Evaluating the 3D Printing Capabilities

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Abstract

In recent years, with the booming 3D printing industries and applications, the process capability and the specifications for the 3D printers and the associated products have been tightened due to performance and cost competition. Companies are trying to develop the manufacturing capabilities to meet the tighter specifications and quality requirements of the customers, but at the same time struggling to keep the offered prices within accepted levels. This study focuses on exploring and evaluating experimentally the manufacturing process capability of the 3D printers to produce 3D printed parts of different geometries and internal designs to minimize the costs lost. This has been achieved by estimating the actual specifications limit of the studied 3D printers. Moreover, the study starts with exploring the manufacturing process capability and the specifications limit of the available 3D printers in UAEU as well as commercial and industrial 3D printers available in the domestic market. Besides, to come up with guidelines and conclusions to help in understating the specifications of the 3D printers that aimed to be used. Different 3D printers are built to test the process capability of assembled 3D painters to support the objective of the study.

Keywords
Dimension tolerance, precision, process capabilities

1. Introduction

Recently, 3D printing has become a robust field that is developing significantly to revolute the manufacturing processes. Many disciplines like mechanical, electrical, biomedical and aerospace industries utilize 3D printing to improve the design manufacturing and to minimize the lead time, as well as reducing the tooling cost for new components produced. 3D printing differs from conventional machining such as turning, milling, and drilling, which helped people many decades ago to build products. However, in the past few years, they are no longer used as much as before because they have some limitations and constraints, such as the expensive cost of the production processes. In this regard, the concept of 3D printing has presented. It is also known as additive manufacturing, which is a part of rapid prototyping in which 3-dimensional products can be formed from a digital file. Additive manufacturing meant to be the deposition of a specific material layer by layer until the desired object is created as per the given design. Those layers that combined one on top of the other is nothing more than a horizontal cross-section of the product itself. The quality of the object printed using 3D printer relies on the composition of the material added, the manufacturing process, the speed in which the printer operates, the type of 3D printer used, and eventually, the volume of the part printed using that printer. In general, 3D printing technology has a significant contribution to the world in many directions because of the remarkable advantages to the industrial sector and has a substantial impact on the other fields [1,2]. Moreover, this revolution has been extended to other applications, like in prototyping, simulations, and failure mechanism [3,4], whereas the aerospace sector is one of the promising sectors due to the vast and numerous applications that could be adopted of using 3D printing technology [5]. However, the 3D printing technology started being embraced in schools [6] for the learning purposes [7], as well as implemented in different university levels [8].

1.1 3D printing Technologies

There are numerous technologies that 3D printers use to print the products where the process starts from 3D Cad model and ended at producing a real physical object, as illustrated in Fig.1. In some techniques, the material from which the layers of the object are formed needs to be liquefied or softened. While in other cases high powered UV laser is used to cure photo-reactive resin and print the object. Some of the most commonly used 3D printing techniques these days are:

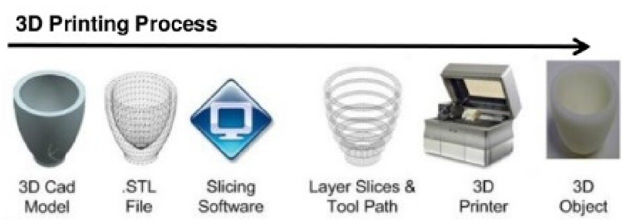

Figure 1 : 3D printing process from design to printing [9]

1.1.1 Stereolithography process

Stereolithography (SLA) is defined as a 3D printing technology that is mainly used for creating models, patterns, and prototypes, as shown in Fig.2. It is said to be a laser-based process because ultraviolet laser and a vat of resin are essentials to make a part using this strategy. The laser beam shows the design on the liquid polymer surface. Ultraviolet laser exposure creates a link between the chains of atoms in the polymer gum [10]. After that, the photopolymer resins response to the laser to make a solid object in a particular form. Stereolithography is considered to be the best prototyping method, while it is less time-consuming and somehow cheaper than the other methods [11]. Post processes this technology involves a chemical bath to clean the part plus laying the piece in an oven-like machine to entirely harden the resin.

