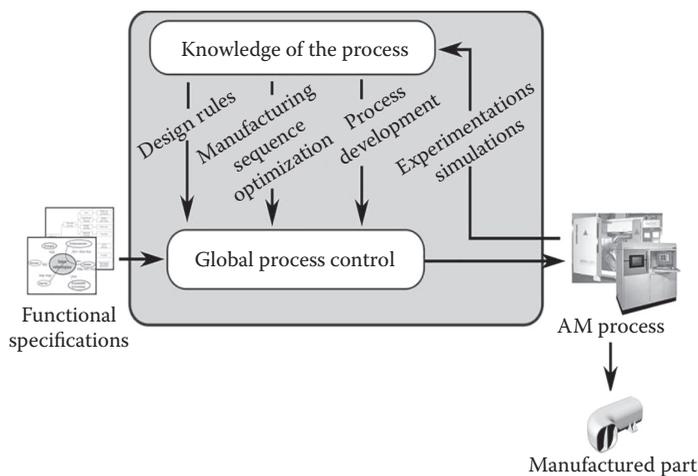


Figure 11.1 Global numerical chain concept.

process [12,13], which may have an impact on parts quality [14] and therefore on their manufacturing time and cost. Concerning manufacturability improvement, there have been very few studies reported on AM processes. General build guidelines have been established [15,16] and a methodology proposed by [17] enables modification of some non-critical geometric features. Moreover, a method for providing mesostructures within a part so as to achieve improved functional requirements part has been established [18]. Here again, the purpose is to minimize fabrication cost and time without a real awareness of the process planning, which do not allow to guarantee the parts quality expected. In addition to these limitations, classical DFM approaches may restrict the new perspectives of design opened up by the AM processes.

### 11.1.2 Partial approach versus global approach

Indeed, all these works enable to determine and to improve the manufacturability of a part from its computer aided design (CAD) model for a given AM process. Because they start from an initial geometry (given by the initial CAD model), these analysis can be qualified as *partial approaches* (Figure 11.2). In this case, it is difficult to determine the real optimized characteristics for a given AM process while fulfilling original functional specifications. Indeed, the initial CAD model was thought to be manufactured by an initial manufacturing process often very different from an AM process (e.g., machining which is the most often used); moreover the proposed modifications are local, and the result is never far from the initial design. The CAD model that is obtained is thus never really designed for the AM process that is chosen. On the contrary, a *global approach* (Figure 11.3) starts directly from both the chosen manufacturing process characteristics and the functional specifications of the parts to design. Designers can thus determine the geometry which optimizes the use of the chosen AM process characteristics while meeting the functional specifications. The purpose is not to limit geometry by an initial idea of the part shapes but to define it only from the manufacturing process and the functional specifications. This new way of thinking is in opposite with traditional DFM methodologies. However, capitalization of the entire knowledge about the manufacturing processes is needed. A beginning of a global approach, based on topology optimization with manufacturing constraints, has been applied to casting process [19].

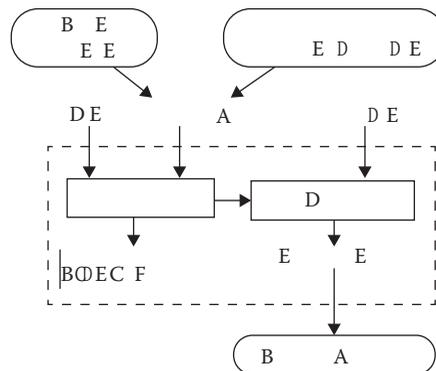


Figure 11.2 Partial approach.

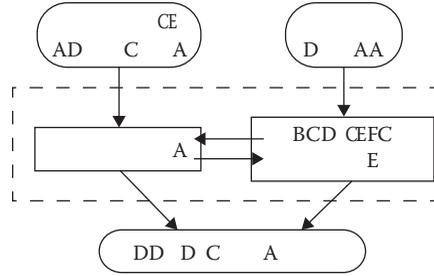


Figure 11.3 Global approach.

### 11.1.3 Scope of the paper

Although the global approach seems very interesting, no existing work has been carried out in this way in AM. Because these processes are quite new, still little known and very different from the other manufacturing processes, the psychological inertia phenomena may prevent the designer from utilizing all their capabilities in the best way [20].

Moreover, most of the AM processes are based on a layer-by-layer manufacturing where the material is locally merged, thanks to a local moving energy source (usually a laser or an electron beam) which follows a programmed manufacturing trajectory. It entails that the characteristics of the manufactured volumes, in terms of microstructure [21], geometry [14], and manufacturing time [10] depend first on the manufacturing direction (MD) and secondly on the manufacturing trajectories (MT). In addition to the consideration of the processes' characteristics, the choice of the MD and the MT according to functional specifications is thus the key of a global DFAM which would facilitate designers to explore new design spaces. That is why a new methodology which starts directly from both the functional specifications and the process characteristics is proposed in this paper.

