Test artefacts for additive manufacturing: a design methodology review

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For the past few decades, additive manufacturing (AM) has paved the way to several processes through a wide range of commercially available machines. Benchmark artefacts were developed to set a common reference in order to assess and compare AM machine limitations. In this paper, a review of different AM benchmark artefact design methodologies is presented. More precisely, the evolution of design methods is described. Originally, additive manufacturing machines were assessed by establishing their ability to produce defined features. Indeed, AM benchmark artefact design inherited traditional subtractive manufacturing methods by defining simple geometries. However, due to the AM available freedom, no standard artefact can be sufficiently representative of the diversity of studied criteria. Furthermore, metrology aspects were not considered. Facing the variety of benchmark artefacts available, proposed guidelines then focused on defining systematic design methods rather than standard artefacts. Several methods have been proposed to help designing benchmark artefact suited for considered criteria. Nevertheless, some traditional simple geometries are found incompatible with measuring instruments that can hardly characterise AM free-form surfaces for example. That is why, more recently, significant efforts have been made to consider measurement issues and uncertainties in the artefact design stage. As this paper concludes, benchmark artefacts now tend to be designed in a more metrological way integrating the whole post-manufacturing measurement process relying on statistical modelling and instrument comparisons. Regarding the raised stakes, a final set of recommendations is provided to conciliate both manufacturers' and metrologists' point of view in benchmark artefact design.

***Index Terms*—Additive manufacturing, artefact design guidelines, measurement strategies**

I. Introduction

Additive manufacturing (AM) refers to the layer-by-layer approach of producing parts. Since the 90's, AM allows the achievement of complex geometries inaccessible to conventional subtractive or formative methods [1]. Although ISO defines seven AM families [2], there are hundreds of available machines relying on different processes, technologies and materials reviewed in [3, 4, 5, 6]. Such AM diversity is specifically reviewed for metallic materials in [7, 8] and for laser technologies in [9]. The increasing number of these AM machines and processes raises the need for developing tools and methods to assess their capabilities and limitations. Indeed, geometrical and dimensional quality inspections are important stakes to give industrials confidence into AM products [10]. More precisely, in order to compare different AM machines or processes, the same 3D model can be used as a common basis to make comparisons [11]. Consequently, many authors developed a single part comprising defined geometrical features and shapes, manufactured by different AM machines. This part is called a benchmark artefact [12] and allows AM machines limitations to be highlighted by comparing resulting artefact to another.

However, since there is currently no standard benchmark artefact suitable for all AM machines and processes, authors design customised benchmark artefact matching with specific properties to investigate. For the last decades, there has been hundreds of designed artefacts [13]. Mahesh is the first author to propose a three-fold classification according to their main definition [12, 13]. The first group of artefacts refers to geometric artefacts manufactured to characterise accuracy and dimensional performances of AM machines. Geometric artefacts are often defined based on a set of criteria implicitly translated into design requirements and geometrical constraints [14]. The second group of artefact encompasses benchmark artefacts designed to test and to validate mechanical properties such as stiffness, shrinkage or warping. The third group named 'process benchmark' refers to artefacts designed to optimise process parameters such as orientation, hatching space or layer thickness.

In this paper, a review of geometrical benchmark artefacts is presented and more precisely, evolutions in their design methodology are highlighted. Section II summarises the most commonly used methodology for benchmark artefact design. This section also reviews standardisation attempts to turn the design step into a systematic procedure linked to a need-based approach. Section III highlights limitations of previous benchmark studies measurement campaigns and develops the need to assimilate the manufacturer's and the metrologist's points of view. This point is discussed in section IV by presenting a final set of recommendations in the design process of benchmark artefact. Conclusions are drawn in section V regarding recently published papers suggesting the integration of metrology issues in the design process.

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II. Benchmark artefacts for geometrical assessments of AM machines and processes

A. An artefact design framework for AM

AM offers a freedom of design specifications and each researcher can define their own benchmark artefacts. Reviews refer to various benchmark artefacts and all of them rely on a diversity of studied properties [12, 13]. Nevertheless, most of the considered artefacts reference Richter and Jacobs [15]. Indeed, Richter and Jacobs are the first authors who foresaw the need to design artefact in order to provide with qualitative comparisons through an 'ideal accuracy test part'. More precisely, benchmark artefact:

- should be large enough to test performances on borders as well as near the center of the building volume
- should have a substantial number of small, medium and large features
- should comprise different holes and bosses
- should have a reasonable time-to-build
- should not consume a large amount of material
- should be easy to measure
- should comprise a wide range of real part features (thin walls, surfaces, hole...)

Many authors have relied on these rules. For example, Byun et al. [16] conducted a geometrical benchmark study in order to investigate dimensional and surface quality according to Richter and Jacob's rules. Their artefact comprises many features such as holes, spheres, steps and walls accessible to coordinate measurement machine (CMM). Indeed, measuring these features and comparing with the design specifications allows machine limitations to be quantitatively evaluated. However, as highlighted by Yang et al. [17], the limiting parameters for artefact designs are features size arrangement and orientation. That is why Byun et al. [16] focused their research in a benchmark study which would take into account these limiting parameters. They ended up arguing that features should be aligned with the machine coordinate axis in order to facilitate measurements and to best identify capabilities and limitations of the AM system. As an example, Figure 1 highlights the alignment definition provided by Byun et al. [16] in the artefact design step.

