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A Characterization of 3D Printability

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3D Life
Crafting Perfection

Overview

References [2, 7, 10, 15, 21]

Additive manufacturing (AM) technologies are considered as the spark of a new industrial revolution, due to its versatility in creating 3D structures of unprecedented design freedom and geometric complexity in comparison with conventional manufacturing techniques

Raising issues regarding:

- Accuracy
- Surface finish
- Robustness
- Mechanical properties
- Functional constraints
- Geometrical constraints

Technical Contributions

- **Proposes a novel approach for a succesful 3D print of a CAD model on a specific AM technology based on *model mesh complexity* and certain *part characteristics***
- **Studies the number of triangles in the STL file**
- **Compares volumes, bounding boxes of different triangulated models and calculates deviations**
- **Examines the geometric charateristics of a model**

→ **Evaluation of printability**

Final Result → ***Printability score*** = the probability of obtaining a robust and accurate end result for 3D printing on a specific AM machine

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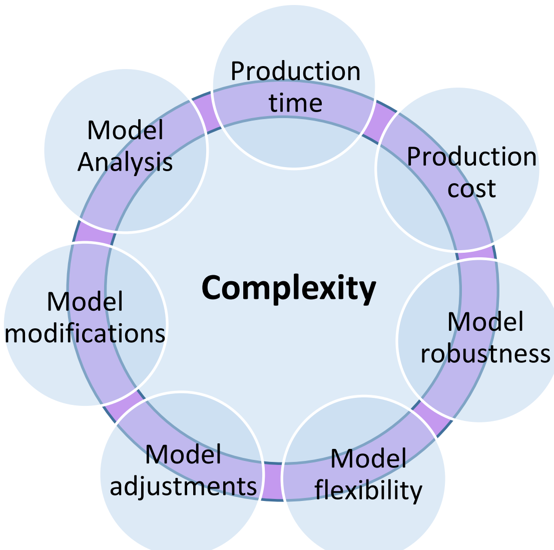
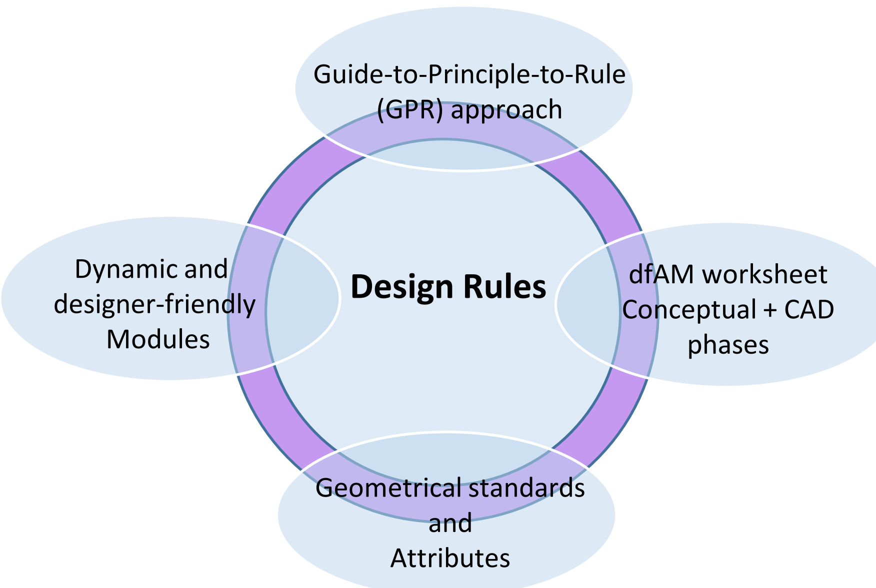
Related work (1/2)

References [4, 8, 12, 18, 11, 9, 3, 24]

❑ Model Complexity



❑ Design principles and rules



By suppressing the less significant features of the model → Data describing these features in the CAD model is reduced → Complexity of the model is reduced