First, in Section 11.2, the required data are presented. Then in Section 11.3, the different steps of the methodology, based on the choice of MD, are explained. The methodology has been applied on a part manufactured by a powder-based metal deposition (PBMD) process [22]; this constitutes the fourth section.

## 11.2 Proposed requirements for a global DFAM

In this section, requirements for a global DFAM are presented. They constitute the required data for the proposed methodology.

### 11.2.1 Functional specifications

The global purpose is to propose a structured approach which would help the designer to integrate the knowledge of the chosen AM process in his design to meet the functional specifications. The functional specifications can be detailed as follows:

- *Functional surfaces (FS)*: type, dimensions, and position.
- Dimensional and geometrical specifications linked to the FS.
- *Mechanical requirements*: They depend on the chosen material characteristics.
- *Empty volumes*: dimensions and position. They correspond to the volumes which must not contain material, due to the assembly constraints of the designed part into the system to which it belongs.

### 11.2.2 Context

The study context is an influential factor. Because it can be translated into a concrete objective in terms of mass, cost, or manufacturing time, it has thus to be taken into account too.

### 11.2.3 Manufacturing characteristics

Manufacturing characteristics are linked to one another, and they cannot be seen separately; a global view which draws upon all the knowledge and experience of the community is consequently needed. The main characteristics of the manufacturing machines which must be taken into account are

- Kinematics
- Maximal and minimal dimensions
- Capability in terms of accuracy
- Required accessibility

But the physical phenomena that are involved in the manufacturing process and which are decisive in terms of final properties of parts, are also linked to the manufacturing sequence.

### 11.2.4 Finishing process characteristics

Similarly, if specifications (geometrical and dimensional) cannot be directly reached by the AM process that is chosen, a finishing process is needed. Because it can influence the final geometry, particularly in terms of overthickness and required accessibility, it has to be taken into account.

## 11.3 The proposed design methodology

From this data, a structured methodology can help designers in taking into account the manufacturing constraints while suggesting him an appropriate design for AM. The methodology is presented in [Figure 11.4](#). It is divided into three main steps which enable to include gradually manufacturing knowledge in the shapes and the volumes of the parts to be designed. The first step is a global analysis which allows delimiting the design problem in terms of geometrical dimensions in relation to the dimensional characteristics of the AM process. The second one allows to fulfil the dimensional and geometrical specifications in relation to the AM process capability and the finishing process characteristics. Finally, the third step allows to fulfil the physical and assembly requirements in relation to the capability of the AM process.

### 11.3.1 Step 1: Analysis

The FS are obtained from the functional analysis of the product and are given by the designer. The first methodology step enables to find out if all the surfaces can be merged with one another by the chosen AM process into a single part. A first geometrical analysis is carried out; it takes into account the maximal and minimal dimensions, which can be obtained by the chosen manufacturing machine. If the dimensions are not suitable, the product has to be modified or divided into different parts by the designer, and the functional specifications of these new parts are then studied.

