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PAPER

Quality of 3D Printed Objects Using Fused Deposition Modeling (FDM) Technology in Terms of Dimensional Accuracy

Alaa Aljazara[1], Nadine Abu Tuhaimer[1], Ahmed Alawwad[1], Khalid Bani Hani[1], Abdallah D. Qusef[1], Najeh Rajeh Alsalhi[2](✉), Aras Al-Dawoodi[3]

[1]Princess Sumaya University for Technology, Amman, Jordan

[2]College of Arts, Humanities, and Social Sciences, University of Sharjah, Sharjah, U.A.E.

[3]College of Computer Science and Information Technology, University of Kirkuk, Kirkuk, Iraq

nalsalhi@sharjah.ac.ae

ABSTRACT

3D printers are known for providing parts with relatively good accuracy. However, the level of accuracy in the dimensions of printed objects may not matter if they do not have a mechanical purpose. When multiple 3D-printed parts are intended to be integrated with each other to create a larger system, even a fraction of a millimeter can have a significant impact on the entire system. This study aims to investigate the variation in dimension when a single print file is replicated using the same slicing settings. The findings are then analyzed using quality control tools and compared to the designed measurements. Fused deposition modeling (FDM) technology or fused filament fabrication (FFF) technology was chosen for this study due to its availability to the common user, its relatively low cost, and its increasing popularity in different applications and industries. The material used in this study is polylactic acid (PLA) which is a thermoplastic and the most widely used plastic filament in 3D printing. It has a low melting point, high strength, low thermal expansion, and is relatively cheap. The dimensional accuracy of FDM-produced parts was evaluated by comparing the dimensions of the fabricated specimens with their computer-aided design (CAD) models. Statistical analysis revealed that the mean dimensional deviations were within the specified tolerance limits for most of the tested parts. This suggests that FDM technology is reliable in terms of achieving dimensional accuracy.

KEYWORDS

3D printed, FDM technology, FFF technology, accuracy of 3D printed parts, polylactic acid (PLA)

1 INTRODUCTION

Additive manufacturing (AM), commonly known as 3D printing has revolutionized the manufacturing industry and had a huge impact on how various industries operate. Additive manufacturing has provided users with the freedom to design complex parts that are not easily manufactured using traditional manufacturing methods. This

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flexibility has provided us with the ability to design and fabricate lightweight objects with various geometric features using a wide range of materials that possess different properties such as strength, flexibility, melting temperature, etc. There are many factors that can affect the outcome of a 3D-printed part. The first factor to consider is the type of technology to be used. There are over 10 different technologies available, as shown in Figure 1. The chosen method for this study is material extrusion (FDM–fused deposition molding or FFF–fused filament fabrication), which was chosen due to its availability among regular users. Figure 1, shows the types of AM technology.

