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Axiomatic Design of Customised Additive Manufacturing Artefacts

Saint-Clair T. Toguem[a,b]*, Charyar Mehdi-Souzani[a], Hichem Nouira[b], Nabil Anwer[a]

[a]*LURPA, ENS Paris-Saclay, Univ. Paris-Sud, Université Paris 13, Sorbonne Paris Cité, Université Paris-Saclay, 94235 Cachan, France*
[b]*Laboratoire National de Métrologie et d'Essais (LNE), 1 Rue Gaston Boissier, 75015 Paris, France*

* Corresponding author. *E-mail address:* stoguemt@ens-paris-saclay.fr

Abstract

Additive Manufacturing (AM) opens new horizons and paradigms for design, manufacturing and even tertiary activities. However, the quality of built parts in terms of mechanical properties, surface texture, geometrical and dimensional accuracy, remains highly dependent not only on AM systems' parameters, but also on the chosen process among the numerous available AM processes. Therefore, to control the quality of built parts, it is essential to evaluate the influence of each process-related and system parameter. This can be done by building meta-models for the prediction of printed parts' output properties or through experimentations using artefacts. Another approach consists in pure analytical modelling of AM processes and systems based on physics and thermo-mechanical phenomena occurring during the build phase. Finally, there are hybrid compensation models based on process physics analysis and experimentations using artefacts. In all of the aforementioned methods, AM artefacts are crucial to predict, build and validate models. However, essentially due to a lack of systematic design guidelines, several proposals for standardised AM artefacts ended up unsuccessfully. By taking advantage of concepts and tools of axiomatic design, this work introduces a detailed and systematic design approach for customised AM artefacts. A case study is also detailed and discussed.

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Keywords: Axiomatic Design, AM Artefacts, Design guidelines, GD&T specifications

1. Introduction

In order to increase the viability of AM, many researches are conducted to assess and improve AM systems performances with regard to geometrical dimensioning and tolerancing (GD&T), surface texture and mechanical proprieties of built parts [1]. Yet, because of technological limitations, the current efforts are mainly based on the usage of artefacts to establish, evaluate and validate performance models. However, the large variety of AM systems and processes makes it practically difficult for one single artefact to be suitable for all AM systems and processes. Consequently, the introduction of systematic design guidelines for customised designs of artefacts may be useful.

Few attempts in the literature aim at establishing design methodologies for AM artefacts. Jacobs and Richter [2] first introduced a set of design criteria for AM artefacts. Several artefacts have been developed based on these [3] [4]. However the proposed criteria are mainly defined in the solution domain. This can restrict the scope of solution and may lead to non-optimal design and confusions between concepts such as spatial repeatability and repeatability of AM systems. Misconceptions from these criteria definition are well discussed by [5] and [6].

As an attempt to improve Jacobs and Richter's criteria, Buyn and Lee [7] recommend to align features along all the axes of the AM system. The latter also propose a guideline for optimal arrangements of features. Scaravetti *et al.* [8] state that the part should require no post-processing while Souzani

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et al. [9] emphasise the importance of complex features to evaluate the systems' capabilities for complex shapes and lattice structures.

To cope with these limitations, Moylan [5] proposed a set of design criteria, appropriately defined in the functional domain. These criteria inspired many AM artefacts designs. Nevertheless, two critical characteristics still need to be fulfilled: the collective exhaustiveness and the independence between defined criteria [6]. These characteristics depict the two axioms of Axiomatic Design; the independence axiom and the information axiom. In addition to its self-consistency and the provided metrics for quality, the AD approach especially deals with complexity reduction and non-productive iterations. Moreover, with its adaptability, robustness and simplicity represented by a comprehensible semantic [10], AD stands out among the numerous other design methodologies.

Following a previous review and mapping of current AM design criteria into design requirements [4] [6], the present work intends to discuss an enhanced design guideline for AM artefacts based on AD tools and concepts. The next sections of this paper will first introduce AD concepts and tools for the design of AM artefacts, then a brief review of current design criteria will lead to the definition of FRs and CONs for AM artefacts. Finally, through a discussion of a case study, optimal DPs for AM artefacts will be introduced.

Nomenclature

AD	Axiomatic Design
CNs	Customer Needs
FRs	Functional Requirements
CONs	Constraints
DPs	Design parameters

2. AD for an optimal design of AM artefacts

This approach is based on the definition of a systematic analysis process through the design space, consisted of four domains: the customer domain, the functional domain, the physical domain and the process domain. The customer domain is the space of CNs. The functional domain consists in set of FRs hierarchically arranged. The physical domain is the space of DPs, also called the solution domain and the process domain is where the process variables are defined.