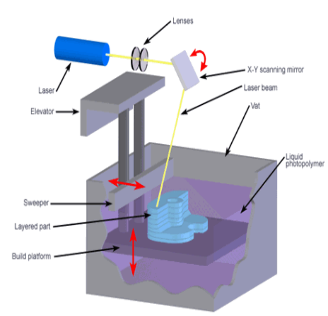

Figure 2 : Stereolithography [12]

1.1.2 Digital Light Processing (DLP)

DLP technology, the 3D printing technique, is similar to stereolithography but is unique in that it uses a different light source and uses a liquid crystal display panel [13]. This technology utilizes more conventional light sources, and the light is controlled using micromirrors to regulate the incident of the light on the surface of the object to be produced. The liquid crystal display panel performs as a photomask. This mechanism permits for a significant quantity of light to be projected onto the surface to be cured, thus allowing the resin to harden rapidly [13].

1.1.3 Electronic Beam Melting (EBM)

This technology is similar to SLM as well. Though, it makes use of an electron beam as an alternative of a high-powered laser [13]. The electron beam would melt the metal powder to form the desired object. The process is considered as a slower and more expensive than for SLM, with a more significant limitation on the material available.

1.1.4 Laminated Object Manufacturing (LOM)

It is considered a prototyping process. In this process, layers of substantial coated with adhesive are fused together with heat and pressure and then cut into shape employing a laser cutter or knife [13]. Precisely, a foil coated with resin is covered in the previous film, and a heated roller as sketched in Fig.3 heats the glue for adhesion between the two films. Films can be fabricated from paper, plastic, or metal laminates [13]. Post-processing steps that include machining and drilling may be included in the process. As a consequence, this is a simple and cheap 3D printing method [13]. No chemical process is required with the use of an adhesion system, and relatively large parts can be produced.

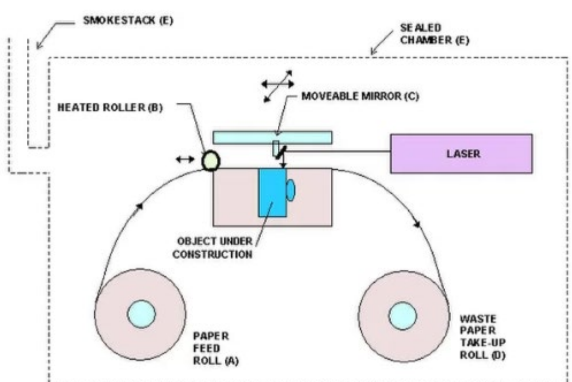

Figure 3: Laminated Object Manufacturing[14]

1.1.5 Fused Deposition Modelling

Fused Deposition Modelling (FDM) (Fig.4) is a 3D printing technique that is building models and prototypes layer by layer using a continuous heated thermoplastic filament [15]. Similar to SLA, post-processes are necessary for the parts printed in FDM. By comparison with SLA, FDM is cheaper but less accurate. Furthermore, the material in FDM is limited to thermos plastic.

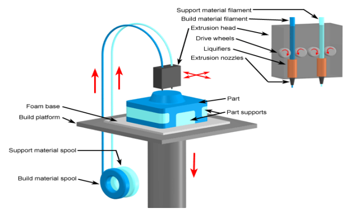

Figure 4: Fused Deposition Modelling [16]

1.1.6 Selective Laser Sintering

Selective Laser Sintering (SLS) is another type of additive manufacturing technology where a small particle of various materials such as polymers, ceramics or glass are bonded together by using heat from a high-powered laser beam to create the solid part [17].

1.2 Standard Deviation

The standard deviation is a statistic that measures a data set's dispersion relative to its mean and is estimated as the variance's square root. By evaluating the difference between each data point relative to the mean, it is determined as the square root of variance. There is a higher variance within the data set if the data points are further from the mean; thus, the more the data is distributed, the higher the standard deviation [18].

$$Standard\ Deviation = \sqrt{\frac{\sum_{i=1}^{n}(x_i-\bar{x})^2}{n-1}} \quad (1)$$

Where:

x_i=Value of the ith point in the data set

$\bar{x}$=The mean value of the data set

n=The number of points

1.3 Tolerance

Tolerance is also denoted as dimensional accuracy. Machining tolerances are the amount of deviation caused by the manufacturing process in a particular dimension of a part.

Dimensional tolerances are applied to parts as limits for the appropriate construction, with sufficient degrees of variance being set simply because no machines can hold measurements correctly. The main concern when it comes to tolerances is how high tolerance can be stripped without ending up influencing specific parameters or system outcomes.

Once a product has been manufactured with dimensions that are out of tolerance, it becomes unfeasible as the core features and functions of that part are not design-intentioned [19].