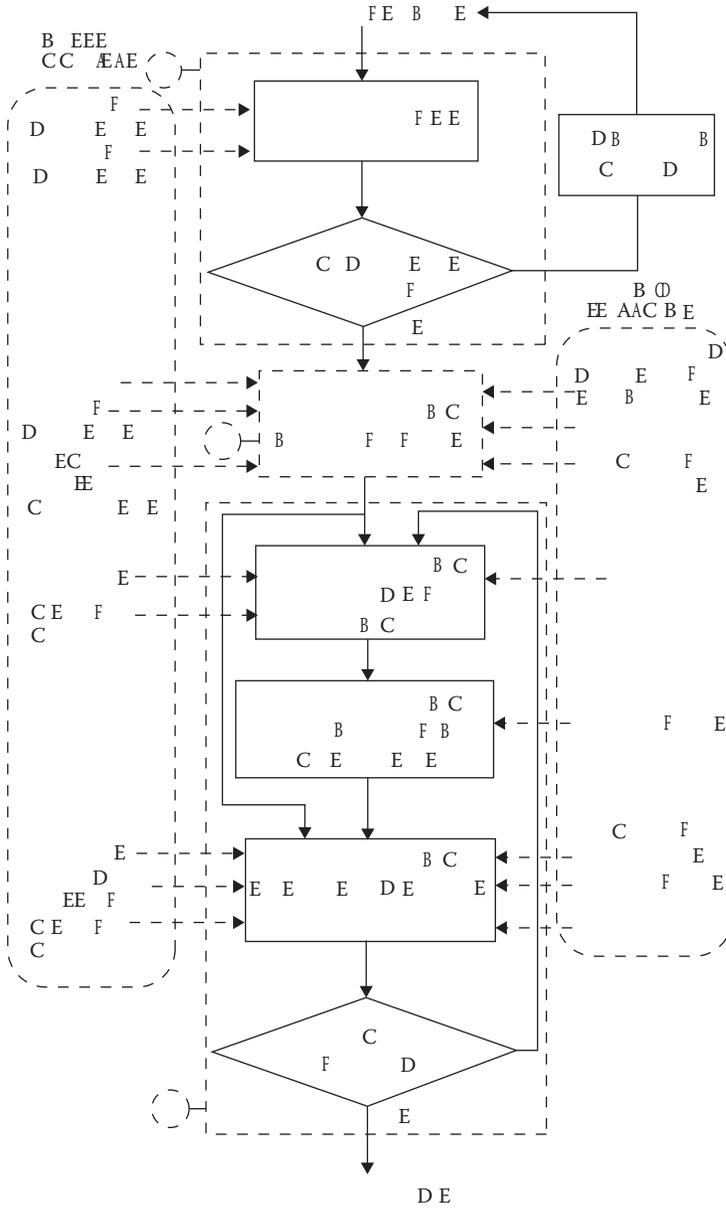


Figure 11.4 The proposed DFAM methodology.

### 11.3.2 Step 2: Determination of the functional volumes

The functional volumes (FV) are defined directly from the FS on to which a thickness is added. Indeed, only the tolerances in the normal direction of the surfaces are significant in terms of functionality. The others are initially ignored. The thickness, denoted  $E$ , depends on

- Dimensional accuracy of the AM process denoted  $a$ .
- Tolerances linked to the FS, denoted  $p$ .

For each FS, there are two different possibilities: first, if a finishing step is not needed ( $p \geq a$ ), thickness is determined from Equation 11.1 which ensures the functional minimal thickness and from Equation 11.2 which ensures the compatibility with the AM process.

$$E \geq t + \frac{a}{2} \tag{11.1}$$

$$E = n.d - (n - 1).d.\alpha \tag{11.2}$$

where:

- $t$  is the minimal thickness corresponding to the local mechanical requirements.
- $d$  is the minimal dimension that can be obtained by the chosen AM process.
- $\alpha$  is the overlap between two adjacent paths.
- $n$  is a positive integer.

Equation 11.1 is illustrated in Figure 11.5a. If a finishing step is needed ( $p < a$ ), then the thickness is determined from Equations 11.2 through 11.4 (Figure 11.5a).

$$E \geq t + \frac{a}{2} + e_{\min} \tag{11.3}$$

$$E \leq t + \frac{a}{2} + e_{\max} \tag{11.4}$$

where  $e_{\min}$  and  $e_{\max}$  are the minimal and maximal overthicknesses, which depend on the finishing process and the surfaces geometry. There can be different values of the parameters  $d$ ,  $\alpha$ , and  $a$  (according to the MD).

### 11.3.3 Step 3: Determination of the linking volumes

The purpose of this step is to merge the FV to define the volumes of the part while taking into account at best both design requirements and manufacturing constraints. In the

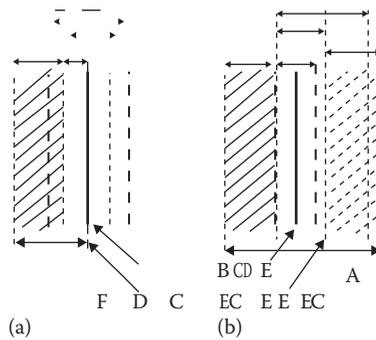


Figure 11.5 Definitions of the thickness: (a) without finishing and (b) with finishing.

case of AM, volumes are usually obtained layer-by-layer. It involves that their geometries strongly depend on the *MD*. Indeed, the choices of the *MD* have a direct influence on material quantity (need of supports), build time [23], and mechanical properties [24]. Moreover, the *MT* defining the energy source path during the process have a strong impact on the physical phenomena that occur during the manufacturing process and therefore on the final part quality [25]. That is why, the determination of the *MD* and *MT* is at the center of the methodology. The linking volume (*LV*) definition is divided into four steps. The first step is to determine the most critical *MD*, which can be characterized by the shape or the number of *FV* which can be manufactured in the same way. It is carried out according to the study context and the capability of the process given by its kinematics and the physical phenomena involved. The second step is, in the chosen *MD*, to merge the selected *FV* which can be manufactured from the same substrate. It is carried out according to the empty volumes, which must not be, in the *MD*, between two *FV* manufactured from a same substrate. In the third step, the substrates and supports' shapes are determined according to

- The selected *FV*.
- The other *FV*.
- The kinematics of the process.
- The accessibility required by the process.
- The mechanical requirements.
- The empty volumes.
- The study context.
- The physical phenomena that occur during the process.

The latter being strongly linked to the type and the shape of the *MT* that are used, it is essential to select suitable *MT* among all the possibilities to control them and to guaranty the expected geometrical quality. A classification of the different *MT* that are possible has been done (Figure 11.6) to describe and parameterize each one of them.