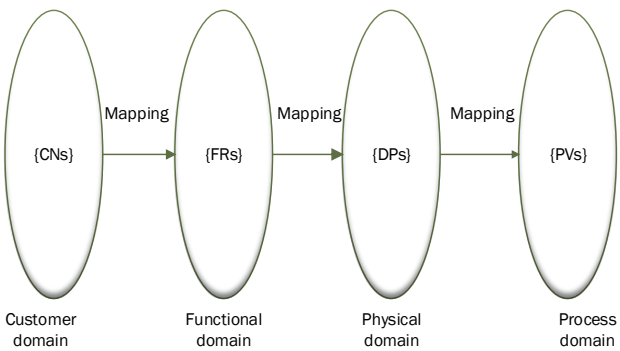

Fig. 1. Schematic representation of the design space [11].

AD approach consists in defining the functional requirements (FRs) based on customer needs (CNs) and then choosing the design parameters (DPs) to fulfil those FRs. Each step of the design process in governs by the axioms. This structured approach offers the possibility to ideally decompose the complex design problem of AM artefacts into smaller elements to make the solution obvious.

AD approach minimises random choices in the design process ruled by a set of axioms. In order to improve design processes, P. Suh discovered the axioms in the late 70s and stated them as follows [12]:

Axiom1: the independence axiom; "maintain the independence of the functional requirements."

Axiom2: the information axiom; "minimize the information content of the design"

The corollaries and theorems resulting from the axioms are well discussed in [13]. Furthermore, Brown *et al*. [10] discussed the metric for FRs development and DPs selection.

The mapping between FRs and DPs is represented by equation (1), where [A] is the design matrix. The coefficients a_{ij} of [A] denote the relationship between the ith FRs and the jth DPs.

$$\{FRs\} = \overbrace{\begin{pmatrix} & \cdots & \\ \vdots & \ddots & \vdots \\ & \cdots & \end{pmatrix}}^{[A]} \{DPs\} \tag{1}$$

The type of design depends on the form of [A]. When the design matrix is diagonal, the design is uncoupled. A decoupled design is represented by a triangular design matrix. For other forms of [A], the design is decoupled [14].

3. Discussion of the case study

As a part of a more global project aiming at pre-evaluating the performances of AM systems and processes, the study conducted here focusses on the evaluation of AM systems. This analysis may help in the choice of suitable AM systems from the numerous existing systems. However, the introduced analysis and the design methodology could also apply to AM processes evaluation.

3.1. FRs and CONs definition

Characterising AM systems is looking into the mechanical properties, the GD&T accuracy and the surface texture of built parts. Another important aspect is the fit for assembly performances which has currently received comparably less attention in the literature. Thus, the higher-level FRs can be stated as follows:

FR0 = Characterise AM systems

- FR01 = Evaluate mechanical properties of built parts
- FR02 = Evaluate GD&T accuracy of built parts
- FR03 = Evaluate surface texture of built parts
- FR04 = Evaluate fit for assembly performances

In the following, the analysis is detailed only for the GD&T accuracy evaluation. GD&T is about form, orientation and dimensional characteristics. One can also add the repeatability

and minimum feasible size properties. Therefore, the lower-level FRs for FR02 may be defined as follows:

FR02 = Evaluate GD&T accuracy of built parts
- FR021 = Evaluate form accuracy
- FR022 = Evaluate orientation accuracy
- FR023 = Evaluate dimensional accuracy
- FR024 = Evaluate spatial repeatability
- FR025 = Evaluate repeatability
- FR026 = Evaluate system's minimum feasible size

FR023 to FR026 are at their leaf-level and does not need additional decomposition.
Form accuracy stands for straightness, flatness, circularity, cylindricity, line and surface profile accuracy. The corresponding FRs can be defined thusly:

FR021 = Evaluate form accuracy
- FR0211 = Evaluate straightness accuracy
- FR0212 = Evaluate flatness accuracy
- FR0213 = Evaluate circularity accuracy
- FR0214 = Evaluate cylindricity accuracy
- FR0215 = Evaluate line profile accuracy
- FR0216 = Evaluate surface profile accuracy

Orientation characteristic is about perpendicularity, parallelism and angularity. Hence, FR022 may be decomposed as follows:

FR022 = Evaluate orientation accuracy
- FR0221 = Evaluate perpendicularity accuracy
- FR0222 = Evaluate parallelism accuracy
- FR0223 = Evaluate angularity accuracy