B. Geometrical approach for benchmark artefact design

Even though Richter and Jacobs's original rules for benchmark studies are considered as the main criteria for designing artefacts [14, 15], reviews referenced hundreds of different artefacts [13, 18]. However, they commonly rely on the same generic approach. As reported by Rebaioli et al. [13], overall artefact size is firstly chosen in line with the main objective of the benchmark study. For example, large artefacts may evaluate the part position influence on printing accuracy within the building volume. Then, simple features are chosen according to the studied parameters. For example flatness criterion would require the design of cubes, walls or slots. Reviews [13, 14, 18] summarise the links between the geometric dimensioning and tolerancing and the corresponding features to design. A simplified approach is presented in Table I. As Toguem Tagne et al. explain [14], the final artefact depends on the design approach, the integration of criteria, and constraints translated into the definition of the computer-aided-design (CAD) model.

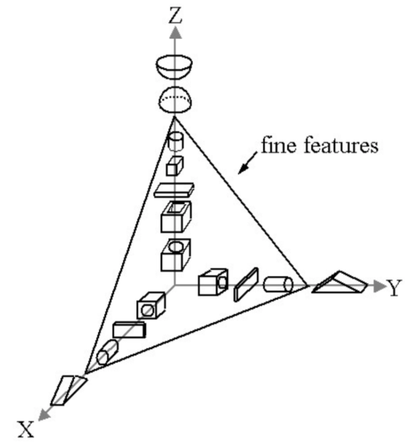

Fig. 1. Byun et al.'s definition of axis aligned features [16]

TABLE I
Example of common features used to assess AM main geometric capabilities

Geometrical definition and tolerancing	Corresponding feature
Flatness	Cubes, flat beam, slots, thin walls, base surface
Straightness	Cubes, flat beam, slots, thin walls, base surface
Circularity	Circular holes, cylinders
Parralelism	Cubes, rectangular or square holes and bosses, walls
Perpendicularity	Cubes, circular holes and bosses, square holes
Cylindricity	Circular holes and bosses, solid and hollow cylinders
Concentricity	Cylindrical holes
Angularity	Tilted surfaces
Position	Holes, cylinders
Profile	Cones, spheres, hemispheres
Minimum feasible size	Fine features, holes and pins

C. Artefact manufacturing

Benchmark artefacts are representative of the manufacturing process and machine performance. However, in order to fully understand the process and to precisely characterise the measured defects, artefact should be linked to the manufacturing framework. As described by Gibson et al. and by Thompson

[1, 19], additively manufactured parts are produced following eight steps:

- Step 1: CAD. The designer creates a 3-dimensional (3D) model to match specific geometries
- Step 2: Conversion to standard tessellation language (STL) file format. The CAD model is translated into a triangulated mesh representative of the CAD geometry.
- Step 3: File transfer to the AM machine. The STL file is transferred to the AM machine where inner procedure slices it into successive layers. According to the AM process considered, machine code is generated to manufacture each of these layers.
- Step 4: Machine setup. The user sets up process parameters.
- Step 5: Build. The part is built within the machine building chamber. As fully automated, only partial human monitoring is needed to ensure the smooth running of the process.
- Step 6: Removal. When the part is built, some remaining processes may be needed to extract the part such as cooling timeouts of the building chamber.
- Step 7: Post-processing. Some additional post-processing steps may be needed such as clean-up or support structures removal. This time-consuming step requires user manipulation.
- Step 8: The part is now built and post-processed, ready to be used.

Although AM benchmark artefacts are built following the same procedure, CAD step may be more thoughtful to identify specific studied properties. However, the design of a specific feature for test artefacts can be considerably affected by different AM system capabilities such as machines and materials. That is why, CAD artefact definition mainly relies on the manufacturer's experience on printability according to the machines and the materials.

D. *Artefact to defect source correlation*

Moylan et al. [18] considered that previous artefact designs were not sufficient because characterising AM limitations and capabilities on the one hand, and identifying an AM defect diagnosis on the other hand, had always been separately studied. The noteworthiness of Moylan et al.'s artefact is the combination of these concepts into a single artefact. For example, Scaravetti et al. [20] developed an approach to design artefacts dedicated to highlight the correlation between defects and machine parameters. More precisely, although they highlight the difficulty to dissociate influence factors of the defects, their procedure identified for example part shrinkage as depending on the thickness and material compression on part edges would change with cooling processes. Moreover, Moylan et al. [18] argue that previous artefacts are not sufficient because they did not take spatial repeatability into account. Moylan et al. thus designed their own artefact to integrate this aspect. The resulting artefact is shown in Figure 2. In the same wake, Fahad et al. [11] realised that previous artefacts comprised different but single features. None of these artefacts focused on a process repeatability study. To perform such an investigation, several and repeated artefacts are needed. To simplify, Fahad et al. designed a benchmark artefact which would take the AM process spatial repeatability into account. Such artefact is shown in Figure 3. More precisely, their part is divided into sections of symmetrically distributed repeated features. Such compact and spatially repeated features enable to characterise not only performances of the AM process but also help understanding the AM process spatial repeatability. Indeed, by measuring the repeated features, discrepancies can be outlined and the machine spatial repeatability is then highlighted. However, Bauza et al. [22, 23] investigated the impact of the part removing step on the measured geometry. As a post-processing step, authors argue that measuring artefact after having removed it from the building volume arouses major geometric changes such as part warping due to residual stresses. These geometric changes are believed to increase the difficulty for the metrologist to link observed defect to machine performances.