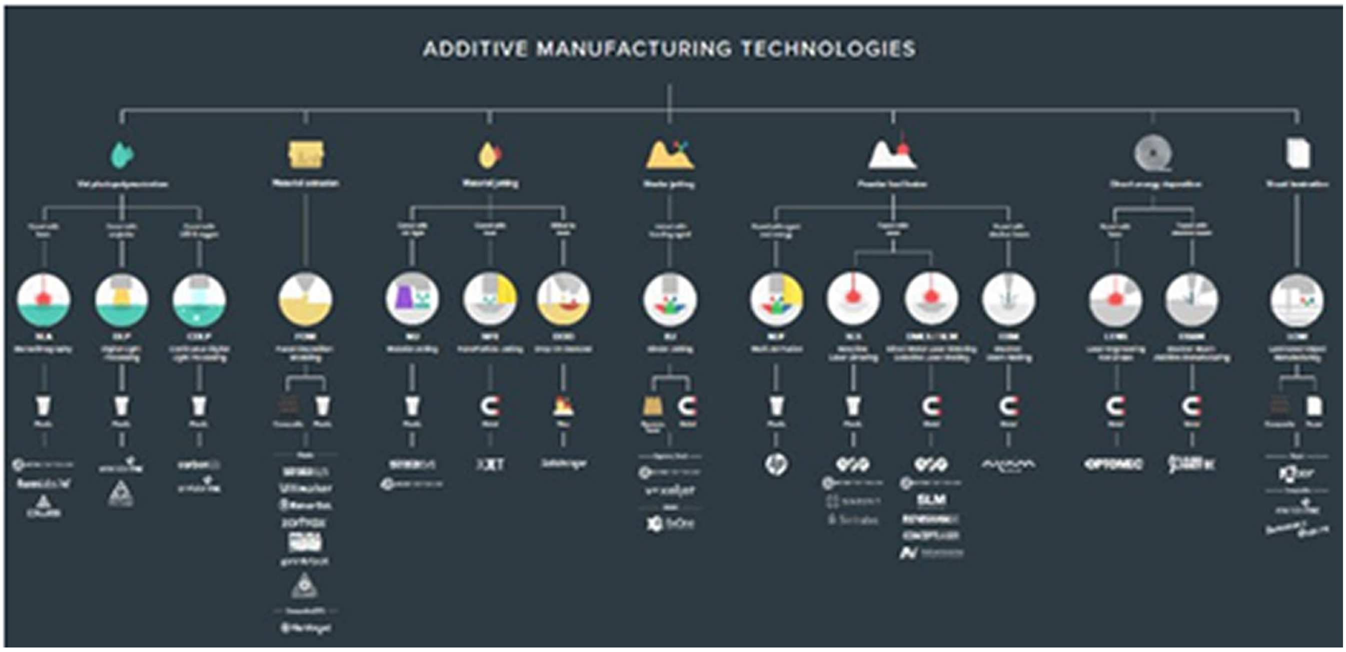

Fig. 1. Types of additive manufacturing technology

Fused deposition molding is one of the most common additive manufacturing processes for prototyping due to its low cost. It generates parts by extruding thermoplastic materials layer by layer to print a model from bottom to top. Figure 2 depicts an FDM printing process utilizing the bottom-to-top technique [1]. Heat is applied to the filament, which is then extruded via the printer nozzle and placed on the printer platform. After cooling to room temperature, the model's printed layers harden. Figure 2 shows how FDM works.

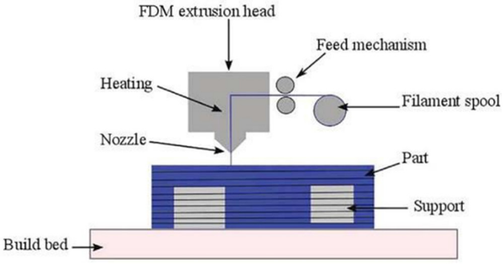

Fig. 2. How FDM works [2]

One of the most important factors is the design. 3D printing has certain rules that need to be followed in order to design an object that can be easily 3D printed.

These rules vary depending on the type of technology used while 3D printing a design. Another factor is the slicing settings used to translate the design into a printable file. The material used can also affect the final dimensions of the printed part. Figure 3 shows the process of obtaining a 3D-printed object using FDM or FFF technology. The FDM printing is shown in Figure 3.