1.4 Process Capability

A process is described as a sequence of interdependent operations, procedures, or steps that consume resources and convert inputs into outputs. Every process or move contributes to the next one to achieve a desired objective or result. There is a certain amount of variation in each process. It is not possible to eliminate variability in a system, but it can be assessed, tracked, minimized and regulated. Variation in a system can have less impact on production performance by using process controls taking measurements and using reliable, well-maintained equipment. The process can be consistently able to produce an acceptable product. We can maintain the capability of processes.

Process Capability (Cp) is a statistical measure of the ability of a process to produce parts consistently within defined limits. In order to determine how our system performs, we can calculate Cp (Process Capability), Cpk (Process Capability Index), or Pp (Preliminary Process Capability) and Ppk (Preliminary Process Capability Index), depending on the process state and method of calculating the standard deviation or sigma value. In rational subgroups, the equations of Cp and Cpk use sample deviation or deviation mean. The calculations of Pp and Ppk use standard deviation based on data (whole population) studied. The indices Cp and Cpk are used in statistical control to test existing, established processes. The indices Pp and Ppk are used to evaluate a new or non-statistical method.

Process capability indices Cp and Cpk measure the performance of the process against the design limits determined by the tolerance range and the target value. Cp tells you if your system is capable of making parts within requirements, and Cpk tells you if your process dimensions are between the limitations. When engineers are designing components, they must consider the capability of the machine or process selected to produce the part.

The Cp index is fundamental that refers to the process capability. Process capability is determined based on the process target set by customers with certain requirement limits. Essentailly, USL (Upper Requirement Limit) and LSL (Lower Specification Limit), these are the acceptable limits already taken into account by consumers, and the general equation is as follows:

$$c_p = \frac{USL - LSL}{6\sigma} \qquad (2)$$

The process capability Cp = 1.33 or higher, is required by most of the manufacturing companies.

The process center's Cpk index goes one step further by examining how close a process is to the specification limits taking into account the typical variation of the process. The higher the value of the Cpk, the closer the mean of the data to the target value. Cpk is calculated using the limits of specification, standard deviation or sigma, and mean value. The value of Cpk should be between 1 to 3. If the value is less than 1 the process needs to be improved.

The indexes of Cp and Cpk are just as strong as the data used. Accurate studies of process capabilities depend on three basic data assumptions:

- There are no specific causes of variation in the process, and statistical control is in place. It is essential to discover and solve some special purposes.
- The data fit a Normal distribution, exhibiting a bell-shaped curve and can be estimated numerically to be less or more than three Sigma. There are cases when the data does not match the normal distribution condition.
- The population is reflective of the sample data.The data should be randomly collected from a large production run. Most organizations need to collect at least 25 to 50 sample measurements preferably [20].

1.4.1 Why measure Process Capability

Reducing waste and providing a quality product is imperative in manufacturing and many other types of businesses if they are to continue and succeed in today's marketplace. Many forms of waste can exist in the process. Looking at a wider image, process capability is more than just calculating the values of Cp and Cpk. Process capability is only one tool in the toolbox of the Statistical Process Control (SPCImplementing SPC requires data collection and analysis to clarify the process's analytical performance and to determine the causes of variability within it. Essential knowledge is obtained by focusing on the capability of the process. Process capacity monitoring allows the performance of the manufacturing process to be evaluated and adjusted as needed to ensure that products meet the design or the requirements of the customer. If this data is used efficiently, it can minimize waste, increase product quality and consistency, and reduce production costs and low quality costs.

1.5 Reviewing Literature

A study was carried out to explore the effect of process parameters such as Layer thickness and raster angle on linear and radial dimensional accuracy Poly Latic Acid component fabricated through Fused deposition modeling. It was concluded that dimensions of the fabricated parts were smaller than CAD Model due to the shrinking occurs during the cooling of material after the deposition of the layer. The dimensional inaccuracy of the radial dimension (RD) was higher than that of the linear dimension (LD) due to the slicing and squaring of edges. International tolerance grade (IT-grade) was evaluated for both LD& RD. IT-grade is the measure for dimensional accuracy of any machining. Results show that the linear dimension has a smaller IT-grade than the radial dimension. It was noticed that IT-grade was consistent within a specified range for all the experiments [21].