Related work (2/2)

References [8, 12, 18]

Types of complexity

CAD model	Component representation, features and relationships between them
Geometrical	Basic elements such as points, lines, surfaces, etc
Combinatorial	Number of elements of a model, number of vertices in a polynomial mesh, edges, faces
Dimensional	Characterization of a model as 2D, 2.5D or 3D
Algebraic	Complexity degree of the polynomials required to represent the exact shape of a model
Topological	3D geometries, models with internal structure, non-regularized shapes, holes, non-manifold singularities, self-intersections, genus, e.t.c
Morphological	Number of features of a shape, size, smoothness and regularity

- Number of surfaces
- Number of triangles in the STL file for component representation
- Comparison of the volume of a component with the volume of its bounding box

→ **Other complexity metrics**

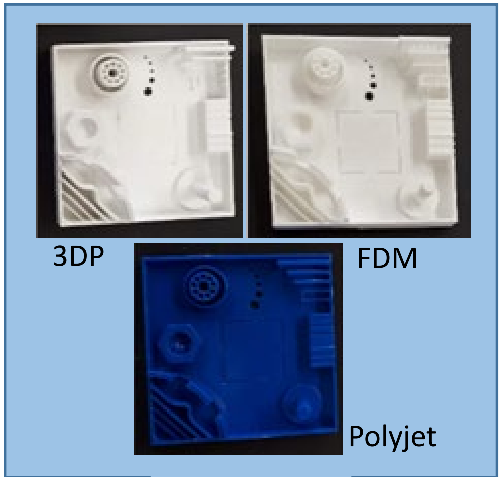
MODEL AND PART CHARACTERISTICS THAT AFFECT PRINTABILITY (1/3)

CAD models used for analysis and validation

References [1, 5, 6, 17, 13]

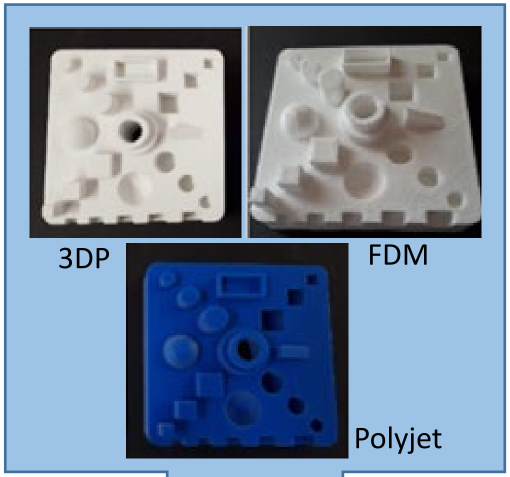
B1

Unsupported walls: 0.3 < THK < 2.0 mm
Unsupported walls: 10◦< angles < 50◦
Supported walls: THK = 1.0 mm
Engraved details: h, w = 1.0 mm
Pin dia: 1.0 mm



B2

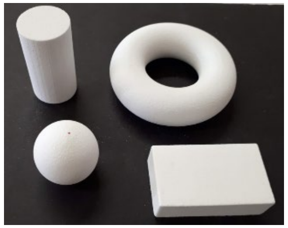
Supported walls: 0.3 < THK < 1.5 mm
Unsupported circular wall: THK = 1.0 mm
Through holes: 0.2 < dia < 2.0 mm
Horizontal bridges: 0.3 < THK < 2.0 mm
Embossed/Engraved details: 0.5 < h, w < 1.0 mm

