Milan Sljivic
Full Professor
Faculty of Mechanical Engineering,
University of Banja Luka,
Bosnia and Herzegovina

Ana Pavlovic
Adjunct Professor
Department of Industrial Engineering,
Alma Mater Studiorum University of Bologna
Italy

Jovica Ilic
Researcher
Faculty of Mechanical Engineering,
University of Banja Luka
Bosnia and Herzegovina

Mico Stanojevic
Researcher
Faculty of Mechanical Engineering,
University of Banja Luka,
Bosnia and Herzegovina

Slavisa Todorovic
Researcher
Faculty of Mechanical Engineering,
University of Banja Luka
Bosnia and Herzegovina

Comparing the Accuracy of Professional and Consumer Grade 3D Printers in Complex Models Production

This study aims at comparing the accuracy offered by professional and consumer grade 3D printing machines, inside a Fused Deposition Modelling (FDM) process of Additive Manufacturing (AM), in the realisation of complex models. It intends to verify, using an experimentally based approach, how much these two groups of 3D printers differ in terms of achieving complex geometry, surface quality and dimensional stability of additive models. Two consumer grade and professional 3D printers were selected and used for creating a complex model. Limits and benefits provided by each of them in engineering terms were investigated and reported. A religious building was used as a complex model, created by both 3D printers, scanned by reverse engineering technology, then processed by a software package for image processing. In this way, a comparison in models' accuracy was achieved. Results, graphically represented, show some notable differences between 3D printers in terms of accuracy and applicability. They also permit to make recommendations on practical usability of this technology.

Keywords: *Additive Manufacturing, Fused Deposition Modelling, 3D Printer, Professional grade, Consumer grade, Accuracy, Complex models*

1. INTRODUCTION

Additive Manufacturing (AM) Technologies emerged as a new and innovative technology based on Rapid Prototyping which overcomes the shortcomings of traditional methods of prototyping.

This terminology is under the jurisdiction of the F42 Committee on Additive Manufacturing Technologies and of F42.91 Subcommittee on Terminology, through a mutual agreement with ASTM International (ASTM) standards development process, and the Society of Manufacturing Engineers (SME), available from ISO Standard [1,2].

Materials play a key role in the AM process. According to the type of AM technology [1-6] used in certain AM processes, Table 1 gives the selection of materials and the field of application of AM processes.

The review paper [7] demonstrated a development procedure of alternative feedstock filament of low-cost composite material for Fused Deposition Modelling (FDM) to extend the range of rapid tooling applications.

The study [8] is a comparison based on a reference part that was designed to fit into the building volume of most low cost FDM machines through part quality using IT grades [9].

A comparative study [10,11,12] presents the additive manufacturing of certain parts on two different 3D printing machines and the comparisons of the quality of the resulting parts in order to plan for hybrid processes and improve final manufacturing quality with a CNC milling machine. A key feature of AM is that it enables generating physical models directly from computer data (CAD), without using tools (as cutting tools [13]) and accessories, layer by layer, significantly reducing the time needed for prototyping and increasing chances for the placement of quality and successful products.

Table 1. Selection of AM processes according to typical materials and field of application

Process	Typical materials	Application
Material Extrusion – Fused Deposition Modeling (FDM)	Polymer (ABS, PP, PC, PPS, ASA,), Composite, Wax, WPC	Prototypes, Casting Paterns, Soft Tooling, Functional Parts
Material Jetting Multi-jet modeling (MJM)	Polymer (ABS, PP, Acrylic, Rubber), Wax	Prototypes, Casting Patterns, Soft Tooling
Binder Jetting Powder bed and inkjet head, plaster based 3D printing	Composite Gypsum, Ceramic, Sand, Metal, Polymer	Functional Parts, Prototypes, Casting Paterns, Soft Tooling
Sheet Lamination Laminated object manufacturing (LOM), ultrasonic consolidation	Paper, Metal (Steel, Aluminium, Titanium, Cooper)	Functional Parts, Prototypes, Casting Paterns, Soft Tooling
Vat Photopolymerization Stereolitography (SLA), digital light procesing	Polymer (Epoxy, ABS, PP), Compostie Gypsum, Ceramic, Wax	Prototypes, Casting Paterns, Soft Tooling
Powder Bed Fusion Thermal energy selectively fuses regions of a powder	Metal (Alloy Steel, Aluminium, Titanium), Ceramic, Polymer (ABS, PP, PA, PA-Glass filled), Composite, Rubber, Silicate	Functional Parts, Prototypes, Casting Paterns
Directed Energy Deposition Focused thermal energy is used to fuse materials – Laser metal deposition (LMD)	Metal (Alloy Steel, Aluminium, Titanium)	Functional Parts

