Available online at www.sciencedirect.com
ScienceDirect
Procedia CIRP 60 (2017) 56 – 61
www.elsevier.com/locate/procedia

27th CIRP Design 2017

Smart Manufacturability Analysis for Digital Product Development

Steven Goguelin[a], Joshua Colaco[a], Vimal Dhokia[a], Dirk Schaefer[a,*]

[a]Dept. Mechanical Engineering, University of Bath, Claverton Down Road, Bath, BA2 7AY, UK

* Corresponding author. Tel.: +44 1225 386163; *E-mail address:* d.schaefer@bath.ac.uk

Abstract

Cloud-Based Design and Manufacturing is a service-oriented networked product development model in which service consumers are enabled to configure, select and utilize customized product realization services ranging from computer-aided engineering software to reconfigurable manufacturing systems. So far, this paradigm has mainly been tested for digital design and fabrication processes including the usual steps of designing an artefact with a CAD system to then have a prototype manufactured with a 3D printer. Unfortunately, a common mishap that can often be observed is that artefacts that look perfectly fine on the CAD computer screen come out severely misshaped on the 3D printer. In this paper, we first investigate and document this phenomenon and explain its root cause, which concerns a) the data transmitted to the 3D printer, b) inappropriate design features, and c) a mismatch between geometry requirements and printer capabilities. As more and more entrepreneurs, hobbyists in maker communities, and other not always fully trained individuals pursue their design and make ideas, there is a need for smart computer-based support to facilitate a successful design-to-print process. Such a digital DfM assistant might pop up to prompt a designer to modify identified critical areas of the design so that it can be printed with a chosen printer or alternatively propose another type of printer that may have the technical capabilities to accommodate the design in its current form. Acknowledging this need, we propose a two-stage smart manufacturability assistant. The first stage decomposes the digital model into a series of part features; the second stage of the model involved defining the capabilities of the 3D-printer. Finally, we begin to realize this manufacturability assistant by creating and evaluating a bespoke test part which can be used to define a machine-material capability map for an example FDM process.

Peer-review under responsibility of the scientific committee of the 27th CIRP Design Conference

Keywords: Digital Design for Manufacture; Manufacturability Analysis; STL; CAD/CAM; 3D-Printing; Cloud-Based Design and Manufacturing; Industry 4.0

1. Introduction

Cloud-Based Design and Manufacturing (CBDM) refers to a service-oriented networked product development model in which consumers are able to configure, select and utilize customized product realization services such as computer aided design (CAD) software and distributed reconfigurable computer aided manufacturing (CAM) platforms [1].

Advantages of CBDM include ubiquitous access to design and manufacturing resources, less maintenance cost and attractive pay-as-you-go price structures. CBDM makes it possible for individuals to develop products which would typically require vast initial capital investment at a comparably low cost.

A further advantage of increasing numbers of cloud-based CAD/CAM platforms is that the barrier to entry for entrepreneurs or hobbyist consumers within the extended maker communities and hence society as a whole decreases. There is also a noticeable general trend toward adopting low-cost desktop 3D printers with currently over 300 companies producing fused deposition modelling (FDM) printers with a consumer spend of $173.3M each year [2].

Whilst additive manufacturing (AM) has many advantages as a manufacturing process including cost being mostly independent of complexity and the ability to manufacture complex hierarchical structures [3], there are still many obstacles to overcome before AM becomes a *'click-and-print'* technology.

Understanding the intricacies of the process is required to optimize print quality and reduce the number of unsuccessful prints. Furthermore, a designer must also understand the limitations of a selected 3D printer to ensure that the features

Peer-review under responsibility of the scientific committee of the 27th CIRP Design Conference
doi:10.1016/j.procir.2017.02.026

that are designed within the CAD environment are producible in the physical world.

In this paper, the use of cloud-based smart manufacturability assistants will be explored as a method of decreasing the knowledge required to produce AM realizable designs, with the hope of reducing the amount of wasted material and associated incurred cost from failed prints.

2. Background Work

In this section, literature on digital manufacturability analysis will be reviewed. Additionally, the limitations associated with the FDM process will be discussed.

2.1. Digital Manufacturability Analysis

Traditional Design for Manufacturing (DfM) methods use feature-based decomposition to analyze the manufacturability of defined features on a CAD part. However, for AM this type of approach is no longer relevant as many 3D prints move away from a feature based definition towards organic geometries.