3D printed parts with HoneyComb Internal pattern by Fused Deposition Modelling was investigated based on statistical analysis in a separate study. Because of its exceptional ability to resist mechanical loads, the HoneyComb inner pattern was used to create within samples. 3D was utilized for slicing the 3D model and for adjusting layer thickness, infill percentage, and extruder temperature. Build time, max failure load, elongation at break, and part weight was selected as output responses and analyzed by response surface method. Analysis of variance results identified layer thickness as the significant controlled variable for all reactions. Interaction of infill percentage and extruder temperature had a considerable influence on elongation at break and, therefore, severe fracture and lesson build time [22].

In the past few years, the dimensional accuracy of the internal structure has gained little attention relative to the mechanical properties of the printed parts. Therefore, research was carried out to measure and compare the dimension accuracy of the inner structure using different scanning strategies. The results show that the internal structure printed along the direction of scanning is more accurate than the vertical printing process to the direction of scanning on dimensional accuracy. The results of the FEA (finite element analysis), revealed that the temperature distribution along the path of scanning is uniform relative to the direction of scanning of the printed vertically. Consequently, this will cause a dimensional deviation during printing [23].

2. Preparing printed samples

Samples with different dimensions were printed using Ultimaker 2 Extended + printing machine. The material used to print these samples is PLA, and they all have a rectangular shape. Each set of samples includes 4 rows. All rows have the same base dimensions 20mmx20mm, except the height varies along the rows. Each row consists of 3 samples. The height is 20mm for the first row, 40 mm for the second, 80 mm for the third, and 150mm for the fourth row. Ultimaker printing machine was able to provide various types of infill patterns such as Triangular, Concentric, rectilinear, Gyroid, and Honey-comb filling (Figs.5 and 6). The raft was used to stabilizing the model with a small footprint and to create a rigid basis on which building the upper layers of the parts will be executed. The thickness of the used raft was 1.12 mm.

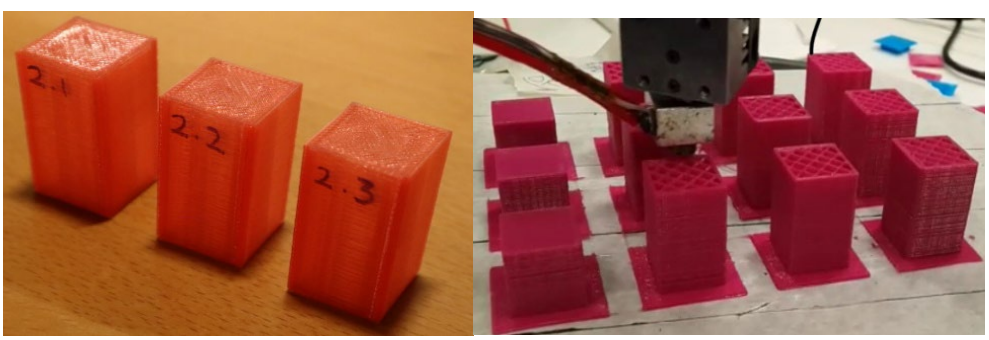

Figure 5: Printed samples using a 3D printer

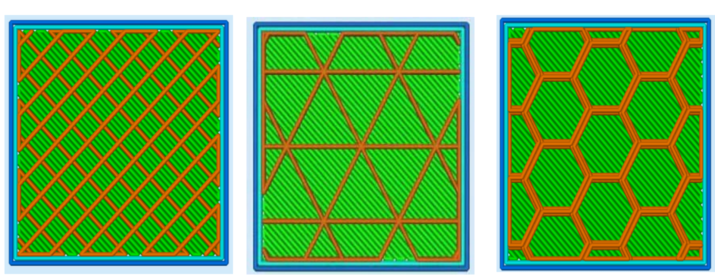

Figure 6: Triangular, Honeycomb, Rectilinear infill patterns

3. 'Ultimaker 2 Extended ' printing machine specification

Table 1: Ultimaker specification [24]

Technology	Fused filament fabrication (FFF)
Print head	Single print head with swappable nozzles
Material	PLA
Print head travel speed	300 mm/second
Max Build Size	150 x 150 x 150 mm
Nozzle Diameter	0.4 mm
Nozzle temperature	180 ^{0}C
Filament Diameter	2.85 mm
XYZ resolution	12.5 micron
Software	Ultimaker Cura

4. Measuring procedure

New smart technology was used to measure the dimensions of the printed parts. A digital Vernier caliper was linked directly to the computer, giving us the exact measurements saved in the excel sheet. This new technique helped save time and minimize human error. The X, Y and Z dimension as presented in Fig. 7 was measured three times from bottom, mid, and top-level to reduce the error and to evaluate 3D printer performance along with different levels.