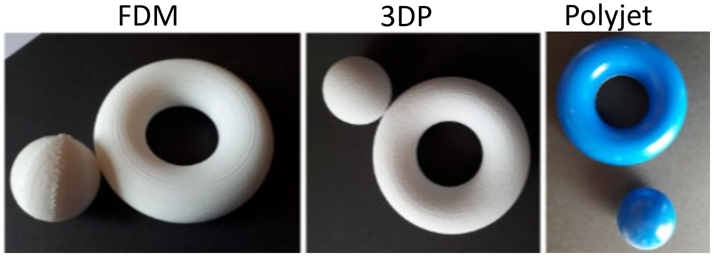


B3

Supported walls: THK = 1.0 mm

Benchmarks printed using three AM technologies





Geometric Primitives printed using three AM technologies

MODEL AND PART CHARACTERISTICS THAT AFFECT PRINTABILITY (2/3)

Mesh Complexity

- 4 different **mesh resolution** (lowest to highest)
- **Mean Curvature Analysis**

➢ Mesh complexity *C* of a CAD model *M* with a *PLG(M)* set of triangles

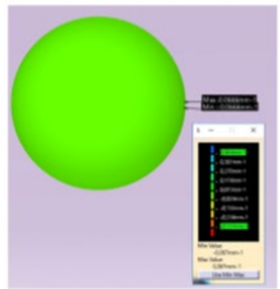
$$C_M = |PLG(M)|$$

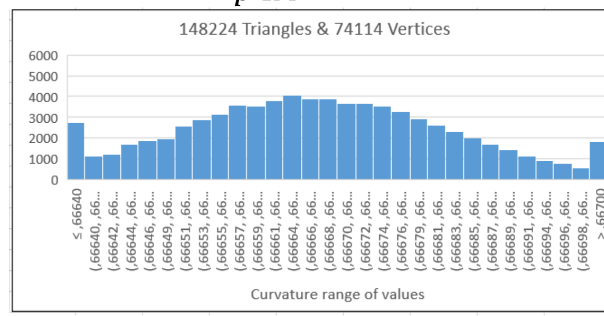
➢ Overall mesh complexity for convex polygons *p* with *u(p)* vertices

$$C_M = \sum_{p \in M} u(p) - 2$$

Sphere D: 3 cm - Volume: $1.414 * 10^{-5}\ m^3$

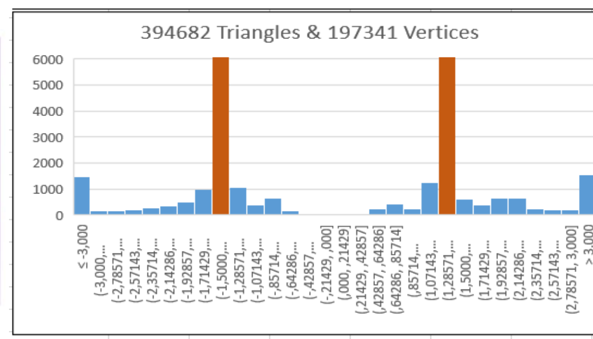
	Triangular Mesh No of faces	Volume ($10^{-5}\ m^3$)	Bbox (cm) X axis	Y axis	Z axis
- 8%	168	1.299	3.00	2.92	2.88
	1520	1.399	3.00	3.00	3.00
	14640	1.412	3.00	3.00	3.00
0%	148224	1.414	3.00	3.00	3.00





B3 V: 8,0 cm & H: 2,5 cm & D: 8,0 cm- Volume: $9,534 * 10^{-5}\ m^3$

	Triangular Mesh No of faces	Volume ($10^{-5}\ m^3$)	Bbox (cm) X axis	Y axis	Z axis
- 1%	634	9.511	8.00	2.50	8.00
	6382	9.534	8.00	2.50	8.00
	44984	9.534	8.00	2.50	8.00
0%	394682	9.534	8.00	2.50	8.00