The last step is to check if all the volumes are merged. If it is not the case, the first three steps are repeated while taking into account the *FS* that have not yet been analyzed and

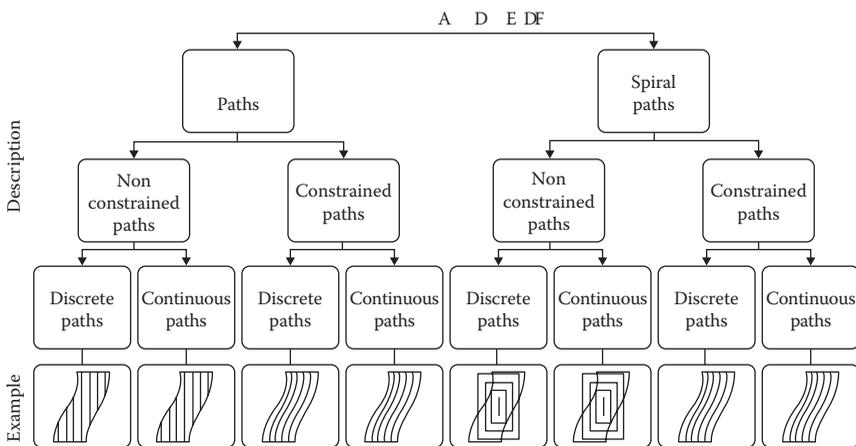


Figure 11.6 Classification of the manufacturing trajectories (*MT*).

the substrates obtained previously, and so on, until all the *FV* are merged. In the end, the process is complete, and an appropriate design for the chosen AM process is obtained. Indeed, the AM process specifications are taken into account step by step in parallel with the functional requirements. This ensures that the most possible process-related knowledge is taken into account to obtain the final shapes of the studied part.

## 11.4 Example

The proposed methodology has been applied to a case of a robot hinge in stainless steel (Figure 11.7). The study input data are detailed, and the three steps of the DFAM methodology are illustrated in this section.

### 11.4.1 Input data

#### 11.4.1.1 Functional specifications

The case is composed of 20 *FS*: four bearing holders (hollow cylinders) and 16 flat surfaces, which are shown with their nominal dimensions in black in Figure 11.8. To enable the assembly of the case with the other parts of the robot, some empty volumes are defined. They are represented by the transparent volumes.

The functional analysis of the robot has enabled to determine the geometrical and dimensional specifications linked with each surfaces. An extract is shown in Figure 11.9. The mechanical requirements are translated into a final minimal thickness  $t$  for each surface. It is 5 mm for the hollow cylinders and 3 mm for the based planes.

#### 11.4.1.2 Context

Because of the robotic context, the global objective is to minimize the mass of the studied part.

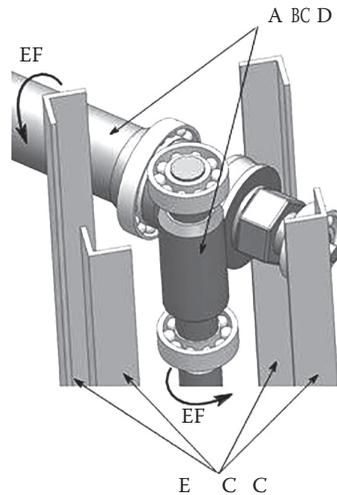


Figure 11.7 Global view of the studied system.

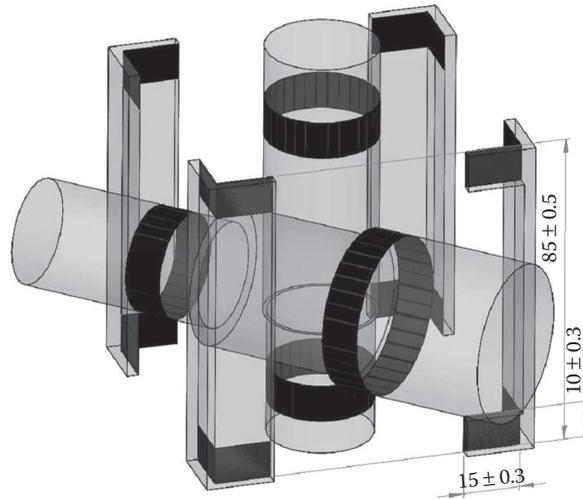


Figure 11.8 The FS and the empty volumes of the part to design.