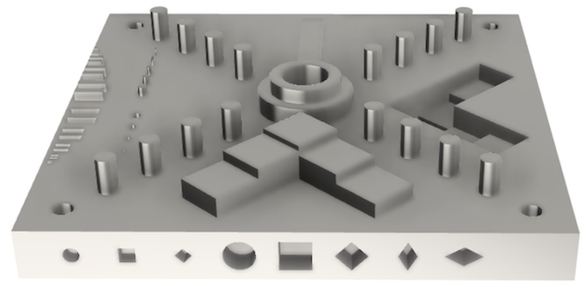

Fig. 2. Moylan's artefact, accessible in [21]

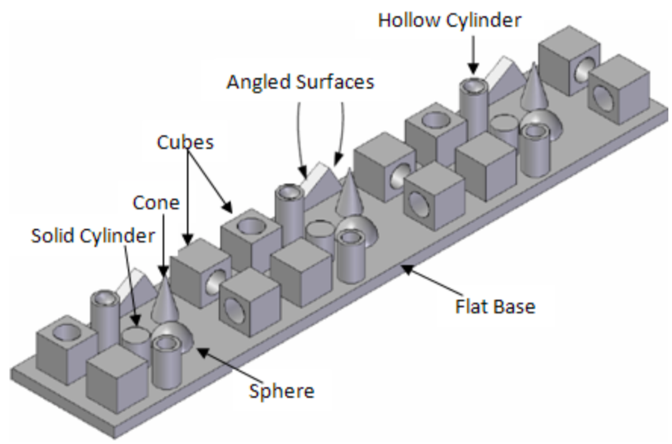

Fig. 3. Fahad et al.'s artefact comprising spatial repeatability of features [11]

Furthermore, Yang et al. [17] focused their works on defining a good practice guide in benchmark studies. They esteemed that Moylan et al.'s artefact (see Figure 2) was not sufficient and could be improved. Indeed, as they explained, benchmark studies inherit from subtractive and formative manufacturing history. Firstly, they considered that common AM artefacts were not representative enough of the design freedom enabled by AM. Thus they added overhanging

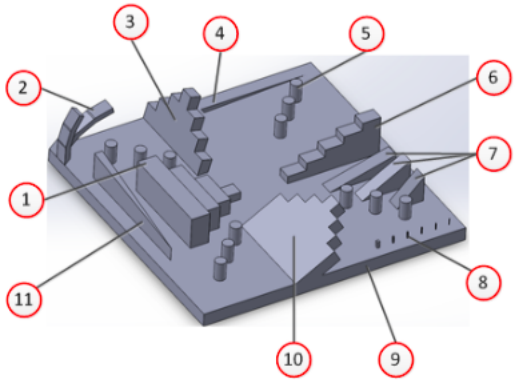

Fig. 4. Yang et al.'s artefact [17]

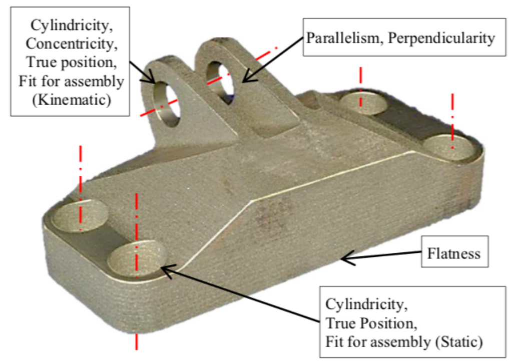

Fig. 5. Rupal et al.'s case study [24]

and freeform features. Moreover, they reckon some studied properties to be redundant such as perpendicularity which in many AM cases, can be deduced from the combination of straightness and parallelism [17]. Therefore, they re-designed Moylan et al.'s artefact with simplified features and a more dedicated-to-AM approach. The resulting artefact is shown in Figure 4. More precisely, they focused their work on a seven-characteristic study comprising straightness, parallelism, perpendicularity, roundness, concentricity, true position for z plane and true position for pins. It is worth noting commonalities shared between this methodology and Table I.

E. Toward a systematic design methodology

Literature on AM presents a large number of benchmark artefacts. However, according to Rupal et al. [24], the latter are designed in a too generic way, adapting previous artefacts to match with studied properties. Resulting artefacts lack of systematic design approach. According to the authors, previous artefacts maintain a characterisation ambiguity, mixing up design and usage aspects. As previously explained, researchers designed generic artefacts to compare AM machines capabilities to produce typical features for example. In other words, researchers first choose the geometrical definition and tolerancing parameters they want to study and secondly pick up the typical feature (such as the procedure described in Table I). However, Rupal et al. [24] suggest that such method is not advisable as it only provides a high-level overview and does not specifically characterise the AM machine capabilities and limitations. Indeed, benchmark artefacts should be specifically designed according to geometrical requirements and taking into account the AM machine and process applications. That is why, according to Rupal et al. [24], researchers should conduct the opposite approach: they should first think about feature size, position and orientation according to the specific process. Then, geometric definition and tolerancing analysis would be conducted in a second time by leading a measurement campaign. Indeed, Rupal et al. [24] consider that accuracy of printed features are deeply linked to the thermo-physical mechanism, to the process and to the toolpath generation of the specific studied AM machine. For example, characterising errors of nozzle position is adapted for material extrusion but not for laser-based processes. The authors then propose an easy-to-use guideline to wisely conduct benchmark design and characterisation of AM processes and machines. This method is two-fold and may use several artefact designs: firstly, AM processes are considered relying on a knowledge base stemming from experiments. This step aims at finding optimised parameters (such as orientation, layer thickness...), ranking geometrical parameters which influence geometrical quality and which allow tolerance data to be understood. Secondly, the specific benchmark study is performed with a need-based approach, by taking tolerance, geometric and kinematic specifications, assembly constraints or process applications, into account. This method leads to a robust feature-based characterisation of an AM process and machine. Rupal et al. applied their methodology on a case study engine bracket part shown in Figure 5