A number of authors [4–6] have attempted to create design guidelines for the FDM process which aim to guide the user in designing parts that can be manufactured. However, these design guidelines are often cumbersome and require technical expertise to translate them back into the realm of the digital CAD model. They are often process-specific and not detailed enough to cover the intricacies of machine-material combination guidelines. This is a large oversight given that the FDM process covers machines ranging from hundreds to tens-of-thousands of dollars and machine capabilities can vary substantially [2].

Several authors have attempted to transform these guidelines into usable approaches that help assess the manufacturability of a designed part. Kerbrat et al. [7] used an octree decomposition on a CAD model to establish areas of the part which would be challenging to manufacture using both additive and subtractive technologies. Ranjan et al. [8] exploited a graph-based method to develop a manufacturability index for a part based on the geometry of a sliced .STL file input. Nelaturi et al. [9] established a printability map for 3D geometries using techniques from mathematical morphology. This process allowed the authors to specify a print resolution and determine the manufacturability of features such as thin walls, protrusions and holes.

An example of a cloud-based 3D printing assistant was proposed by Rosen et al. [10]. The assistant allowed users to upload .STL files which were subsequently examined for areas with thin regions and small features. If small features were detected, the failed regions were highlighted to the user. Whilst this system provided a good example of a cloud-based manufacturability assistant, it lacked the specificity to analyze prints based on material-machine print data which would cater the manufacturability analysis to individual users.

Further work is required to increase the performance of cloud-based manufacturability assistants that can assess the manufacturability of parts based on machine specific information.

2.2. Errors in the Digital Model

The .STL file format has become the de-facto standard for 3D-printing technologies. This format approximates the surfaces of the CAD model with triangles. With simple part geometries, the .STL file is normally exported in an error-free form suitable for 3D printing. However, if the geometric complexity increases then occasionally the .STL file will require further processing (fixing) before the design can actually be printed.

.STL files exhibit a number of potential issues including missing facets, degenerate facets, overlapping facets, and non-manifold topology conditions [11].

A key requirement of a digital manufacturability assistant therefore must be to ensure the mesh is error-free before providing further insights with respect to the general manufacturability of the design.

2.3. FDM Process Limitations

Due to the nature of the FDM process, there are many reasons why a CAD part is not necessarily representative of the final product. One example of this occurs when the starting and stopping locations of the deposition process occur in the same location. If the start and stop positions are in the exact same (x,y) location for each z-increment, then a 'seam' is created, causing a geometric defect as shown in Figure 1.

All layered manufacturing processes require the digital model to be divided into slices before the part can be manufactured. These slices then form the basis of a material deposition plan for the part [12]. Slices can contribute to several errors that occur when comparing the original CAD model to the printed file. One example, termed the stair-stepping effect occurs when the discretized contours of the 2.5D layers are printed. This phenomenon can significantly reduce the surface quality of the design.

2.4. Geometry Requirement and Printer Capability Mismatch

To generate digital models which can be manufactured, the designer must first understand the capabilities of the target machine. Overhanging faces that occur within the design can be self-supporting if the angle between the feature and the base plate is below a certain limit. This limit is approximately 45° for ABS material however, different materials and machines will have different values. Dimensional accuracy is also an issue with FDM technology. It is typical that tolerance settings selected within the machine software are not always capable of being manufactured.

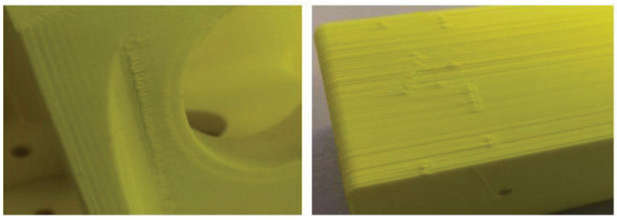

Fig. 1. Seam caused by stop-start error in 3D-Printing.

The first stage in understanding the machine limitations is to develop a method in which the machine capabilities can be ascertained.

3. Cloud-Based Smart Manufacturability Assistant

This section of the paper will discuss how a cloud based manufacturability assistant can be realized and identify the technical requirements such a system would have to fulfill.

To realize a cloud-based manufacturability assistant, it is first necessary to integrate cloud-based analysis into the CBDM platform model. There are two feedback options for these assistants: CAD and CAM related feedback. CAD related feedback provides a system that can inform the designer of potential issues with their current design. This can either be down to a problem with the .STL mesh or alternatively the designers are aiming to manufacture features which are outside the tolerances and capabilities of the machine.