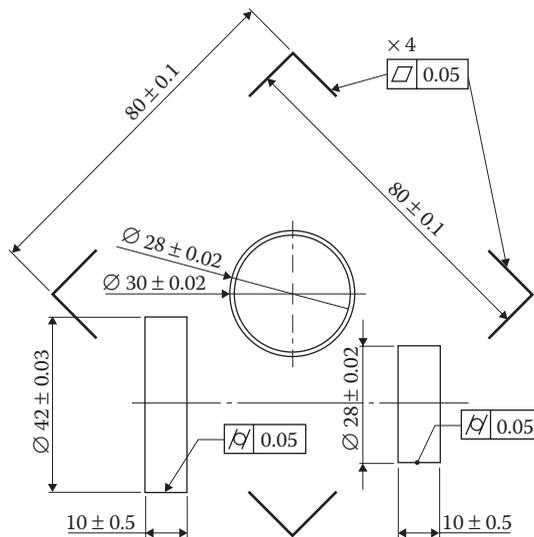


Figure 11.9 An extract of the specifications taken from the functional analysis of the case.

## 11.4.2 Manufacturing characteristics

### 11.4.2.1 The additive manufacturing process

The AM process chosen to manufacture this case is the construction laser additive direct or direct laser additive construction (CLAD) process (Figure 11.10). It is a PBMD process, based on the 3D layer-by-layer deposition of laser-melted powders. Its main characteristics are presented in Table 11.1.

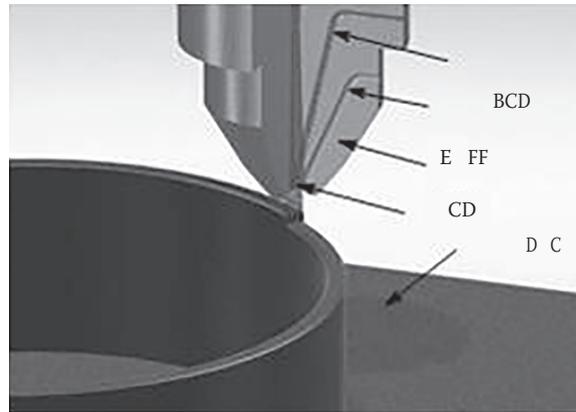


Figure 11.10 Clad process.

Table 11.1 CLAD process characteristics

Kinematics	Required accessibility (mm)	Maximal dimensions (mm)	$d$ (mm)	$a$ (mm)	$a$ (mm)
5 axis	0.60	500*560*700	0.8	0.3	0.2

In this example, the assumptions that parameters  $d$ ,  $a$ , and  $\alpha$  are equal in all the directions are made.

The constraints due to the physical phenomena linked with the process (in particular, the thermal phenomena) are considered in ways: first, the substrates' thickness must be at least equal to the thicknesses of the volumes that it enables to manufacture. Second, because the discontinuities in the  $MT$  may generate an unwanted variation of the process parameters and also a gap between the designed and the manufactured part, the geometry will be chosen to limit them.

#### 11.4.2.2 The finishing process

The finishing process that is chosen is high-speed milling; in view of the specification related to the  $FS$ , this choice involves a minimal and a maximal overthicknesses of 0.5 mm and 1 mm, respectively.

#### 11.4.3 Step 1: Analysis

According to the geometrical analysis of the  $FS$  (Figures 11.8 and 11.9) and to the maximal and minimal dimensions imposed by the manufacturing process (Table 11.1), all the dimensions are compatible, and all the  $FS$  can be merged in only one part.

#### 11.4.4 Step 2: Determination of the functional volumes

The thicknesses  $E$  are determined from the different parameters of Equations 11.2 and 11.3; for each  $FS$ , the results are given in Table 11.2. All the  $FV$  are shown in Figure 11.11a.

Table 11.2 Definition of the FS thicknesses

Surface type	$t$ (mm)	$a$ (mm)	$e_{\min}$ (mm)	$e_{\max}$ (mm)	$d$ (mm)	$E$ (mm)
Cylinder	5	0.2	0.5	1	0.8	5.9
Flat	3	0.2	0.5	1	0.8	3.6