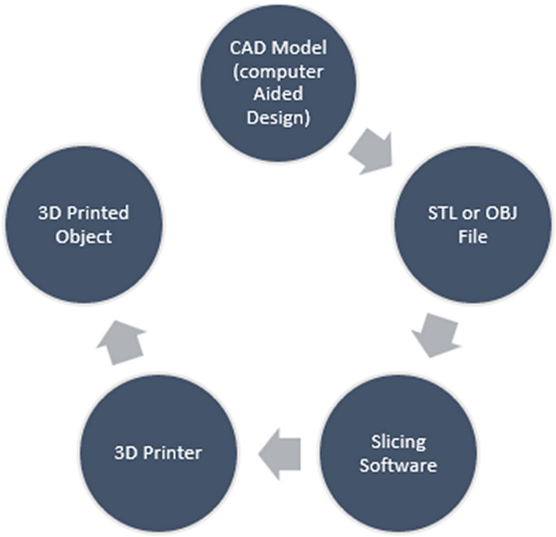

Fig. 3. FDM printing process

The first step in the above graph is the computer-aided design (CAD) model, which needs to be designed taking into consideration the design rules that should be followed when designing a part that will be 3D printed using FDM or FFF technology. The second step converts the 3D model into STL or OBJ format. The difference between these formats is that OBJ will have the color specifications of the model, while STL format discards them. The STL file is then inserted into the slicing software. The slicing software segments the 3D model into slices (layers) to be printed. The software used in the study is Ultimaker Cura, which is an open-source slicing software. After the process of slicing, we end up with a g-code file that can be sent to the 3D printer to start the printing process.

2 RELATED WORK

Several studies have been conducted to explore the dimensional accuracy of FDM 3D printing in order to better understand the elements that influence precision and compliance with design parameters. This section provides a synopsis of relevant research in this field. Smith and colleagues [3] investigated the dimensional accuracy of FDM-printed objects using a variety of printing parameters and geometries. They discovered that layer height, nozzle diameter, and print speed all had a substantial impact on dimensional accuracy. Lower print speeds enhance dimensional precision, but increasing layer heights and nozzle diameters decrease accuracy. Chen et al. [4] investigated how printing orientation affects dimensional accuracy in FDM 3D printing. They discovered that part orientation affected shrinkage and warping, resulting in deviations from the desired dimensions. They suggested that part orientation be optimized depending on geometry and the required dimensional precision. Garcia-Garcia et al. [5] investigated the effect of infill density on dimensional accuracy in FDM printing. Higher infill densities reduce dimensional deviations and enhance accuracy, but exceedingly high densities increase printing time and material consumption. Wang et al. [6] studied the effects of external factors on the dimensional accuracy of FDM-printed parts, such as temperature and humidity. They discovered that changes in ambient conditions influenced material thermal behavior, resulting in dimensional changes. Their research highlighted the importance of managing the printing environment in order to obtain constant dimensional accuracy. N. K. M. C. Jayasundara, S. Subramanian, and P. Renaud [9] examined how process variables affect the precision dimensions of FDM-printed parts. They also investigated how printing speed, infill density, and layer thickness affect the final dimensions of printed objects. To choose the best process variables for enhancing dimensional accuracy, experimental findings and statistical analysis are presented. The Taguchi method was used by S. Venkateshwara and M. Aravindan [10] to evaluate FDM 3D printing's dimensional correctness. The study examines the impact of important process variables, such as printing speed, nozzle temperature, and layer height, on the precision of the printed items' dimensions. The authors identify the ideal set of variables for achieving higher precision in dimensions by using statistical techniques. V. Das, P. Chowdhury, and D. K. Mondal [11] focused on the ABS products' dimensional accuracy after being 3D printed using FDM. To determine the impact of different process variables, including layer thickness, nozzle temperature, and feed rate, on dimensional accuracy, the authors undertake an experimental investigation. Insights into the ideal parameter settings for reducing dimensional variations in ABS-printed parts are provided by the study. L. A. De Sousa Júnior, T. M. L. Silva, and M. A. M. Melo [12] discussed the effect of infill density and printing orientation on the dimensional accuracy of FDM printed. The study investigated the impact of variations in printing orientation and infill density on the final dimensions of printed products. The relationship between infill density, dimensional correctness, and printing orientation is demonstrated using experimental findings. A. R. Sheikh, S. Singla, and R. Khanna [13] investigated post-processing approaches to increase the dimensional accuracy of FDM-printed items. The influence of different post-processing techniques, including heat treatment, mechanical finishing, and chemical treatments, on minimizing dimensional inaccuracies was covered by the authors. The study included information on how post-processing can be used to produce components produced using FDM that are more accurate in terms of dimension. Doe et al.'s [14] investigation of the impact of process variables on dimensional accuracy included layer height, infill density, and print speed. The accuracy of FDM prints was found to be considerably increased by tweaking these parameters. A unique correction algorithm was also put out by Smith et al. [15] to reduce distortion and improve dimensional accuracy in FDM-printed items. Researchers have also looked into how various materials affect the precision and mechanical attributes of FDM printing. A comparison of different thermoplastic filaments and their impact on part strength and dimensional correctness was done by Johnson et al. [16]. Their research showed that choosing the right material is essential for producing accurate and durable FDM parts. Furthermore, Lee et al. [17] studied how filament moisture content affected dimensional accuracy and came up with methods to lessen the effects of moisture absorption during printing. For many applications, achieving a smooth surface finish is crucial. On post-processing methods to enhance the surface quality of FDM printers, several studies have been conducted. To improve the aesthetics and surface finish of FDM products, Brown et al. [18] investigated a number of surface treatments, including sanding, chemical smoothing, and coating. They gave information about the efficiency of various post-processing techniques and their effect on dimensional correctness. Accurate FDM prints require careful design considerations. To improve dimensional accuracy and lower print mistakes, researchers have looked into a variety of design optimization techniques.