Based on the summary of common design criteria for AM artefacts introduced in [6], the main design constraints are related to the evaluation of the system's performances across the entire building volume and along the different axis. The building scale is also an important element to consider as well as the process-related constraints and the measurement systems. For instance, with Computed Tomography (XCT), axis-symmetric features are preferable to cubic and cuboid. This will further affect the choice of DPs in the solution. Also, feature sizes, orientation and arrangement may be affected by accessibility issues which depend on the measurement system. We also have resources' consumption (building time and material consumption) and digital chain errors. Therefore, the following CONs can be formulated:

CON1 = Evaluate system abilities across the entire building volume
CON2 = Evaluate system abilities at different building scales
CON3 = Evaluate system abilities along the different axis (x, y, z)
CON4 = Consider specific process-related constraints
CON5 = Consider measurement systems constraints
CON6 = Minimise resources consumption
CON7 = Minimise digital chain errors

3.2. Design process and optimisation: DPs definition

The zigzagging process applied here, consists in iteratively move back and forth from the functional domain to the physical domain until the decomposition is completed. This means defining the optimal DPs at each level of decomposition that leads to an uncoupled or decoupled design. The best DPs should be in interrelation with the minimum FRs possible and ideally with only one FR. In addition, they should not be in conflict with any constraint. This can be formulated as follows: $t(DP_j) = 1$ for all design parameters DP_j with: $t(DP_j) = \prod_i f(CN_i, DP_j)$. Where f is a Boolean function defined by the following equation (2).

$$f(CN_i, DP_j) = \begin{cases} 0 \; if \; CN_i \; is \; in \; conflict \; with \; DP_j \\ 1 \qquad\qquad\qquad\qquad otherwise \end{cases} \tag{2}$$

When many alternatives for DPs are available, it might be useful to analyse each combination to improve the design matrix.

For the highest-level functional requirement FR0, three elements can be identified in the solution domain:
DP0_1 = meta-models for the prediction of printed parts' output properties
DP0_2 = experimentations using artefacts
DP0_3 = analytical modelling of AM processes based on physics and thermo-mechanical phenomena

However, building meta-models needs a large volume data. This requires important resources in terms of time and material. Therefore, DP0_1 is in conflict with CON6 and $t(DP0_1) = 0$. Furthermore, the complexity of analytical modelling makes its implementation practically difficult. Also, it appears that all the previous DPs are artefacts' dependent for the building or the validation of models. Thus DP0_2 is a convenient solution.

For FR01, FR02, FR03 and FR04 the design solutions can be defined as follows:
DP01 = Test samples; the form is based on the measurement system chosen.
DP02 = Features arranged on a base plate.
Another solution is to use many different and separated parts.
DP03 = Set of planes arranged on a base.
DP04 = Assembled parts.
None of the DPs are in conflict with the defined constraints $t(DP01) = t(DP01) = t(DP01) = t(DP01) = 1$. Also, the corresponding design matrix shown in Table 1, is uncoupled.

Table 1. Design matrix for FR0 (X represents a relationship between the corresponding FRs and DPs).

	DP01	DP02	DP03	DP04
FR01	X			
FR02		X		
FR03			X	
FR04				X

For the subset FRs of FR02, the design solutions may be formulated as follows:
DP021 = Features with privileged forms (complex/simple forms).
DP022 = Features aligned with respect to the orientation to evaluate.
DP023 = Set features dimension as equal or proportional to reference sizes.
DP024 = Duplicate features with the same sizes and orientations across the building surface.
DP025 = Build the same set of features several time at the same location on the building surface.
DP026 = Use repeated features with decreasing sizes.

Table 2. Design matrix for FR02 (X represents the interrelation between FRs and DPs).

	DP021	DP022	DP023	DP024	DP025	DP026
FR021	X					
FR022		X				
FR023			X			
FR024				X		
FR025					X	
FR026						X

The previous table representing the corresponding uncoupled design matrix shows the adequacy of the chosen DPs.

For FR021, the groups of design solutions corresponding to FR0211-FR0216 may be stated as follows:
<DP0211> = Features with intersecting parallel cylinders, features with intersecting plane surfaces: cubes, cuboids, prisms (hexagonal, triangular, etc.), pyramids (square-based, tetrahedra).
<DP0212> = Features with flat surfaces: cubes, cuboids, prisms (hexagonal, triangular, etc.), pyramids (square-based, tetrahedra, hexagonal), cylinders, cone holes, truncated spheres.
<DP0213> = Truncated axis-symmetric protrusions and depressions: cylinders, truncated cones, truncated spheres, etc.
<DP0214> = Cylindrical protrusions and depressions: cylinders.
<DP0215> = Intersecting NURBS and quadric surfaces with a datum reference.
<DP0216> = NURBS and quadric surfaces with a datum reference.