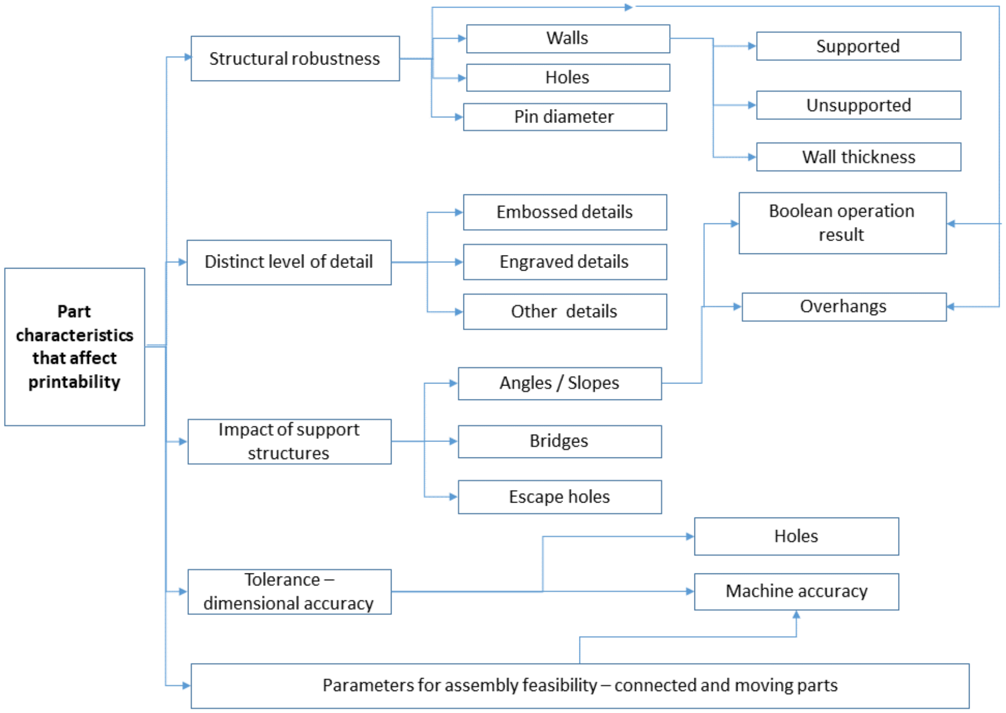
MODEL AND PART CHARACTERISTICS THAT AFFECT PRINTABILITY (3/3)

References [5, 19]

Part Design Characteristics

❑ This work examines design characteristics and design rules that affect printability of a CAD model on a specific AM technology

- Part characteristics that ensure structural robustness
- Conform with size limitations for each AM technology
- Achieve distinct level of detail
- Support construction
- Ensure functionality for connected and/or moving parts



Print failure:

- × Structural problems (e.g. collapsed walls)
- × Dimensional accuracy deviations (e.g. holes with small diameter)
- × Functionality and assembly issues (e.g. parts that fit together, screw)
- × Models with high detail concentration on a small surface area
- × Plurality of support structures

A CHARACTERIZATION OF 3D PRINTABILITY (1/4)

This work defines a measure that characterizes the printability *P* of a model *M* on a 3D *AM technology T*
→ **printability score**

0 < **printability score** < 100 ,
where *0: print model failure*
100: structurally robust model, print success

- The printability score is defined by two factors:

1. **Global probability function: $P_G (C_M, T, A)$** based on C_M: Mesh Complexity, *T*: AM Technology, *A*: Application
   where $P_G (C_M, T, A)$ = *print failure and* $(1 – P_G (C_M, T, A))$ = *print success*

2. **Part characteristic probability function: $P_F (i, D, T, A)$** based on *i*: part characteristic, *D(i)*: set of characteristic parameters, *T*: AM Technology, *A*: Application
   where $P_F (i, D, T, A)$ = *print failure and* $(1 – P_F (i, D, T, A))$ = *print success*

The **overall probability** of a model *M* with *n* number of part characteristics to be successfully printed on technology *T* is:

$$P(M,T) = (1 - PG(C_M,T,A)) * \prod_{i=1}^{n} (1 - PF(i,D,T,A))$$

- **The printability measure (score)** of *M* on *T* is:

$$PS(M,T) = 100 * P(M,T)$$

A CHARACTERIZATION OF 3D PRINTABILITY (2/4)