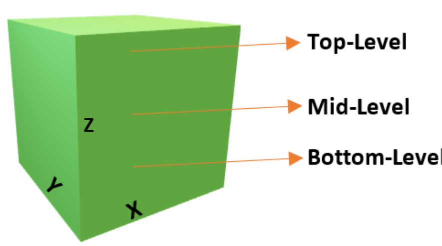

Figure 7: Sketch of the locations of the dimensions considered.

5. Process Capability Index (CPk) Calculation & Results

After recording the measured dimensions, the process capability of 3D printing machine was calculated using Eq. (1) and Eq. (2) which were mentioned previously. Calculations were repeated for all printed samples for different rows and levels. Histograms show in Fig.8 the spread or dispersion of measured data therefore it was used to represent the spread of the measured dimensions and to check if it is within the specification limits. Box& Whisker plot was used to describe the distribution of the measurement data through their quartiles for Mid-Level & Top-Level. Tables 2 to 4 illustrate the results of the calculated statistical parameters related to the process capabilities investigated in this study. It is clear that for the results that there is an apparent discrepancy in the process capabilities of the 3D printed samples using various infill patterns used in the study. Besides, it is evident that the process capability changes concerning the hight of the printed samples that should be taken into consideration in the design of the 3D printed components.

Table 2. CPk Calculation For Top-Level Triangular

Top					
	Row 1	Row 2	Row 3	Row 4	Row 5
Std. Deviation	0.070922	0.127069	0.038416	0.103428	0.073877
Cp	0.94	0.52	1.74	0.64	0.9
Cpu	-0.3	-0.16	-0.22	-0.11	-0.26
Cpl	2.18	1.21	3.69	1.4	2.07
Cpk	-0.3	-0.16	-0.22	-0.11	-0.26
CR	1.06	1.91	0.58	1.55	1.11

Table 3. CPk Calculation For Mid-Level Triangular

Mid					
	Row 1	Row 2	Row 3	Row 4	Row 5
Std. Deviation	0.067967	0.118203	0.038416	0.100473	0.091608
Cp	0.98	0.56	1.74	0.66	0.73
Cpu	-0.22	-0.16	-0.27	-0.15	-0.24
Cpl	2.18	1.29	3.75	1.48	1.69
Cpk	-0.22	-0.16	-0.27	-0.15	-0.24
CR	1.02	1.77	0.58	1.51	1.37

TABLE 4: CPK CALCULATION FOR TOP LEVEL-TRIANGULAR

Bottom					
	Row 1	Row 2	Row 3	Row 4	Row 5
Std. Deviation	0.067967	0.115248	0.053191	0.106383	0.097518
Cp	0.98	0.58	1.25	0.63	0.68
Cpu	-0.11	-0.06	-0.04	-0.1	-0.15
Cpl	2.07	1.22	2.55	1.36	1.52
Cpk	-0.11	-0.06	-0.04	-0.1	-0.15
CR	1.02	1.73	0.8	1.6	1.46

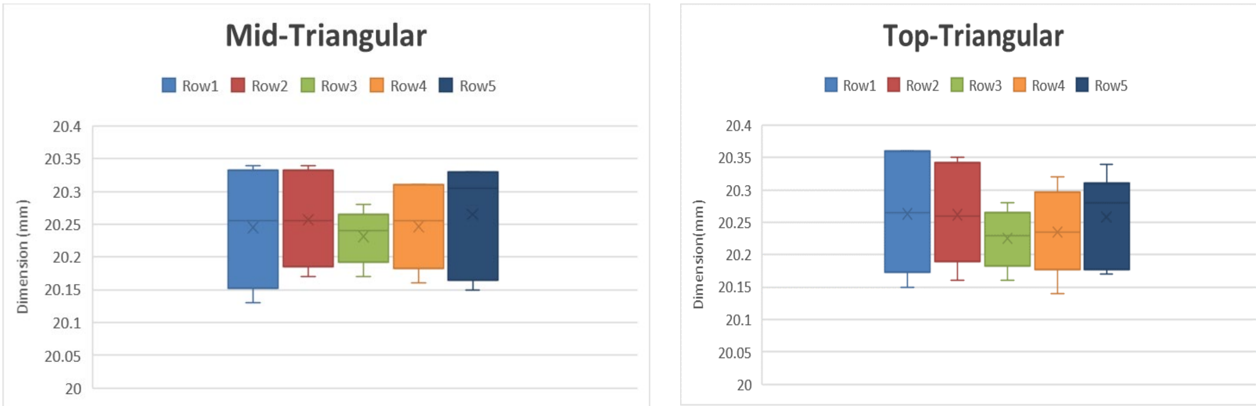

Figure 8: Box& whisker plot representing the distribution of the measurements through their quartiles for Mid-Level & Top-Level.