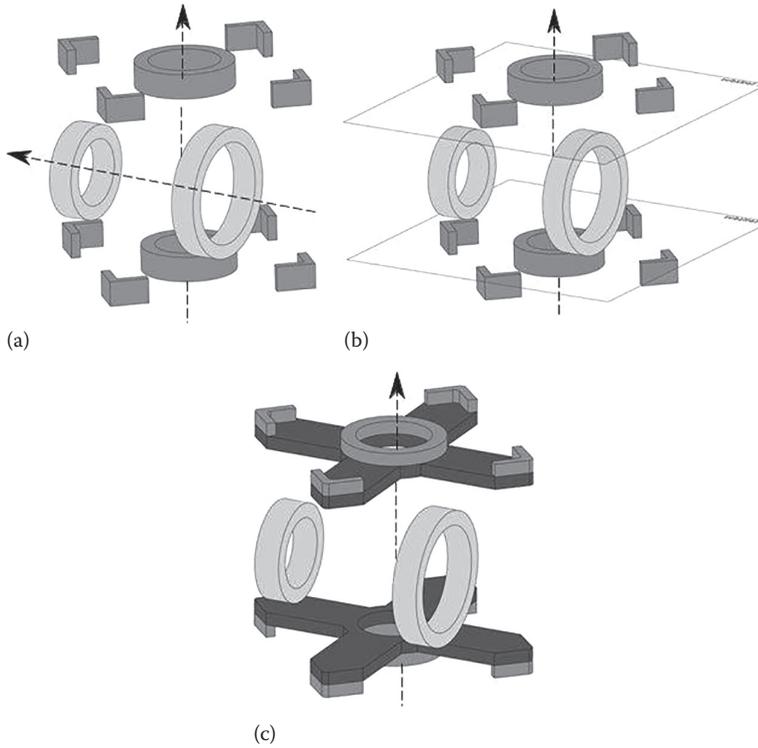


Figure 11.11 Definition of the LV in  $Z_1$  when  $Z_1$  is favored (a) the FV, (b) position of the substrates, and (c) the LV geometry in  $Z_1$ .

### 11.4.5 Step 3: Determination of the linking volumes

The MD are determined, due to the robotic context, to minimize the mass of the part and therefore the support structures' quantity. A geometrical analysis of the FV enables to determine two MD:  $Z_1$  and  $Z_2$  (Figure 11.11a).  $Z_1$  enables to manufacture heighten FV (in dark gray), and  $Z_2$  enables to obtain the two last (in light grey). If one or other of the MD is favored (which means that it is analysed in first), the final part geometry could not be the same. Both cases will be therefore analyzed, and the geometry which represented the best way of satisfying the study context will be selected. In case 1,  $Z_1$  is favored whereas in case 2,  $Z_2$  is favored.

#### 11.4.5.1 Case 1: When $Z_1$ is favored

**LVs in  $Z_1$**  To minimize supports in the empty volumes shown in Figure 11.8 and thus to minimize the finishing operations, all the selected FV linked to  $Z_1$  must not be manufactured together but from two different substrates. Their positions are determined (Figure 11.11b)

to minimize supports and time of finishing and to guarantee accessibility for the powder feed nozzle.

The selected *FV* geometry is locally modified in relation to the value of  $e_{\max}$  and  $e_{\min}$  to minimize the discontinuity of the *MT*. In particular, in the case of the raster discrete paths, it involves to define a radius  $R$  (Figure 11.12), which is given by Equation 11.5:

$$R = \frac{(2) \cdot (e_{\max} - e_{\min})}{(2) - 1} \quad (11.5)$$

Then the geometry of the substrates is defined according to the *FV* position and their thickness (in black in Figure 11.11c). Because all *FV* are not merged, a second *MD* is analyzed.

**LVs in  $Z_2$**  As previously discussed, because of the empty volumes, the two cylinders linked to  $Z_2$  cannot be manufactured together. It involves two substrates (Figure 11.13a). Moreover, the space between these *FV* and those already analyzed (those linked to  $Z_1$ ) being lower than the required one by the powder feed nozzle of the CLAD machine (Table 11.1), the accessibility requirements are not satisfied, and the *MD*  $Z_2$  cannot be used; the process is repeated one more time.

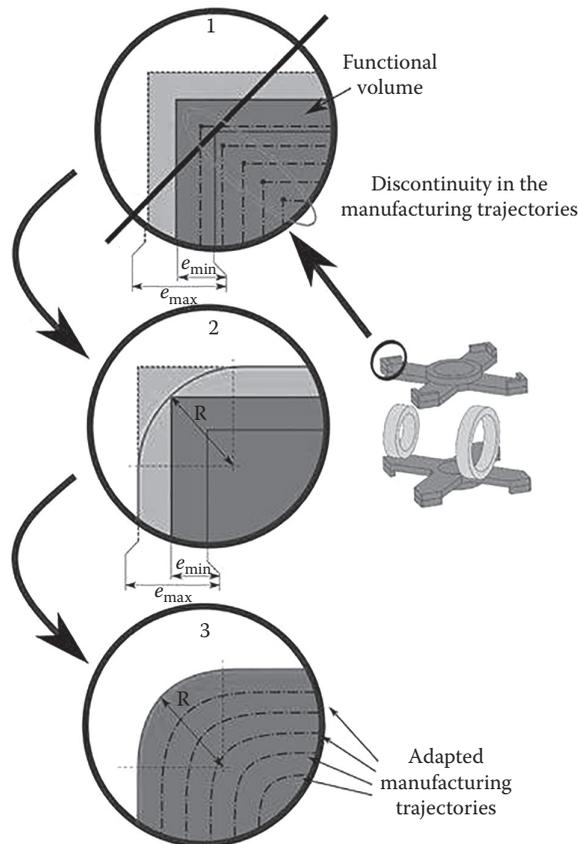
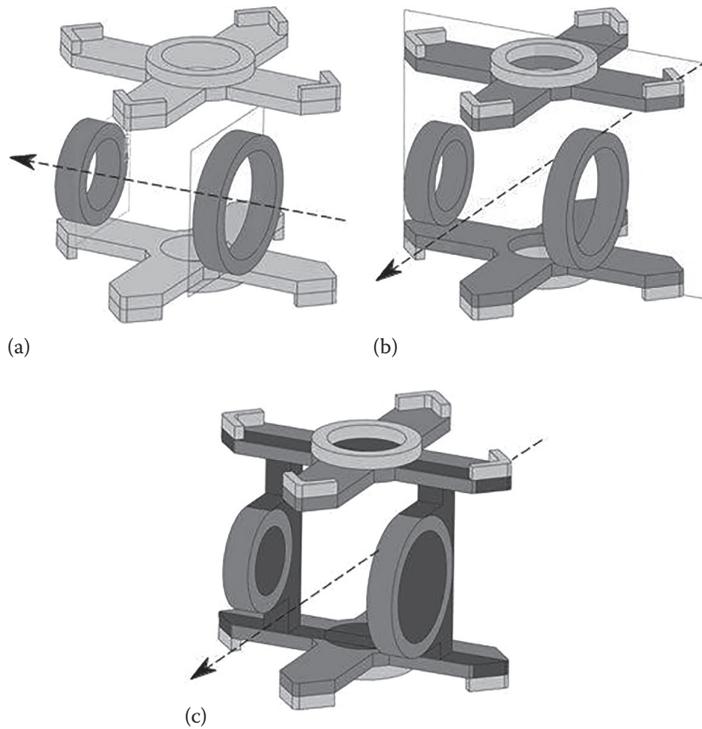