References [14, 16]

Global Probability Function (1/2)

- P_G is related to the characteristics of the technology employed for printing
- An initial **defect score $DS_T^{Perfect}(x)$** is assigned to each characteristic *x* based on technical specifications of each technology T and experimental technology assessment
- $DS_T^{Perfect}(x)$ expresses the probability of a characteristic *x* to cause a printing failure using the highest mesh resolution

Characteristic / Technology	FDM	Binder Jetting	Material Jetting
Accuracy	**	**	***
Surface Texture	*	**	***
Various Abnormalities (Warping, shrinkage etc.)	*	**	***
Support Construction	**	***	**

✓ The values can be altered depending on the requirements, restrictions for a specific application

Low probability → Defect probability value: 0.01 (1% probability)

High probability → Defect probability value: 0.05 (5% probability)

Average probability → Defect probability value: 0.03 (3% probability)

A CHARACTERIZATION OF 3D PRINTABILITY (3/4)

Global Probability Function (2/2)

- **Defect score probability function** *$DS_T(x)$* of a technology printing characteristic *x* on technology *T* as:

$$DS_T(x) = 1-(1-DS_T^{Perfect}(x))*QS_{C_M}$$ where $$QS_{C_M} = Area(M)/Area\ (O)$$

- **The global probability function P_G** of a model *M* for an application *A* on a printing technology *T* is:

$$P_G(C_M, T, A) = 1 - \prod_{x \in S}(1 - DST(x) * k(x, A))$$

where *S*: set of global technology characteristics and *k (x,A)∈[0,1]* : factor for the sensitivity of application *A* to characteristic *x*

- For k(x,A) = 0 not affected
- For k(x,A) = 1 fully affected

- P_G values expressing printability for different meshes of a sphere

Global probability function: $1 - P_G(C_M, T, A)$

	Results for k=0.1			Results for k=0.5		
C_M	FDM	Binder Jetting	Material Jetting	FDM	Binder Jetting	Material Jetting
168	0.97239246	0.978116384	0.981823174	0.867419752	0.89389853	0.911550807
1520	0.982638713	0.988553692	0.992496154	0.915394871	0.943702897	0.962885818
14640	0.983937057	0.989876312	0.993848738	0.921572972	0.950117484	0.969498937
148224	0.984078112	0.990020005	0.993995687	0.922245513	0.950815781	0.970218865

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A CHARACTERIZATION OF 3D PRINTABILITY (4/4)

Part Characteristic Probability Function

- For each design part characteristic *i* we determine a **part characteristic probability function (PCP function)** P_F with the following parameters
  - **Weight** $w(T, i) \geq 0$, numerical parameter depends on T, i and is the dimension value of *i* that has probability 50% to exhibit a significant flaw during printing on *T* [5]
  - **Significance** $0 < s(A,i) \leq 1$ expresses the impact of *i* on the printed model regarding *A*

<u>**The PCP function (P_F) of a part characteristic**</u> that corresponds to thin parts or small holes can be described as:

$$P_F(i, d, T, A) = 1 - \left(\frac{1}{1+ew^{(T,i)-d}}\right) * s(A, i)$$

where *i* is the characteristic under evaluation, *d* is its dimension (for holes and thin parts *D(i) ={d}*)

Parameters and Thresholds

<u>The designer determines:</u>
- Sensitivity of *k(x, A)*)
- Effect of *i* on the robustness *s(A,i)*

→ Overall printability score

- For printability score < 80% → model has a high chance of exhibiting structural robustness problems and undesired characteristics
- For printability score = 75% → only one out of four prints will fail due to any characteristic or design rule

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VALIDATION OF THE PRINTABILITY MEASURE (1/4)

The evaluation of the proposed scoring method was performed using three different AM technologies:

- FDM technology → printer: Ultimaker 3 Extended, dimensional accuracy: 0.2−0.02mm (0.4mm nozzle), PLA as feedstock material
- 3DP technology (Binder Jetting) → printer: ZCorp 450, dimensional accuracy: +/−0.102mm
- Polyjet technology (Material Jetting) → printer: Stratasys Connex3 Objet 260, dimensional accuracy: Up to 200μm (0.2mm)

Procedure

- Geometric primitives → printed 5 times and Benchmarks → printed 3 times, on each AM machine
- Printability score for each model on each T was calculated before printing with k= 0.1 for the P_G
- High sensitivity for holes and thin parts
- For geometric primitives PCP function = 0 → **printability scores = P_G**
- Printability scores of the benchmarks: **PCP functions** evaluated for thin walls, pins and holes
- After printing and post processing, evaluation of the fabricated parts:
  - dimensional accuracy
  - structural robustness
  - surface quality
- Overall evaluation the printability scores of each model on each AM technology

VALIDATION OF THE PRINTABILITY MEASURE (2/4)

- Printability score for each model on each technology for P_G
- For the benchmark models, PCP functions were evaluated for thin walls, pins and holes

	Printability Score ($k = 0.1$)		
Model	FDM	Binder Jetting	Material Jetting
Sphere	98.379%	98.973%	99.370%
Cylinder	98.406%	99.000%	99.397%
Torus	98.409%	99.004%	99.401%
Rect. Parallelep.	98.406%	99.001%	99.398%
B1	22.110%	12.100%	28.425%
B2	28.679%	17.592%	39.421%
B3	86.998%	74.239%	86.025%

- × Sphere on FDM technology has a higher probability to display printing errors
- ✓ Cylinder, rectangular parallelepiped and torus have a printability score of over 99% on Polyjet technology and 3DP
- × B1 had a lower printability score due to the presence of many thin parts whose dimensions were at or below the limits of the AM technologies

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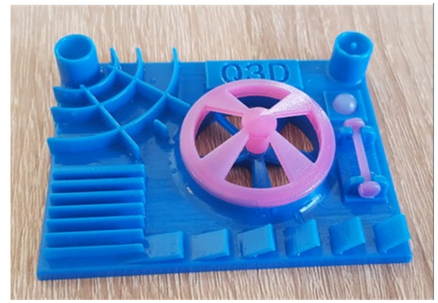
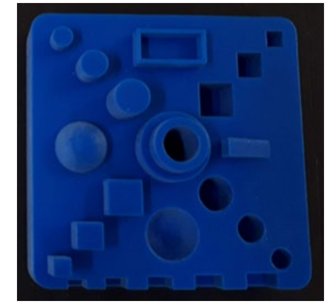
VALIDATION OF THE PRINTABILITY MEASURE (3/4)