Alternatively, CAM feedback would provide information regarding the suitability of selected machine. For example, it could suggest selecting a printer that has a higher print resolution. A schematic of the cloud-based manufacturability tool methodology is shown in Figure 2.

The software would have to understand limitations of all the 3D printers that it has access to. By evaluating the CAD geometry it would be possible to highlight features which exist within the digital model that are outside the capabilities of 3D printer.

3.1. Feedback on the Digital Design

One method of realizing a smart manufacturability assistant is to integrate such a cloud-based analysis tool as a cloud-based middleware between the CAD and CAM systems. Analysis of the part would be achieved by analyzing specific AM features within the geometry. Any type of digital part decomposition should have the capability to identify specific areas of the design which fail to meet the machine capabilities and are therefore inherently non-manufacturable.

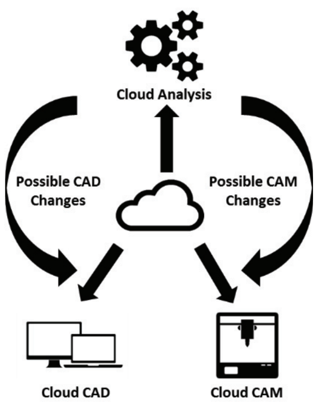

Fig. 2. Example of feedback from a cloud-based analysis system into cloud-based CAD/CAM

This would be achieved by analysis of both the raw .STL data and also by decomposing the .STL file into slices corresponding to the slice thickness that will be printed. The maximum part dimensions can be calculated by computing the minimum bounding box volume of the .STL file; these values can be used as an indication of whether the part will fit within the build volume of a selected printer.

Further information from the raw .STL file such as facet normals can be used to calculate the angle between the digital part and the build plane, giving information on overhanging faces. By decomposing the CAD file into slices corresponding to print layer thickness; and analyzing the individual slices, it is possible to detect geometric defects such as thin walls and fusible contours.

3.2. Feedback on Manufacturing Capabilities

The cloud has the advantage of being able to hold a vast range of possible printers that have all been characterized for their full print capabilities. To understand whether a part can be manufactured it is important to define the features that a part can manufacture. To achieve this, a test part needs to be defined that contains all relevant features required to understand the capabilities of a particular machine. A capability map documenting the test part performance information will be uploaded onto a cloud database.

3.3. Realizing a Cloud-Based Manufacturability Assistant

The proposed cloud-based manufacturability assistant, shown in Figure 3, works as a two-stage process, existing in both the digital and physical worlds unified by the cloud. |The first stage exists in the digital world, the CAD part is uploaded to the cloud-based analysis tool in the form of a .STL file. In the second stage, the printer capabilities are ascertained by printing and evaluating a physical test artefact.

The first stage of the manufacturability tool may be realized as follows: An .STL file is uploaded and checked to ensure that the mesh is free from errors described in section 2.2. The digital part representation can then be analyzed for its overall part dimensions and AM specific manufacturability features, including detection of thin regions and openings, excessive

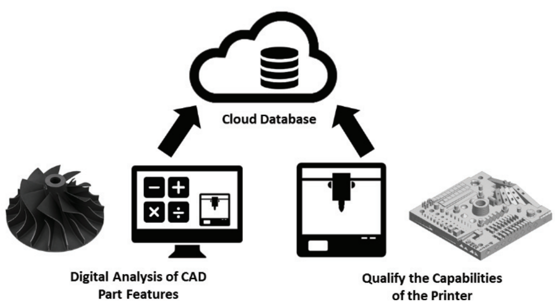

Fig. 3. Schematic of a cloud-based manufacturability assistant

overhang angles and sharp corners contributing to fusible features.

The user is then able to select an appropriate printer from the cloud that is believed to satisfy the requirements required to build the part. This can be an existing printer in the database which they have access to, or a printer that they have quantified and added to the database. Alternatively, the user may not have access to a printer and instead may wish to query all the printers in the database and use a printing hub to print their design. If a printer is selected then the output from the manufacturability analysis can be directly compared to the values derived from the capability map of the selected printer.

If the digital analysis shows that the part is within the tolerances specified from the printer capability map, then the part can be sent directly to the selected printer. However, if the cloud-based manufacturability capabilities are misaligned the system would provide feedback to the user regarding areas of the digital model which require attention. Should the part specification be tightly constrained, the assistant could suggest alternative processes better aligned with the geometric tolerances specified by the designer. This would be manifested in the form of a decision tree for each of the digital features and physical capabilities.