Dordlova et al. [25, 26] investigate a design-for-qualification artefact design guideline for space applications. Indeed, aforementioned guidelines aim at validating geometrical definition and tolerancing (GD&T) or providing methodology to qualify AM process and machine performances. However, none of these guidelines focus on the product-life scheme. In the design-for-qualification methodology, authors provide tools to develop qualification of AM part for critical applications where additively manufactured parts are challenging to produce as they should stick to very restrictive specifications. In this approach where behavioural specifications are set as design requirements, artefacts allow AM uncertainties to be explored and process capabilities to be estimated towards the part application.

Toguem Tagne et al. [27] provide a complete benchmark artefact design methodology for tolerance evaluation. In other words, from requirement specifications, authors present an iterative artefact design guideline in order to establish GD&T characteristics of AM processes, taking the measurement and characterisation part into consideration as the artefact features layout is optimised according to arrangement recommendations expressed by Byun et al. [16]. As a further development of this methodology guideline, Toguem Tagne et al. [28] proposed an axiomatic design of customised AM artefacts. More precisely, artefacts are designed relying on a top-down approach of defining functional requirements according to customer needs. Such a methodology allow design parameters to be optimised by minimising geometrical characteristics redundancy in the resulting scope of considered features.

There has been increasing interest for machine learning in AM context. For example Zhu et al. [29] proposed a machine learning tolerance analysis approach to statistically evaluate deviations of printed parts. As reviewed in [30], Yao et al. [31] made design feature recommendations to help inexperienced designers. In a recent paper, Mycroft et al. [32] address the systematic design approach need by developing a machine learning framework to predict small-scale features printability. More precisely, relying on a customised machine learning database, geometric mesh descriptors are defined such as curvature, thickness or overhang and used to analyse printability of a triangulated CAD artefact prior to manufacturing. This systematic methodology allows the design step to be optimised by providing a data-driven artefact, which geometric properties are known to be printable by the considered AM process. In order to provide non-experienced designers with additively manufacturability tools, Brackens et al. [33] proposed a worksheet to identify if parts can be manufactured by powder bed fusion AM process. Relying on this worksheet, non-experienced designers identify AM suitability for the part manufacturing taking into consideration the AM process limitation and the part geometry.

F. Benchmark artefact standardisation

In recent decades, standards developing organisations (SDO) recognise the need to provide common standards towards AM. Details on SDO and their roadmaps are provided in [23]. In 2011, American society for testing and materials F42 (ASTM) and International Organisation for Standardisation/Technical Committee 261 (ISO/TC261) signed a common agreement to jointly develop AM standards [23, 34]. As example of these common works, it should be mentioned ISO/ASTM 52900 [2] which defines general AM principles or ISO/ASTM 52910 [35] which provides standard guides for designing AM parts. Recently, joint ISO and ASTM developed a draft specification relatively to the definition and design methodology of AM benchmark artefact. In line with that previously described feature-based characterisation of AM capabilities, ISO/ASTM 52902 defines eight different artefacts belonging to four main families (recalled in Table II) : accuracy, resolution surface texture and labelling [36]. Each of these artefacts is intended to test a different aspect of the AM machine and process.

- Accuracy
  - Linear artefact: aims at testing the linear positioning accuracy along a specific machine direction
  - Circular artefact: aims at separating material effects and external sources of errors
- Resolution
  - Resolution pins aim at validating the machine capability to produce fine features at different aspect ratios.
  - Resolution holes aim at assessing the minimum feasible hole
  - Resolution ribs aim at validating the minimum wall thickness that can be built by the AM machine and or process
  - Resolution slots aim at defining the minimum spacing between features
- Surface texture: evaluation of surface texture produced by the machine
- Labelling: aims at quickly identify artefact orientation and position but should not interfere with the studied properties.

Table II presents the link between these characterisation families and the defined artefacts.

TABLE II
ISO/ASTM 52902 LINKS BETWEEN DEFINED ARTEFACT AND MAIN CHARACTERISTIC EVALUATION [36]

Characterisation family	Artefact	available characteristic
Accuracy	Linear	Position Straightness
	Circular	Roundness Diameter Concentricity
Resolution	Pins	Pin diameter Pin height Circularity Cylindricity
	Holes	Hole diameter Hole depth Cylindricity
	Ribs	Thickness Straightness
	Slots	Width Flatness Parallelism
Surface Texture	Surface texture	Average roughness (R_a,S_a) Skewness Kurtosis ...
Labelling	Volumetric X and Y letters	–

It is worth noting that available characteristics described in ISO/ASTM 52902 [36] and recalled is Table II, refer to some geometrical definitions aforementioned in Table I. However, the standard makes the difference between accuracy and resolution for instance which was not previously directly linked to the artefact design step. Furthermore, draft ISO 52902 adds surface texture studies to integrate a more metrological point of view discussed in Section III. An example provided in the draft ISO is given in Figure 6. The latter embodies a condensed artefact made of 15 different artefacts to cover all accuracy and resolution characterisation. This condensed artefact may be upgraded with the surface texture and labelling characterisation adding artefacts showed in Figure 7 and in Figure 8.