Overall evaluation

B1 benchmark



B2 benchmark



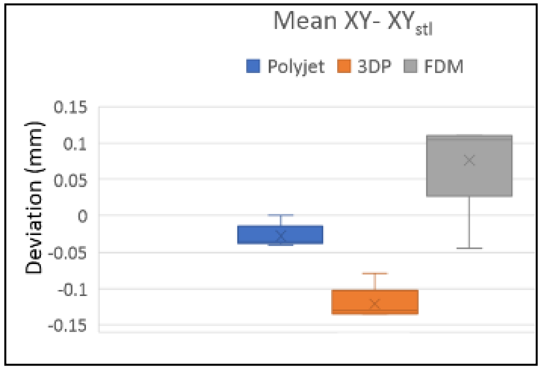
B3 benchmark

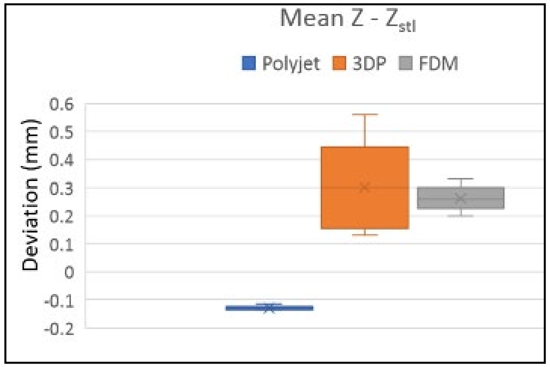
	FDM	3DP	Polyjet
dimensional accuracy	• Larger on both XY and Z directions • Warping	• Smaller on XY directions (lower resolution of the machine on XY) • Larger on Z • Smallest deviation in Volume size	• More accrate on both XY and Z directions • Repeatability • Consistency
structural robustness	• Support removal problem for thinner bridges (B1) • Some holes printed not circular (B1) • Overhangs with smallest angles not printed well (B2) • Thinnest wall was successfully printed but with flaws (B2) • Thin pin printed sucessfully (B2) • Propeller of B2 (thin part) printed but cracked in post-processing	• Thin bridges printed but broken in post-processing (B1) • Thinnest wall was broken or presented warping in some cases (B2) • Thin pin printed sucessfully but collapsed in post processing (B2) • Propeller of B2 (thin part) printed successfully	• Support removal problem for thinner bridges (B1) • Thinnest wall was successfully printed (B2) • Thin pin printed sucessfully (B2) • Propeller of B2 (thin part) printed successfully
surface quality	• Rough parts • Surface anomalies • Hairs • Uneven surfaces from material deposition	• Slightly porous • No anomalies • Better level of detail	• Very smooth surface • Good level of detail

VALIDATION OF THE PRINTABILITY MEASURE (4/4)

Evaluation of dimensional accuracy

- ❑ Display of XY and Z deviations of printed sphere from original sphere mesh

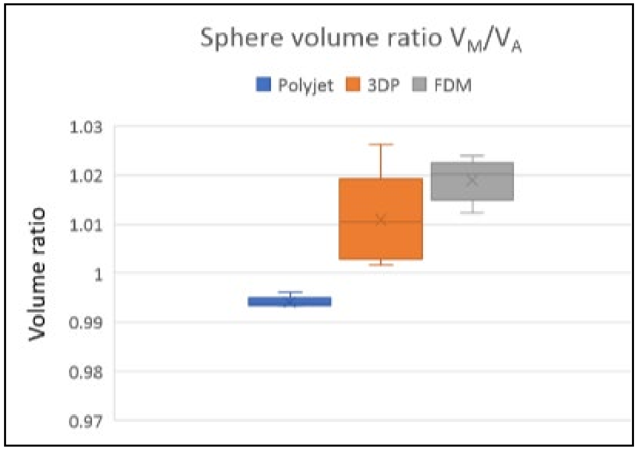




Volume ratios of printed sphere models

	Ratio $l = V_M/V_A$		
Model	Polyjet	3DP	FDM
Sphere-1	0.993682194	1.010465886	1.021082769
Sphere-2	0.993433109	1.001674907	1.017535587
Sphere-3	0.993433109	1.026164459	1.012230231
Sphere-4	0.993682194	1.004181391	1.023875618
Sphere-5	0.996175332	1.012230231	1.020068449

Comparison of the volume ratios for the parts fabricated on the three technologies



CONCLUSIONS - FUTURE WORK

Present Work

- Novel approach for characterizing the efficacy of manufacturing a CAD model on an AM machine of a certain technology, based on its model complexity and part characteristics
- These elements are mapped to parameters and functions, that depend also on the printing technology to be employed, that make up a linear formula that corresponds to a printability score
- By using worst case printing scenarios → determination of which 3D technology is more suitable for manufacturing a specific model or used as a guide for redesigning the model so that it is more suitable for an intended specific technology

Future Work

- Evaluation of more part characteristics and their impact on printability
- Evaluation of the volume ratios of the benchmark models with methods of photogrammetry and laser scanning to further validate our approach
- Also the proposed printing score system can be adapted to include other AM printing technologies and other design intents

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