Figure 11.12 Local geometrical modifications to avoid the *MT* discontinuities.



**Figure 11.13** Definition of the LV in  $Z_2$  and  $Z_3$ , when  $Z_1$  is favored (a) position of the substrates in  $Z_2$ , (b) position of the substrate in  $Z_3$ , and (c) geometry of the substrate and the supports in  $Z_3$ .

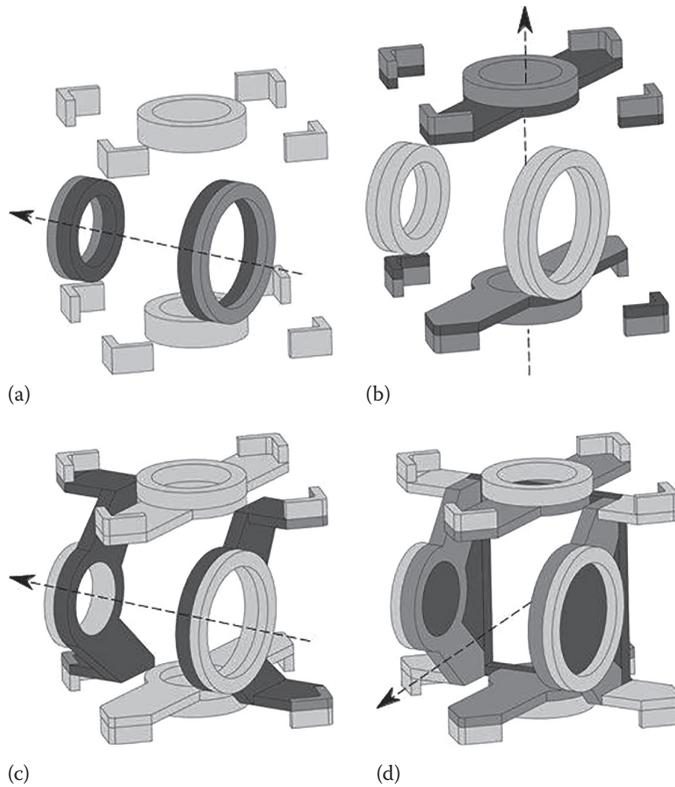
**LVs in  $Z_3$**  A third MD  $Z_3$  is determined from the previous substrates (linked to  $Z_1$ ) and FV (Figure 11.13b). The substrate and supports linked to  $Z_3$  are determined, as previously, due to the context, to minimize the material quantity and to avoid, as much as possible, the empty volumes. The substrate dimensions are given by the volumes that it merges. The supports geometry are simply defined by the orthogonal projection of the volumes linked to  $Z_3$  onto the substrate (Figure 11.13c). Finally, all the FV are merged, the design process is then complete, and the final blank part is obtained.

#### 11.4.5.2 Case 2: When $Z_2$ is favored

From the FV in Figure 11.11a, the same reasoning is applied, starting with the analyzed  $Z_2$ .

**LVs in  $Z_2$**  In the same way as above, because of the empty volumes, the two cylinders linked to  $Z_2$  cannot be manufactured together. Two substrates whose geometry is shown in black in Figure 11.14a are therefore defined.