For each FR, the designer can choose elements from the corresponding group of DPs. The best combination of DPs, should lead to an uncoupled design [12], otherwise, to a decoupled design (upper/lower triangular design matrix).
The general form of the design matrix for the subset FRs of FR021 is as follows:

Table 3. General structure of the design matrix for FR021 (X represents the interrelation between FRs and DPs).

	DP0211	DP0212	DP0213	DP0214	DP0215	DP0216
FR0211	X	X				
FR0212	X	X				
FR0213			X	X		
FR0214			X	X		
FR0215					X	X
FR0216					X	X

The corresponding Design Matrix is neither uncoupled nor decoupled. To cope with this, one may separate the design into small fully coupled designs as shown in Table 4. Thereby an appropriate choice of DPs may lead to a decoupled design.

Table 4. FRs grouping; (a) Group 1, (b) Group 2, (c) Group 3.

(a)

	DP0211	DP0212
FR0211	X	X
FR0212	X	X

(b)

	DP0213	DP0214
FR0213	X	X
FR0214	X	X

(c)

	DP0215	DP0216
FR0215	X	X
FR0216	X	X

For Group 1, if DP0211 = features with intersecting parallel cylinders and DP0212 = cuboids/cubes, the corresponding design matrix becomes upper triangular decoupled as follows:

Table 5. Decoupling of coupled design.

	DP0211	DP0212
FR0211	X	X
FR0212		X

The same process can be repeated with groups 2 and 3 to choose the appropriate DPs for FR021.

Another advisable approach may consist in setting the combination stated as:
DP0211 = features with intersecting parallel cylinders
DP0212 = cuboid holes
DP0213 = hemispheres
DP0214 = cylindrical holes
DP0215 = intersecting NURBS and quadric surfaces with a datum reference.
DP0216 = depression NURBS and quadric surfaces with a datum reference.

The corresponding design matrix depicted in Table 6 is an almost diagonal matrix. This is an interesting alternative to a fully coupled design. Nevertheless, in the context of AM artefacts, a coupled design can be advantageous because it leads to characteristics evaluated by many features. This redundancy in performance evaluation may be useful for the confirmation and validation of results. This is, however, acceptable only in the limits of available resources (building time and material consumption).

Table 6. Design matrix for FR021 (X represents the interrelation between FRs and DPs).

	DP0211	DP0212	DP0213	DP0214	DP0215	DP0216
FR0211	X					
FR0212		X				
FR0213			X			
FR0214				X		
FR0215					X	
FR0216					X	X

For FR022, the design solutions can be defined as follows:

DP0221 = features with surface(s) perpendicular to a reference (e.g. cuboids, cubes, pyramids).
DP0222 = features with surface(s) parallel to a reference (e.g. cuboids, cubes, truncated cones, truncated pyramids).
DP0223 = prismatic primitive features with variating angles.
These DPs lead to an uncoupled design as can be seen in Table 7.

Table 7. Design matrix for FR022 (X represents the interrelation between FRs and DPs).

	DP0221	DP0222	DP0223
FR0221	X		
FR0222		X	
FR0223			X

The final design solution is built in the physical domain by progressively integrating lower-level DPs into the higher ones. This will result in a set of appropriate features optimally sized, arranged and orientated on a base plate. Fig. 2. portrays the FRs decomposition and the corresponding DPs.