To realize this 3D printing assistant, a method of interacting with the user is required. A possible method of achieving this

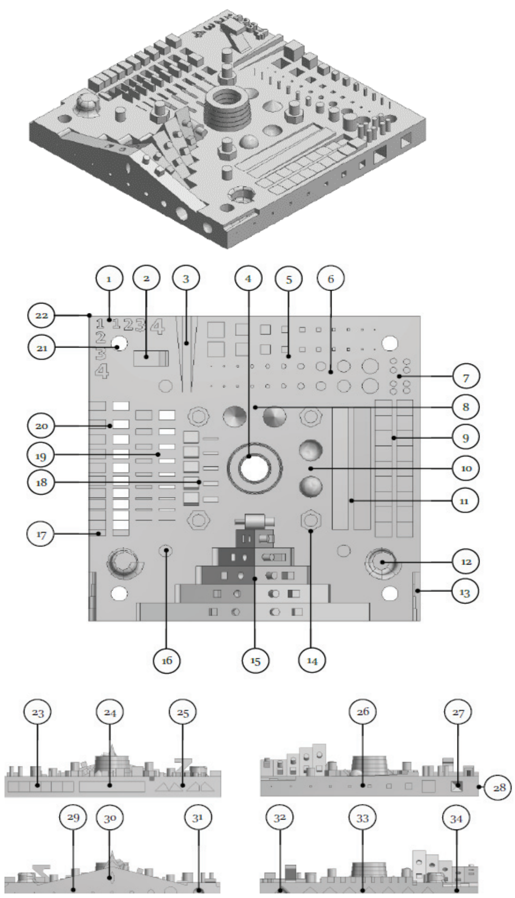

Fig. 4. Machine capability test part showing numbered analysis features.

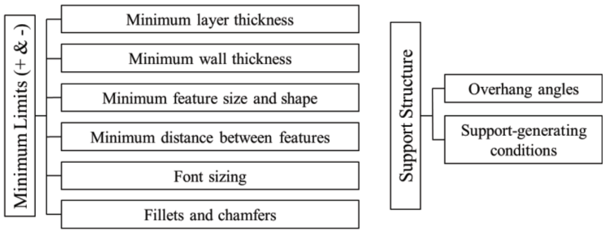

Fig. 5. Test features required for producing a machine capability model.

is with an intelligent character that would provide feedback to the user through the manufacturability analysis process and return feedback to the user where necessary.

4. Qualifying the Capabilities of the 3D-Printer

In this section an overview of the work undertaken to fulfil the requirements for the second stage of the cloud-based manufacturability assistant, as defined in section 3.3, to determine the capabilities of the 3D printer is discussed. A description of how the test part was designed and analyzed to develop the machine capability map will be described.

4.1. Determining Part Capability Analysis Features

A test part as shown in Figure 4 was designed with 34 different feature sets. This test part is based upon the NIST standard test part [13] with a number of additional features. These features include geometries which would be of interest to the hobbyist and maker communities including numbering and text. An overview of the feature requirements for producing the capability map are shown in Figure 5.

This test part was then manufactured on an UP Box printer which is representative of a mid-range desktop FDM machine. Three prints of the test part were produced and analyzed for each feature set. Feature sets are identified by numbers and are shown in Figure 4.

4.2. Results from the Printed Test Parts

The print was analyzed using both qualitative and quantitative methods in order to measure and qualify the capabilities of the printer. The qualitative measurements were taken using Vernier calipers and a micrometer gauge. The smaller features were measured using a micrograph analysis.

The Vernier and micrometer measurements are suitable for positive features, however, for negative features a Leica M205-C microscope was used to record minimum feature sizes.

4.2.1. Qualitative Capability Results

Several features in the model were evaluated using a visual inspection approach to assess the capabilities of the machine.

Figure 6 shows the results of a visual inspection alongside the feature number that was being assessed. Results show that a minimum font size for printing is 5mm to ensure readability. All prints required support structure for 45 degree overhangs. The minimum feature size of the cone is limited by the nozzle

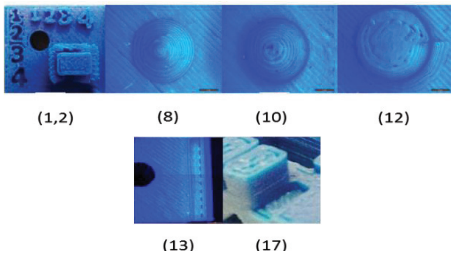

Fig. 6. Qualitative analysis features shown with analysis features.

incident overlap between positive and negative features when printed together.