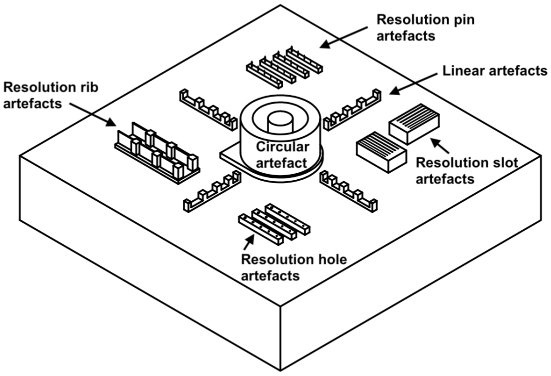

Fig. 6. ISO/ASTM 52902 example of a benchmark artefact configuration to assess accuracy and resolution of an AM machine/process. Explicit legends have been added to original figures to identify considered features

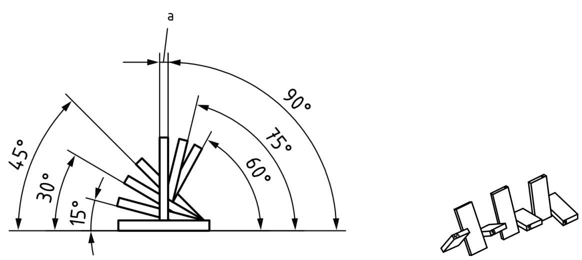

Fig. 7. ISO/ASTM 52902 surface texture benchmark artefact with different slope angles [36].

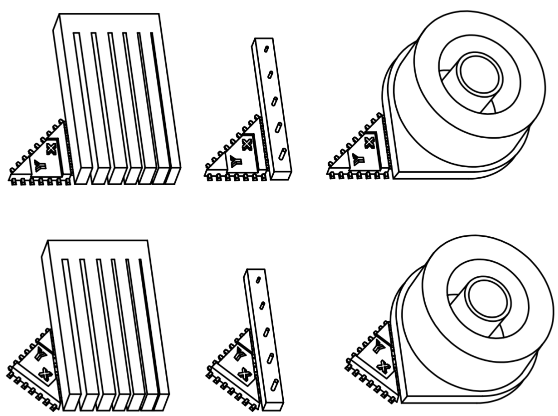

Fig. 8. ISO/ASTM 52902 labelling integration for benchmark artefacts [36]

III. Benchmark artefacts for metrology

A. Measurement issues

1) Free-form surfaces

The noteworthiness of AM is the suitability to make free-form surfaces whereas conventional subtractive and formative manufacturing techniques are proven more laborious when dealing with free-form surfaces. However, as Mehdi-Souzani et al. [37] observed, a very few number of previous benchmark artefacts have been designed in a free-form way neither correctly measured. A large portion of these benchmark artefacts relied on regular and defined geometric features. The National Physical Laboratory (NPL) designed a normative artefact to characterise contactless measurement technologies but was not efficient enough to assess dimensional properties and accuracy

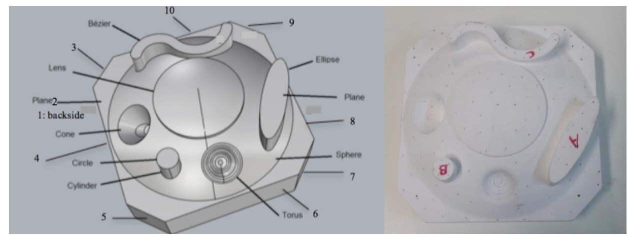

Fig. 9. Mehdi-Souzani et al.'s artefact [37]

of AM machines and processes. Mehdi-Souzani et al. [37] then designed a free-form artefact with defined features such as plane or pin, to cover both free-form and AM characterisation aspects. Resulting artefact is shown in Figure 9. The authors could draw a conclusion on the significant impact of volumetric free-form shapes on geometrical characteristics which account free-form surfaces and their measurements as fully part of the benchmark characterisation study. Moreover, Kurfess and Taylor [38] express metrology needs for AM by precisely explaining the reasons of AM measurement difficulties. More precisely, in a geometric perspective, additively manufactured parts are rarely made of simple geometries such as cylinders or spheres. That is why, coordinate metrology instruments such as non-contact instruments are preferred rather than classical metrology instruments to better acquire the diversity of geometric elements. Kurfess and Taylor [38] also identify data processing such as least mean square as not fully representative of fitting approaches guarantees provided by maximum or least material conditions.