**LVs in  $Z_1$**  Similarly, all the FV linked to  $Z_1$  cannot be manufactured together. First, as in the case where  $Z_1$  was favored, to minimize supports in the empty volumes, a minimum of two separated substrates is needed. Moreover, because of the manufacturing of the cylinders linked to  $Z_2$ , the accessibility required by the powder feed nozzle involves that each one of these two substrates has to be subdivided once again into tree-separated substrates. In the same way as previously, the geometry of the FV linked to  $Z_1$  is locally modified in relation to the value of  $e_{\max}$  and  $e_{\min}$ , and then the substrates' geometry is defined (in black in the Figure 11.14b).



**Figure 11.14** Definition of the different LV, when  $Z_2$  is favored (a) the LV geometry in  $Z_2$ , (b) the LV geometry in  $Z_1$ , (c) the LV geometry in  $Z_2$  after it is reanalyzed and (d) the Orthogonal projection to  $Z_3$ .

**New LVs in  $Z_2$**  As all the *FV* are not merged, another *MD* should be, thus, analyzed. Because of the accessibility requirement, all the substrates previously obtained cannot be merged to one another following only one *MD*.  $Z_2$ , being already selected and allowing to merge again several volumes of the part, is reanalyzed. The result is shown in [Figure 11.14c](#).

**LVs in  $Z_3$**  Because all the *FV* are still not merged, the design process is repeated once again. All the previous substrates (defined in  $Z_2$  and  $Z_1$ ) can be merged into a third *MD*:  $Z_3$ . The substrate position and geometry are determined; then the supports are defined by the orthogonal projection of the volumes linked to  $Z_3$  onto the substrate ([Figure 11.14d](#)).

Finally, all the *FV* are merged; the design process is thus complete, and the final blank part is obtained.

#### 11.4.6 Final result

Thanks to the proposed methodology, each shape of the part has been designed in order to utilize the CLAD $\check{c}$  process characteristics and capabilities to fulfil the study functional specifications while taking into account its general context. In the initial stage, from the geometrical analysis of the FS and according to the objective of minimizing the final part mass, two *MDs* have been selected ( $Z_1$  and  $Z_2$ ). Because the favoring of the one or other may have an impact on the final part geometry, the two cases have been studied. The

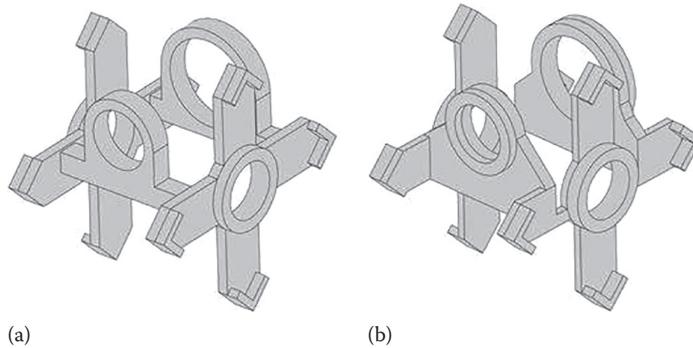


Figure 11.15 The final geometry: (a) when  $Z_1$  is favored and (b) when  $Z_2$  is favored.

Table 11.3 Characteristics of the two proposed solutions

	When $Z_1$ is favored	When $Z_2$ is favored
Blank part mass (g)	775.9	627.5
Finished part mass (g)	548.6	499.0
Maximal von-Mises stress (MPa)	15.3	22.6
Maximal displacement (mm)	0.041	0.015

final results, obtained after considering the finishing operation which enables to meet the required specifications (geometrical and dimensional) and to remove the material in the empty volumes, are shown in Figure 11.15. A finite element method analysis has been done to simulate the mechanical behavior of the proposed designs under the robot normal condition of use. Because, the results are quite close to each other compared with the material limits, they do not really enable to make a choice between both proposed solutions. However, as it is shown in Table 11.3, the favoring of  $Z_2$  over  $Z_1$  results in a lower mass of the blank part (around 19%) and of the finished part (around 9%). It allows, therefore, a lower manufacturing cost and to meet the global objective given by the robotic context of the study better. This solution is thus finally selected.

## 11.5 Conclusion

This paper described the initial stage of a promising research project which deals with a global DFAM approach. A new methodology is proposed to obtain an appropriate design for AM processes. In contrary to the classical DFM approaches, to prevent the psychological inertia phenomena which may limit the design innovation and to best utilize the AM processes' capabilities, the proposed methodology starts directly from both functional specifications and AM processes' characteristics. The required data for such a global DFAM approach have been presented. Then the three steps of the methodology allowing to reach to take into account all of them has been detailed and illustrated by a case study taken from the robotic field.

Further research will be conducted to optimize the methodology in particular regarding the local optimization of the shapes and the internal structures of the LVs in terms of functionality as it is done, for example, by [26]. In parallel, new criteria of choice for

MT will be developed to always adapt the local geometry more regarding the physical phenomena which occur during the manufacturing process.

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