4.2.2. Quantitative Capability Results

As previously mentioned, several different features were measured quantitatively. These are tabulated below with their feature number from Figure 4.

The sharp triangle corresponding to feature 3 was measured using Vernier calipers. The results show that negative features can achieve more precise geometries which are closer to the actual design values. The printed positive geometry fell short of the desired length by approximately 6mm. The results are shown in Table 1.

Table 1. Sharp triangle measurements

Print Number	Designed Length (mm)		Measured Value (mm)	
	+	-	+	-
1	25	25	18.84	24.16
2	25	25	18.79	24.13
3	25	25	18.85	24.11

The minimum wall thickness, feature 3 was tested for both positive and negative features. The results show that the minimum resolution of wall thickness is approximately 1mm. The results are shown in Table 2.

Table 2. Wall thickness measurements.

Print Number	Designed Length (mm)		Measured Value (mm)	
	+	-	+	-
1	0.75	0.75	1.04	1.021
2	0.75	0.75	1.023	1.013
3	0.75	0.75	1.042	0.99

The minimum distance between features corresponding to feature 20 was measured by taking four data measurements using a micrograph analysis. Results show that the positive features typically print results smaller than the desired length, whereas the negative features print features greater than the desired length. The results are shown in Table 3.

Table 3. Minimum distance between features measurement.

Print Number	Designed Length (mm)		Measured Value (mm)	
	+	-	+	-
1	0.25	0.25	0.232	0.281
2	0.25	0.25	0.232	0.281
3	0.25	0.25	0.237	0.271

The part height was measured using Vernier calipers. The results from the print show that the deviation from the designed value was on average 0.023mm. The results are shown in Table 4.

Table 4. Part height measurements.

Print Number	Designed Length (mm)	Measured Value (mm)
1	10	10.03
2	10	10.02
3	10	10.02

The angled square width and the circle diameter, corresponding to feature 15 were measured using Vernier calipers. The maximum deviation from the design value of 2.5mm was 0.3mm. The majority of the features were oversized. The results are shown in Tables 5 and 6.

Table 5. Angular measurements for square width

Print	15°		30°		45°		60°	
	+	-	+	-	+	-	+	-
1	2.49	2.59	2.51	2.68	2.55	2.69	2.52	2.78
2	2.48	2.62	2.51	2.64	2.53	2.71	2.50	2.78
3	2.49	2.59	2.49	2.64	2.57	2.68	2.53	2.80

Table 6. Angular measurements for circular diameter.

Print	15°		30°		45°		60°	
	+	-	+	-	+	-	+	-
1	2.45	2.48	2.35	2.50	2.53	2.41	2.46	2.35
2	2.44	2.46	2.36	2.50	2.51	2.43	2.46	2.35
3	2.49	2.59	2.49	2.64	2.57	2.68	2.53	2.80

4.3 Capability Map for UP BOX Printer

The results from section 4.2 were used to define the minimum and maximum capabilities of the printer for the measured features. Table 7 illustrates a capability map for a printer before it is uploaded into the cloud to form part of the cloud-based manufacturability assistant. This printability map includes details of material used, build dimensions of the printer and the measured print geometry data.

Table 7. Capability map for the UP BOX 3D- printer

Design capabilities for: UP BOX	Material used: ABS	Build dimensions: X-dimension : 255mm Y-dimension : 205mm Z-dimension : 205mm
Minimum layer thickness	+	0.24mm
	-	0.21mm
Minimum wall thickness (x-y plane)	+	0.99mm
	-	1.023mm
Minimum circle size (x-y plane)	+	1.12mm
	-	0.75mm
Minimum distance between features	+	0.232mm
	-	0.271mm
Minimum rectangle size (x-y plane)	+	1.12mm
	-	0.67mm
Geometric deviation if printed on angle	+/-	0.3mm
Tolerance for loose fit (x-y plane)	+/-	0.14mm
Tolerance for loose fit (z-plane)	+/-	0.3mm

4.3. Limitations of the machine capability study.

The qualitative measurements within this study were performed using Vernier calipers, micrometers and a microscope. As human interaction was required in taking the measurements, it is assumed that there could be random error associated with the results. It is believed that low cost methods of performing the quantitative analysis are preferable to using more accurate measurement techniques such as coordinate measurement machines or laser measurements. This is due to the requirement to populate the cloud-based manufacturability assistant with as many machine-material combinations as possible. It is believed that by keeping the barrier to entry in developing machine capability reports low that many users will be able to add to the cloud-based analysis database.