2) CMM limitations

The aforementioned papers focused on benchmark artefacts design to assess AM machine and process. However, recent publications have highlighted that measurement procedures on benchmark artefacts previously performed did not take the measurement complexity into account [10]. As Rabbaoli et al. argue, being able to measure benchmark artefacts is a key issue in the characterisation process and inaccessible-to-measurement features are useless not to mention the waste of time and material [13]. In previous reviews, CMM is the commonly-used instrument and tip-radius defines the minimum feature dimensions which can be characterised. Although the artefact measurability was one of the original rules set by Richter and Jacobs [15], some defined features may remain inaccessible to the measuring device. For instance, when considering holes, the probe length would be the limiting parameter as it could not reach some interesting-to-measure features. To solve that issue, some authors such as Yang et al. [17] defined the CMM measurability as a requirement of their artefact design as they anticipated the measurement procedure at the design step. However, when measuring fine details, small features or difficult-to-access surfaces, CMM is revealed inefficient. For example, Lart et al. [39] faced measurement issues using CMM as they designed a benchmark artefact to characterise AM machines capabilities to print fine details.

Furthermore, Byun et al. [16] analysed surface roughness by measuring different tilted flat surfaces using a profilometer. The latter consists in dragging a spherical probe on the part surface whilst a transducer regularly acquire height positions [19, 40]. As for CMM, the measurement campaign performed to assess part roughness properties is limited by the probe tip radius and many other instrument-linked parameters.

Surface measurability and resolution is not the only problem raised. The measurement itself is not such easy as it introduces many uncertainties stemming from the interaction nature between instrument and measured surface. It is worth questioning the confidence of the measurement campaign performed.

B. *Measurement strategy*

AM paved the way to complex shapes and surfaces which may be challenging to measure. Previous benchmark studies did not sufficiently focus on the measurement procedure and trusted simple CMM measured point clouds as representative of the investigated artefact. However, quality controls which are performed through benchmark studies should be robust to deeply understand the whole process and the different sources of uncertainties. A solution performed by Mehdi-Souzani et al. for measuring their hybrid free-form and regular feature-based artefact, consists in repeating measurements to take measurement uncertainties into account [37]. For example, the authors used repeated CMM measurements on different features. In other words, on specific chosen features, they have consecutively performed five measurement campaigns. On the first hand, they consider regular features to analyse diameters, height, flatness, parallelism and perpendicularity. On the other hand they used their CAD model to study discrepancies with measured points on free-form surfaces. This methodology leads to a statistical model distribution of the reconstructed features which could be discussed relying on statistical characteristics such as standard deviation. Furthermore, draft ISO/ASTM 52902 [36] provides a guideline of measurement methodology for each artefact defined in Section II-F. More precisely, that standard takes both contact and optical instruments into consideration in defining the measurement procedure adapted for each geometrical property artefact. That is why different instruments may be used above the same artefact. For example, resolution pin artefacts may be measured by CMM to check pin diameters and by calibrated microscope to assess its roundness.

C. *Toward an artefact comparison of measurement techniques*

Moylan et al. introduced the various measurement techniques for the analysis of benchmark artefacts [18]. Many contact and non-contact measurement techniques are detailed in [23, 40, 41, 42, 43]. For instance, ultrasonic measurements allow porosity to be estimated and X-rays computed tomography (XCT) measurements reveal micro-structure [18]. Similarly, Hermanek et al. [44] designed an artefact which allows to evaluate XCT accuracy to identify part porosity. Moreover, Tawfik et al. [45] recently developed an artefact to investigate the XCT voxel size effect on unfused powder detection for laser powder bed fusion AM process.
Mehdi-Souzani et al. [37] performed repeated measurements using three measurement techniques on their artefact: laser scanner, CMM and an articulated arm CMM. Thus, they could identify effects which were not related to AM system in their benchmark study. Townsend et al. [46] recently validated the XCT measurement extraction in order to compute ISO 25178-2 [47] surface texture parameters. More precisely, the authors performed an interlaboratory comparison of XCT measurements of a benchmark artefact. Studying ISO 25178-2 [47] surface texture parameter evaluations and their associated confidence intervals relying on statistical modellings, the authors could compare the ability of XCT instruments towards a referenced optical technique. Their artefact was designed in line with their measurement methodology as it allowed authors to separate voxel scaling errors from surface determination errors.

However, due to XCT uncertainties [10, 23, 48], Shah et al. [49] introduced a cylindric benchmark artefact designed to reduce XCT geometrical image artefact. For different AM process, this benchmark artefact is scanned by two XCT machines and results are compared to CMM measurements, set as a reference. Rivas-Santos et al. [10, 50] defined a 'design for metrology' approach of defining benchmark artefact within an instrument comparison method. In other words, a part is defined as an optimisation of the measurement methodology used and quality check process, without changing the part functionality. For example, the artefact designed by the authors does not comprise large planes to avoid cone beam artefacts in the XCT output. The used benchmark artefact, shown in Figure 10, is measured by CMM, XCT and photogrammetry. The authors outline the high dependance of CMM measurement uncertainties on the part surface texture: a rough surface would directly impact the CMM quality measurement of the artefact. Moreover, they highlight the mechanical filtering constraints that affect CMM measurement in comparison to XCT and photogrammetry. Finally, they argue that CMM need a time consuming programming step which makes CMM as the slowest technique when compared to XCT and photogrammetry. However, contactless instruments output dense point clouds which need specific treatment and data extraction.
Table III summarises instruments previously considered in artefact measurement papers and lists corresponding limitations.