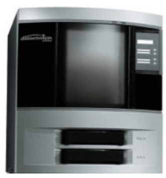
Received: August 2016, Accepted: September 2016
Correspondence to: Milan Slivic, Faculty of Mechanical Engineering, University of Banja Luka, Banja Luka
Bosnia and Herzegovina,
E-mail: milan.sljivic@unibl.rs
doi:10.5937/fmet1703348S

2. EXPERIMENTAL WORK

The complex models of a religious building (Figure 1) were done using AM technology based on FDM - material extrusion process of polymer on a professional 3D printer Dimension Elite - Stratasys and a consumer grade 3D printer LeapFrog - The Netherlands, which are available in the Laboratory for Technology of Plasticity at the University of Banja Luka and comparison of the results was carried out at the Faculty of Engineering of the University of Bologna. Additive manufacturing [14,15] systems and experimental process parameters used in this experiment are described in Table 2.

Figure 1: Cathedral of Christ the Saviour in Banja Luka, built in 1925, rebuild in 2004.

Table 2: Specification of 3D printers and experimental process parameters

	Consumer grade 3D Printer	Professional grade 3D Printer
Machine	 LeapFrog Creatr XL – LeapFrog, Netherlands	 Dimension Elite - Stratasys
Extruder	Double extruder	Double extruder
Build volume	230x270x600 [mm]	203x203x305 [mm]
Material	White ABS	Blue ABS plus
Support material	HIPS	Default
Manufacturing time	14 h 34 min	32 h 59 min
Layer thickness	0,2 mm	0,254 mm
Model interior	7 % fill density	Sparse low density
Process temperature	60 °C (heated plate)	Default
Extruder temperature	200 °C	Default
Raft	Included	Default
Price 3D printers	≈ 5 000 $	≈ 30 000 $

In this additive manufacturing process, a polymer in the form of a 1.75 mm diameter wire is pressed out through a nozzle which follows the cross-section of a part, forming the geometry of the part, layer by layer. The nozzle contains resistance heaters to heat and keep material at a temperature above the melting point, allowing the flow of material and forming of layers. The plastic hardens immediately after leaving the nozzle forming the next layer. When a layer is made, the platform is lowered, and the nozzle continues with the application of the next layer. In addition to the base material, the FDM systems may use the support material which serves as a holder for culverts and holes and passes through particular nozzles. This technology uses software that controls the orientation of the object and formation of layers.

Measurements and process validation is done using the articulated arm MCAx20 – Nikon MCAx20 and the digital handheld laser scanner Nikon MMDx100. The Coordinate MCAx Manual measuring Arm, produced by Nikon, is a precise, reliable and easy-to-use portable 7-axis measuring arm. It is a perfect partner for the Model Maker MMDx/MMCx digital handheld laser scanners and Focus Handheld scanning and inspection software.

2.1 The process on the professional grade 3D Printer

The processing and treatment of the CAD model of a religious building in the STL file on Dimension Elite 3D printer was made in Catalyst EX software, in which the orientation of the model, scale, supporting structure and the internal structure of the model were defined, Figure 2.

The printer status of the CAD model of a religious building with build statistics is shown in Figure 3.

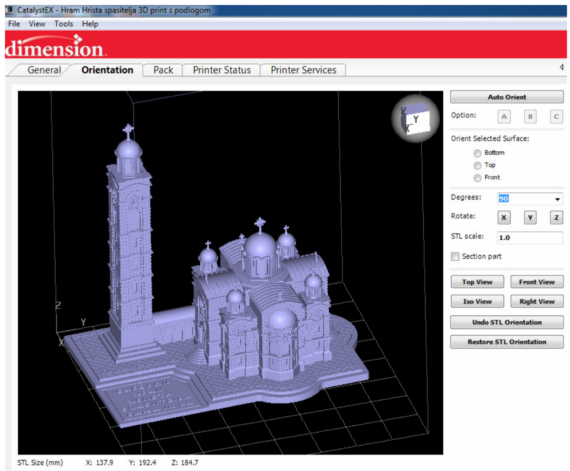


Figure 2: Processing and preparing the CAD model for printing in the Catalyst EX software package