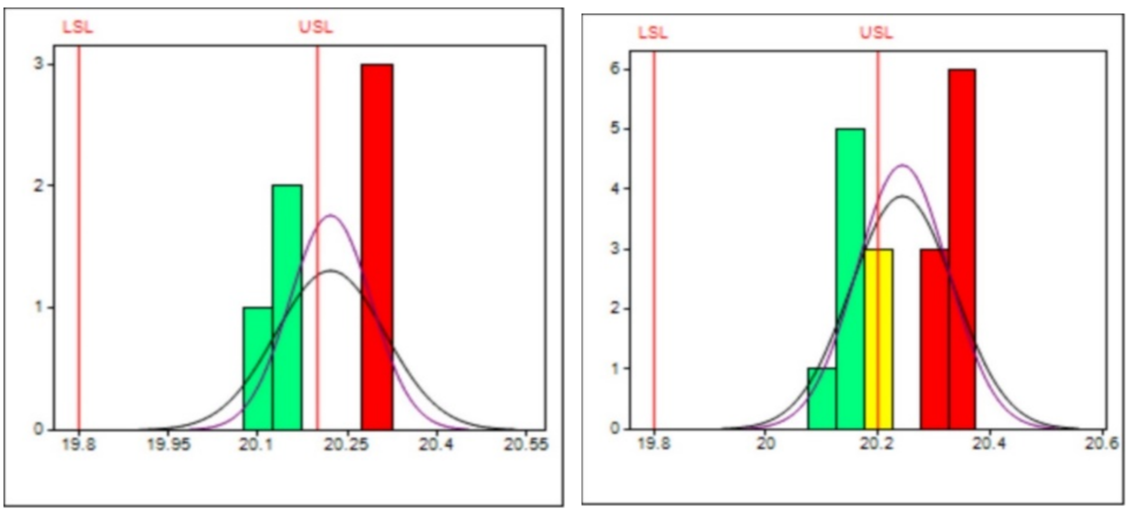

Figure 9: Histogram plots representing Cpk for Triangular shape samples. The fig. in the top is for Row1 & Bottom level& the fig. at the bottom for Row1 & All levels.

6. Discusion

Cpk of printed samples at different levels (bottom, mid, top) was calculated and summarized in table2,3,4. The results show that for all different levels, Cpk is less than 1, which means the process is not capable of meeting its requirement. This is clear in Fig.9, were concluding that the larger part of the curve is out of the upper and the lower specification limits. CPk also varies along Z direction of the printed parts. Cpk at bottom-level at the lower level of the printed part (i.e., first raw) is -0.11 (shown in Table 4) , whereas the Cpk at Mid-Level of the printed samples is -0.22 (depicted in Table3) and at the Top-Level of the printed samples is -0.3 9 (illustrated in Table2). This means that Cpk decreases with z-direction. For different rows where the height changes, Cpk at bottom-level increases with the increase of the height. At mid-level and top-level readings, the pattern is not clear. The apparent discrepancy in the capabilities of the 3D printing process samples is a fact for different infill structures addressed in the investigation. Moreover, it is highly advised while designing the 3D printed components to consider the process capability of the 3D printer concerning the geometry of the 3D printed parts to avoid any problems associated with the final product.

7. Conclusion

In the past few years, the 3D printing field grows rapidly. However, they are no longer used as much as before because they have some limitations and constraints, such as the expensive cost of the production processes. In this study, the Cpk of 3D printed parts of different geometries and internal designs were speculated to minimize the hidden expenses. It was concluded that Cpk decreases with Z direction of the printed part in the same row. And for different rows where the height changes, Cpk at bottom-level increases with the increase of the height.

8. Acknowledgment

Our sincere gratitude and appreciation go to UAE University for giving us this opportunity to work on such valuable projects for its significant role in providing continuous help and guidance to its members to complete this project successfully.

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