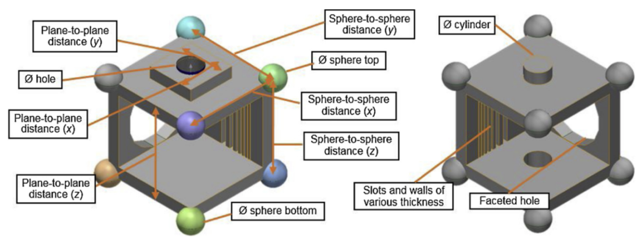

Fig. 10. Santos et al.'s design for metrology artefact [50]

TABLE III
SUMMARY OF MEASUREMENT METHODS, USAGE AND EXPLAINED LIMITATIONS FOR SELECTED LITERATURE ON ARTEFACT MEASUREMENT

Instruments	Authors	Main work	Explained instrument limitations
Profilometer	Byun et al [16]	Surface roughness	Measurement range
	Rivas-Santos et al [50]	Comparative study: Design-for-metrology approach	Dense point cloud needing specific treatment
CMM	Yang et al. [17]	Investigation of standard test part feature design efficiency	
	Mehdi-Souzani et al. [37]	Comparative study	
	Rivas-Santos et al. [50]	Comparative study: Design-for-metrology approach	Time consuming programming steps
Laser scanner	Mehdi-Souzani et al. [37]	Comparative study	
Photogrammetry	Rivas-Santos et al. [50]	Comparative study: Design-for-metrology approach	Limited depth of focus
XCT	Hermanek et al. [44]	Porosity	
	Tawfiq et al. [45]	Micro-structure	
	Townsend et al	Interlaboratory XCT surface texture ISO 25178-2 [47] evaluation	
	Rivas-Santos et al. [50]	Comparative study: Design-for-metrology approach	Acquisition time