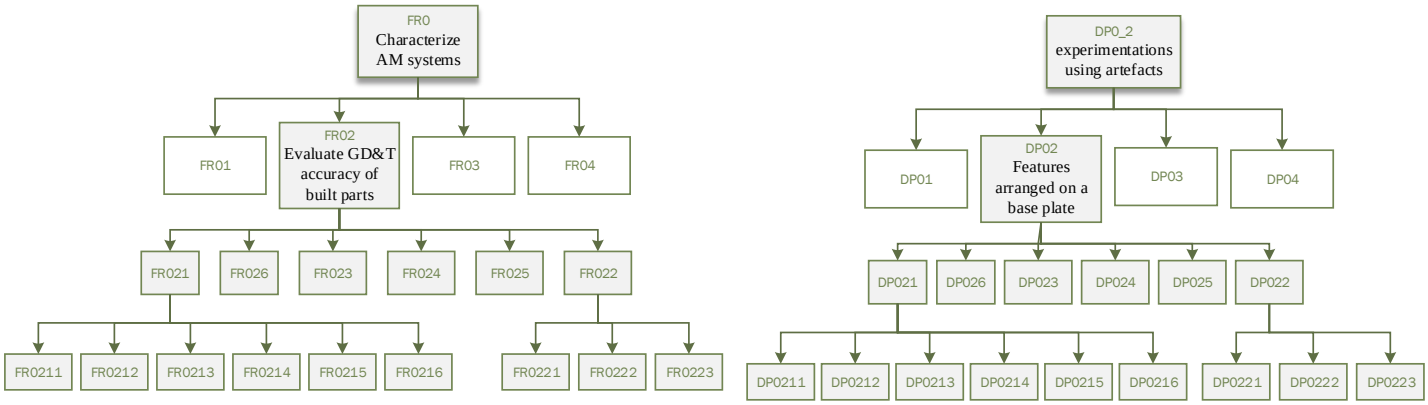

Fig. 2. Summary of FRs and DPs decomposition

3.3. Results

The previous analysis leads to an artefact for (Laser Powder Bed Fusion) L-PBF systems characterisation shown in Fig. 3. Features are arranged on a base plate to cope with post-processing issues. A brief description is given in Table 6. The designed artefact was printed using a L-PBF system (Fig. 4.). The system was characterised by measuring and comparing features' forms, sizes, orientations and locations with the reference CAD model.

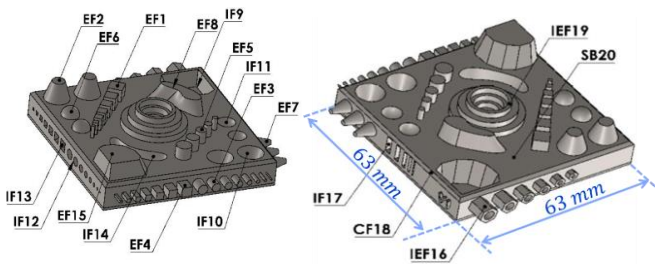

Fig. 3. CAD model of the artefact [6].

Fig. 4. Printed artefact (Z axis represents the building direction) [6]

Table 6. Features description

FEATURES	PERFORMANCE EVALUATED
EF1	Flatness, location, angularity, straightness and orientation at different scales, spatial repeatability of forms (cube).
EF2 & IF10	Circularity at different heights and scales, flatness, tapers, location, spatial repeatability of sizes and forms (cone)
EF3 & IF12	Circularity, cylindricity, minimum feasible size (extruded/holed), location, spatial repeatability of forms (cylinder) along the x-axis/y-axis.
EF4 & IF13	Flatness, location, angularity, straightness and orientation at different scales and along the x-axis/y-axis, spatial repeatability of forms (cube), minimum feasible size (extruded/holed).
EF5	Circularity, cylindricity, location, spatial repeatability of forms (cylinder)
EF6 & IF11	Sphericity, spatial repeatability of forms and dimensions (sphere)
EF7	Circularity at different heights and scales, flatness, tapers, location, spatial repeatability of sizes and forms (cone) along the y-axis
EF8 & IF14	Performance to build complex forms both extruded and holed
IF9 & EF15	Flatness, angularity, straightness both extruded and holed
IEF16	Flatness, angularity, straightness, minimum feasible size, coaxiality
IF17	Minimum feasible size along the y-axis
CF18	Flatness, angularity
IEF19	Coaxiality, cylindricity, flatness, location, perpendicularity
SB20	Flatness, perpendicularity

4. Conclusion

This work intended to propose a design approach for AM artefacts based on AD. Through a review of current design methods for AM artefacts, the lack of systematic design methodology is pointed out. Moreover, the suitability of AD approach for solving such design problems is highlighted.

From the highest to the lowest level, the suitable FRs are defined. For each level, the best DPs are chosen and commented in order to have either an uncoupled design (in the ideal case) or a decoupled design. Redundancy issues are solved by applying AD theorems. The chosen decomposition process is the zigzagging between domains from higher to leaf-level FRs until the solution is evident. The final solution is built by integrating partial solutions into the higher-level solutions.

A case study is discussed and the application of established design methodology leads to an artefact for GD&T accuracy evaluation. Future efforts should focus on moving toward design software for the developments of customised AM artefacts. The targeted design tool will ease the customisation of AM artefacts by guiding the designers throughout the design process for optimal design choices.

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