5. Conclusions and Future Work

This paper has highlighted some of the requirements that are necessary to create the next generation of cloud-based smart manufacturability tools. Firstly, some of the main errors that occur when translating a design from the digital world to the physical world were presented. These included issues with the .STL format and a lack of understanding of the physical capabilities of FDM printers.

To overcome some of the challenges in creating CAD parts which are suitable for manufacturing a cloud-based manufacturability tool was defined. This tool aims to define the minimum feature sizes that exist within a CAD file and compare these to the minimum size features that can be manufactured by a given 3D-printer. Should the CAD file and printer capabilities be incompatible, feedback will be provided to the designer who can then improve the design or select a different 3D-printer model or process.

Work was undertaken to develop a test part which is able to define a capability map for FDM printer-material combinations. Results show that with a combination of relatively low-cost tools it is possible to populate a database with qualitative and quantitative information which will be suitable for assessing the maximum capabilities of a 3D printer.

Future work in this area will involve further development cloud-based manufacturability assistant. One requirement will be to further develop algorithms that can gain an accurate assessment of the design features on an AM CAD model without using the .STL file format and assess the user interaction with the tool.

The smart digital manufacturability assistant could be integrated into a cloud-based CAD system in which the user is able to request feedback on the manufacturability of the design during the design process.

The work presented in this paper provides a new perspective on CBDM, where the cloud element is used as part of a knowledge based appraisal method that will enable the user to gauge the printability of their part. This could have the effect of reducing the knowledge requirements necessary to ensure successful first time right 3D print builds.

References

1. Wu D, Rosen DW, Wang L, Schaefer D (2015) Cloud-based design and manufacturing: A new paradigm in digital manufacturing and design innovation. Comput Des 59:1–14. doi: 10.1016/j.cad.2014.07.006
2. Wohlers T (2015) Wohlers Report 2015. Wohlers Associates
3. Gibson I, Rosen D, Stucker B (2014) Additive Manufacturing Technologies: 3D Printing, Rapid Prototyping, and Direct Digital Manufacturing. Springer
4. Adam GAO, Zimmer D (2015) On design for additive manufacturing: evaluating geometrical limitations. Rapid Prototyp J 21:662–670. doi: 10.1108/RPJ-06-2013-0060
5. Stratasys Direct (2015) Design for Additive Manufacturability: FDM Basics. https://www.stratasysdirect.com/wp-content/uploads/2015/07/fdm-basics.pdf. Accessed 9 Nov 2015
6. Teitelbaum GA, Goaer Y, Schmidt LC (2009) Examining Potential Design Guidelines for Use in Fused Deposition Modeling to Reduce Build Time and Material Volume. ASME 2009 Int Des Eng Tech Conf Comput Inf Eng Conf Volume 8:1–10.
7. Kerbrat O, Mognol P, Hascoët J-Y (2010) Manufacturability analysis to combine additive and subtractive processes. Rapid Prototyp J 16:63–72.
8. Ranjan R, Samant R, Anand S (2016) Integration of Design for Manufacturing methods with Topology Optimization in Additive Manufacturing. J. Manuf. Sci. Eng.
9. Nelaturi S, Kim W, Kurtoglu T (2015) Manufacturability Feedback and Model Correction for Additive Manufacturing. J Manuf Sci Eng 137:21015–21019.
10. Rosen DW, Schaefer D, Schrage D (2012) GT MENTOR: A high school education program in systems engineering and additive manufacturing. 23rd Annu. Int. Solid Free. Fabr. Symp. Addit. Manuf. Symp. (SFF 2012)
11. Leong KF, Chua CK, Ng YM (1996) A study of stereolithography file errors and repair. Part 1. Generic solution. Int J Adv Manuf Technol 12:407–414. doi: 10.1007/BF01186929
12. Kulkarni P, Marsan A, Dutta D (2000) A review of process planning techniques in layered manufacturing. Rapid Prototyp J 6:18–35. doi: 10.1108/13552540010309859
13. Moylan S, Slotwinski J, Cooke A, et al. Proposal for a standardized test artifact for additive manufacturing machines and processes.