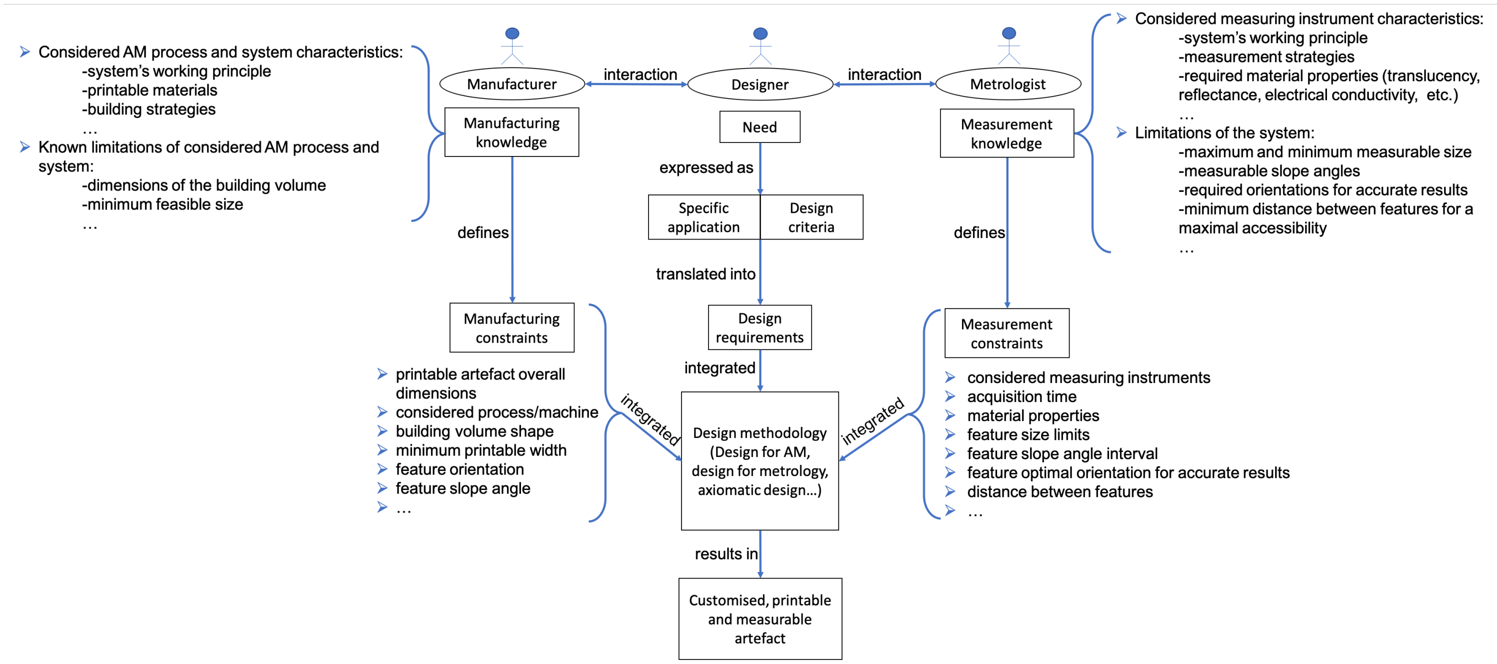

Fig. 11. Recommended design process of benchmark artefact

IV. DISCUSSION

As a result of the present analysis, Figure 11 summarises a structured set of recommendations to address manufacturing and metrology specific concerns when designing benchmark artefact. From the initial need expressed as specific application and design criteria, the designer defines a set of design requirements. In the order hand, the manufacturer defines a set of manufacturing constraints based on the characteristics of the considered AM process and system and its currently known limitations. Similarly, the metrologist defines a set of measurement constraints based on the considered measurement instrument characteristics and limitations. Design requirements, taken with manufacturing and measurement constraints are the inputs of the design process which should rely on suitable design methodologies such as axiomatic design, design for metrology or design for AM. In the following, a simple case study is considered with three interacting actors: a designer with a need, a manufacturer with manufacturing skills and a metrologist with measurement knowledge, a laser powder bed fusion (LPBF) machine [51] and a focus variation (FV) measuring instrument. In this example, the designer's aim is to study the impact of polymer LPBF part slope angle in the building chamber on the resulting part surface roughness. This need is expressed as specific application on the one hand (surface roughness evaluation) and design criteria on the other hand (various feature orientations). At this point of the design process, the design criteria translated into design requirements can be fulfilled with a single part comprising several planes with different slope angles. Now both manufacturer's and metrologist's point of view linked respectively to manufacturing and measurement constraints have to be integrated in the design process by the designer. For the manufacturing constraints, overall part dimension and building volume shape should be considered. Moreover, in this specific example, minimum feasible width is the main manufacturing constraint as it defines the lowest plane width that can be manufactured. Current knowledge on LPBF AM process demonstrates its suitability for overhanging features. Thus, the feature slope angle is not a strong constraint here. Whereas, features slope angle could be of high importance and would require supporting structures in the case of material extrusion AM process for instance. For the metrologist's point of view, FV measurement of polymer will be impacted by material translucency. Additionally, feature slope angle will directly impact measurement procedure as well as measurement time, due for example to the increased focus range needed when measuring tilted features by FV [23, 52]. Moreover, overall plane size should be thoughtfully chosen to be included in the instrument field of view accordingly to the chosen magnification. Otherwise, stitching procedure should be added with stitching uncertainties and processing time. This simple example illustrates the proposed recommended design process of benchmark artefact and should be conducted combining all manufacturing machines and measuring instruments that would be considered in the study. This procedure results in a customised and suited artefact that conciliates both manufacturer's and metrologist's point of view.

However, some AM considerations regarding benchmark artefacts require further investigations and limitations of previous works are highlighted in the following. First, removal from the building volume, removal of building supports or post-processing impacts on the benchmark artefact geometry should be more investigated. Furthermore, general differences and limitations between metal and plastic additively manufactured artefacts have to be outlined. Indeed, in previous works, the same CAD model is often used to compare metal and plastic AM processes without questioning the plastic artefact suitability to be compared to the same metal benchmark artefact. In line with this raised limitation, more research is required regarding multi-material benchmark artefact, that's-to-say benchmark artefact combining several materials. Additionally, AM allows for production of complex geometry such as lattice structures or topologically optimised structures to ensure weight gain of the resulting part for instance. Developing benchmark artefacts for such structures was out of the scope of this study. Therefore, continuous efforts are needed to provide comparative tools between AM machine and process including these specific-to-AM structures in the characterisation method. Furthermore, AM digital simulating tools are being developed in order to predict built geometry by specific process relying for instance on machine learning. Investigations are required to analyse the suitability of these tools towards benchmark artefact. More precisely, further work should focus on the way such tools may help designer, metrologist and manufacturer to create the most suited benchmark artefact to investigate a given criteria.

V. Conclusion

This paper introduces a review of the evolution of benchmark artefact design methodologies. There has been hundreds of benchmark artefacts based on various approaches. Quite a number of these artefacts comply with original design rules which allow a qualitatively study and quantitatively comparison of AM machines and processes. However, due to the wide variety of AM machines and processes, a single artefact cannot significantly be suitable for all existing AM processes/machines. That is why, a standard artefact is not practically advisable and design methodologies rather focus on a standard AM artefact design methodology: the main issue is not to create a standard benchmark artefact but to standardise the design methodology itself. In other words, efforts have been made in providing general guidelines in the design methods used in line with the whole research project. Draft ISO/ASTM specification standard 52902 also proposes an artefact decomposition into simpler artefacts, each of them focusing on different spatially repeated AM features. This draft ISO/ASTM also integrates artefact surface texture in the characterisation procedure. In previous studies, the metrological issue was indeed often underestimated in design methodologies.

On the other hand, measurement strategies have not been thoroughly studied. CMM is the widely spread instrument to measure benchmark artefact. However, many works rely on simple sets of measured data-points without considering measuring instrument uncertainty or repeatablilty. Recent research tends to take measurement as fully part of the benchmark study. Uncertainties of a measuring instrument may be taken into account by repeating acquisition of the measured point and generate its associated confidence interval. Moreover, many works show the noteworthiness of contactless instruments for measuring AM benchmark artefacts. Indeed, each instrument interacts differently with the additively manufactured artefact surface being studied. With several instruments examining the benchmark artefact, comparisons of both repeatability and accuracy of measuring instruments may be defined in line with the AM characterisation. Furthermore, this paper highlights new evolution of the design methodology which considers the artefact measuring procedure before designing the sample. Such benchmark artefact design methodology, validated by the designer, conciliates manufacturing and metrology issues ending up with an optimised and customised artefact to conduct a thorough AM machine and process capability characterisation.

Appendix A
Term definition table (by order of appearance)

Term	Definition
AM	Additive manufacturing
ISO	International standard organisation
CMM	Coordinate measurement machine
CAD	Computer-aided-design
STL	Standard tessellation language
GD&T	Geometrical definition and tolerancing
SDO	Standards developing organisations
ASTM	American society for testing and materials
TC	Technical committee
NPL	National Physical Laboratory
XCT	X-rays computed tomography
LPBF	Laser powder bed fusion
FV	Focus variation

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