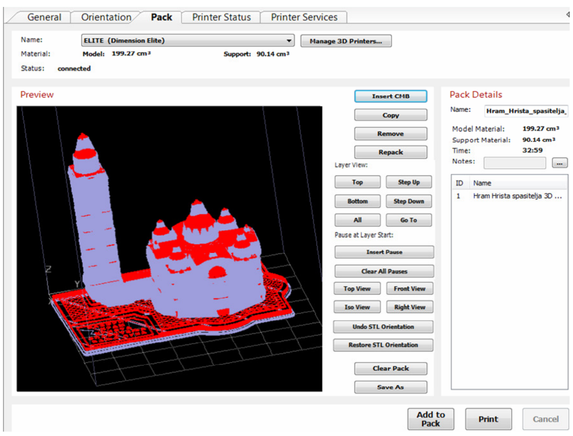


Figure 3. Printer Status of the CAD model of a religious building

2.2 The process on the consumer grade 3D printer

Processing and preparation of the CAD model on the consumer grade 3D printer LeapFrog was done through Simplify 3D software (Figure 4). In this software it is necessary to define a significantly larger number of influential parameters on additive manufacturing because the implemented optimization directly depends on the success of making the CAD model.

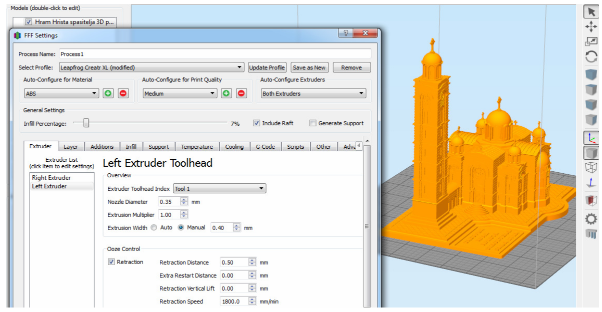


Figure 4. Processing and preparing the CAD model for printing in the Simlify3D software package

The printer status of CAD models, such as build statistics, speed and preview mode is shown in Figure 5.

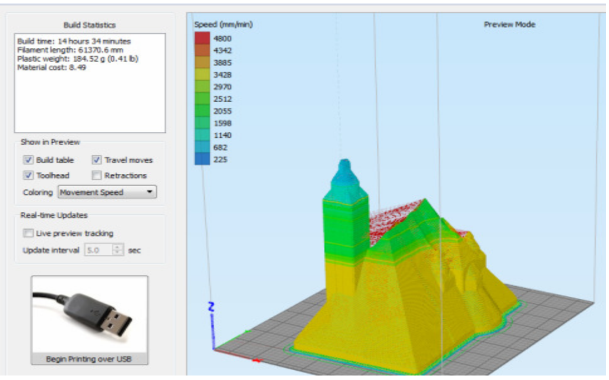


Figure 5. Build statistics, speed and preview mode of the CAD model

3. RESULTS

3.1 Validation testing of manufacturing models on the professional grade 3D printer

The production of the religious building on the professional grade 3D printer Dimension Elite was achieved with the following manufacturing performance: build time 32 hours 59 minutes, the used model material 199.27 cm3 and used support material 90.14 cm3. The support material was removed after printing in a special support cleaning apparatus with a chemical product ICW06 Wax Support at a temperature of 700C for a period of 12 hours. The completed model with the dimensional data achieved and the quality of the surface realized is given in Figure 6.

Inspection of comparison between the geometry of the CAD model of a religious building and the prototype built on the Dimension Elite 3D printer was done with a Coordinate MCAx Manual measuring Arm and the digital handheld laser scanner Nikon MMDx100 (Figure 7). This kind of equipment, originally developed for reverse engineering, is currently used for quality control in industrial processes, especially when the required accuracy in monitoring is extreme [16].

Figure 6. The religious object produced on the professional grade 3D printer Dimension Elite

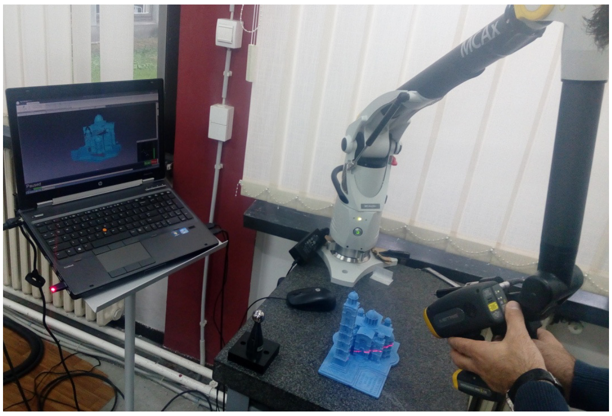


Figure 7. Acquisition of 3D geometry by Coordinate MCAx Manual measuring Arm and the digital handheld laser scanner Nikon MMDx100.

Geometrical acquisitions were provided to the Focus 10.1 software package for image processing (Figure 8). The inspection was done on five tolerance points taking into account the basic geometric parameters, namely the coordinates x, y, z, 3D and deviation - sigma.

The deviation between the nominal and measured values at five marked points on produced prototypes on Dimension Elite was: Sigma = 0.205 mm, Figure 8 and Table 3.

Based on the analysis of the geometrical data achieved as well as the visual appearance, in engineering terms the model was done with high performance surface quality and dimensional stability. It should be noted that the time of additive manufacturing (build time 32 hours 59 minutes) as well as the removal of support material (12 hours) from the produced model is significantly high. Also, the costs of used quality model material (Model Cartridge: 1kg = $ 250) and support material (Support Cartridge:1kg = $ 250) are high. But, compared to the results achieved using additive manufacturing, this increased time of printing as well as the high cost of the used material have an economic justification [17,18].

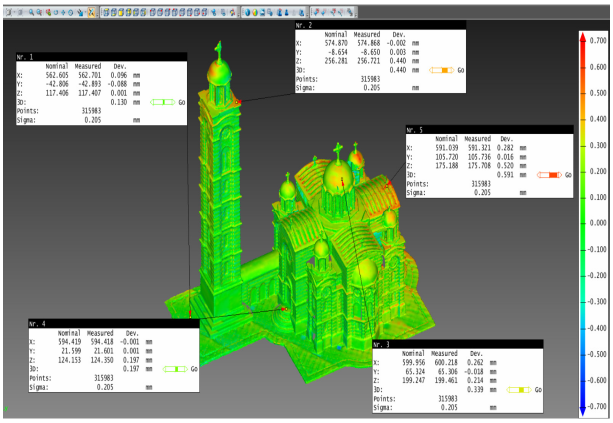


Figure 8. Comparison between the geometry of the CAD model and the prototype built on Dimension Elite 3D printer (Focus 3.1)

Table 3. Deviation - Sigma between the geometry of the CAD model and the prototype built on Dimension Elite

Geometrical data	Deviation – Sigma (mm)				
	Point Nr.1	Point Nr.2	Point Nr.3	Point Nr.4	Point Nr.5
x:	0.096	-0.002	0.262	-0.001	0.282
y:	-0.088	0.003	-0.018	0.001	0.016
z:	0.001	0.440	0.214	0.197	0.520
3D:	0.130	0.440	0.339	0.197	0.591
Points:	315983				
Sigma:	**0.205** mm				

3.2 Validation testing of manufacturing models on the consumer grade 3D printer

The CAD model of the religious building is made on the consumer grade 3D printer LeapFrog with the following technological performance: build time 14 hours 34 minutes, filament length 61370.6 mm, plastic weight 184.52 g, speed 225-4800 mm/min and material cost of € 8.49. The time and cost of production should include the manual finish of the model, the removal of the support structure and raft, which amounted to about 5 hours [19]. The finished model is given in Figure 9.

Deviations between the geometry of the CAD model and the prototype of the religious building produced on the consumer grade 3D printer LeapFrog, generated in the Focus 10.1 software package, are shown in Figure 10.

The deviation between the nominal and measured values at five marked points on produced prototypes on the consumer grade 3D printer LeapFrog amounted to: Sigma = 0.429 mm, as presented in Figure 10 and Table 4.

The analysis of the results achieved using additive manufacturing of the CAD model of a religious building on the consumer grade 3D printer LeapFrog showed significant dimensional variations of geometrical data at all marked points (Fig. 8). The achieved surface quality is not at the professional level and additive manufacturing process does not have the necessary production stability, which, however, does not exclude the use for parts that require less precision and accuracy. But, it should be noted that the production time (build time 14 hours 34 minutes) and the manual removal of support and raft (5 hours) is lower. The cost of the material used is as follows: model material (1kg = $ 30) and support material (1kg = $ 30), which is beneficial for the quality that can be achieved with this material.

Figure 9. The religious object manufactured on the consumer grade 3D printer LeapFrog

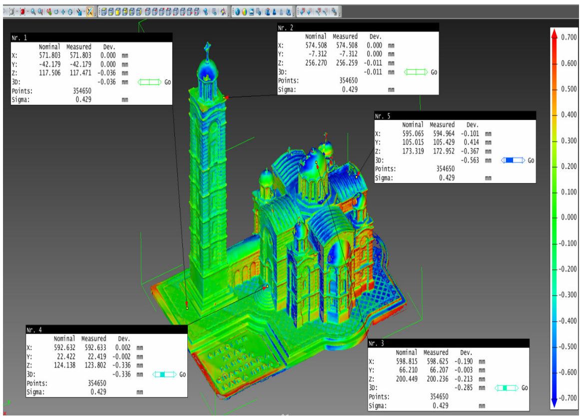


Figure 10. Comparison between the geometry of the CAD model and the prototype built on the consumer grade 3D printer LeapFrog (Focus 10.1)

Table 4. Deviation - Sigma between the geometry of the CAD model and the prototype produced on the consumer grade 3D printer LeapFrog.

Geometrical data	Deviation – Sigma (in mm)				
	Point Nr.1	Point Nr.2	Point Nr.3	Point Nr.4	Point Nr.5
x:	0.000	0.000	-0.190	0.002	-0.101
y:	0.000	0.000	-0.003	-0.002	0.414
z:	-0.036	-0.011	-0.213	-0.336	-0.367
3D:	-0.036	-0.011	-0.285	-0.336	-0.563
Points:	354650				
Sigma:	**0.429**				

4. CONCLUSION

The comparison of additive manufacturing 3D model of a religious building using the professional grade 3D printer Dimension Elite and the consumer grade 3D printer LeapFrog showed significant differences in terms of achieving dimensional accuracy, surface quality and process stability. The deviation between the nominal and measured values in the marked points on produced prototypes on the printer Dimension Elite is Sigma = 0.205 mm and on the LeapFrog amounted to: Sigma = 0.429 mm. This difference determines the dominant advantage of professional 3D printers which can be reliably used in engineering applications. The model done on Dimension Ellite, on the basis of the validation test, showed high performance surface quality and dimensional stability. However, it must be noted that the additive manufacturing time of 32 hours 59 minutes is significantly high and the choice of materials is limited only to the polymer ABS and support material for Dimension Elite, whose production cost is high (Cartridge=$ 250). Here, the research and development in additive manufacturing technology needs to be more based on increasing processing speed, reliable process control, and increase in the use of a set of compatibility materials.

The experiment demonstrates that the quality of the produced 3D models of a religious building on Leapfrog in engineering terms is generally poor. This was influenced by the following factors: the lack of feedback control systems of the manufacturing process, unstable work of extruder and variable quality of printed materials. However, additive manufacturing on the consumer grade 3D printer, taking into account significantly lower cost of materials (1kg = $ 30) and shorter production time (14 hours 34 minutes), could be successfully used for the parts which in functional terms require lower quality and accuracy. In that case, the stability of the additive manufacturing process must be necessarily raised, where double extruders are not synchronized well and the used material which is extruded through a nozzle is of variable quality and the process control is poor, which leads to frequent interruptions of the production process. The removal of these defects on consumer grade 3D printers could provide recommendations for wider use of the additive manufacturing of final consumer parts.

ACKNOWLEDMENT

This investigation is part of a larger research activity aiming at proposing new technical solutions for a rapid manufacturing passing by an advance utilisation of rapid prototyping and in integration with other more traditional processing methods [20].

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УПОРЕЂУЈУЋИ ТАЧНОСТ ПРОФЕСИОНАЛНИХ И ПОТРОШАЧКИХ 3D ШТАМПАЧА У ПРОИЗВОДЊИ СЛОЖЕНИХ МОДЕЛА

М. Шљивић, А. Павловић, Ј. Илић, М. Станојевић, С. Тодоровић

Циљ истаживања је упоређивање тачности коју нуди професионални и потрошачки 3D штампач, унутар Fused Deposit Modeling (FDM) процеса и процеса Адитивне Производње (АМ), у реализацији сложених модела. Намера је да се провери, користећи експериментални приступ, колико се ове две групе 3D штампача разликују у погледу пости–зања сложених геометрија, квалитета површине и стабилности димензија адитивних модела. Два потрошачка и један професионални 3D штампач су изабрани и коришћени за израду комплексног модела. Ограничења и предности које пружа сваки од њих у инжењерском смислу су испитивани и приказани. Религиозна зграда је служила као комплексни модел, реализована од страе оба 3D штампача, скенирана техником реверс инжење–ринга, а затим обрађена од стране софтверског пакета за обраду слике. На овај начин оствbooрена је прецизност модела. Резултати, графички приказани, показују неке значајне разлике између 3D штампача у погледу тачности и применљивости. Они такође омогућавају да дају препоруке о практичној употребљивости ове технологије.