For example, Wang et al. [19] created an automated design optimization system that takes into account constraints and goals unique to FDM to provide designs that can be accurately produced. Through their strategy, they showed improvements in accuracy and printing effectiveness. In practice, certain tolerances are taken into consideration when designing for FDM technology printing. The rule of thumb is to increase or decrease the designed value by a set value. These studies, taken together, highlight the importance of printing settings, orientation, infill density, and environmental variables in affecting the dimensional accuracy of FDM 3D-printed objects. Understanding and adjusting these aspects improves precision and adherence to design criteria in FDM 3D printing. This study differs in that the aspect of the same 3D model is replicated using exactly the same printing settings, and then these 3D printed parts are compared to see if any differences in dimensions arise. Our hypothesis for this study indicates the capability of the FDM 3D printing process to produce parts within the desired specification limits. The outcomes are compared with the industry-known tolerance for this technology, which is ± 0.3 on the value of the designed parameter.

3 METHODOLOGY

We first designed a sample file containing different geometric properties since we had the intention of measuring the accuracy of FDM-printed parts. The CAD file was designed using Autodesk Fusion360 software and contains basic mathematical shapes, as shown in Figure 4. The designed file was sent to a group of qualified individuals in the field of 3D printing; most work in fabrication laboratories and have sufficient experience operating FDM printers. The file was shared along with the slicing settings to be printed; dimensions were then taken and filled into a survey for comparison purposes. The brand of the printer was collected to determine the accuracy of prints depending on the brand. The CAD model is shown in Figure 4.

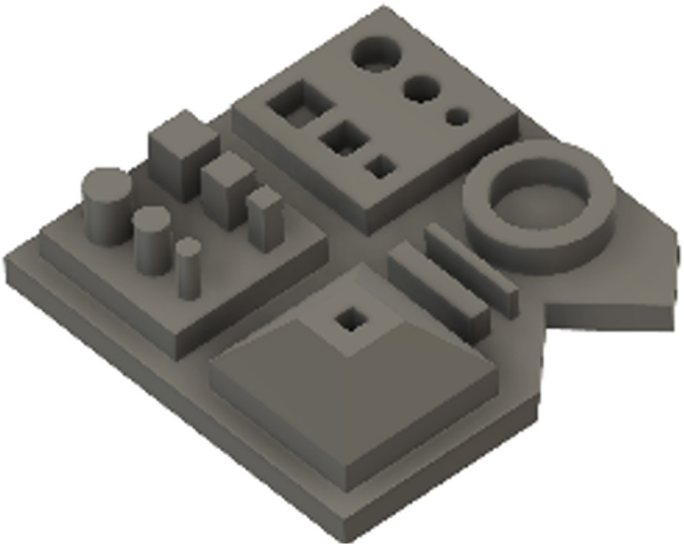

Fig. 4. CAD model

The study was conducted through the analysis of data submitted by qualified individuals who are familiar with 3D printing. The survey was sent to individuals working in fabrication laboratories in Jordan and other countries. 60 objects were printed by various brands and in several countries. The statistics are presented in Figure 5.

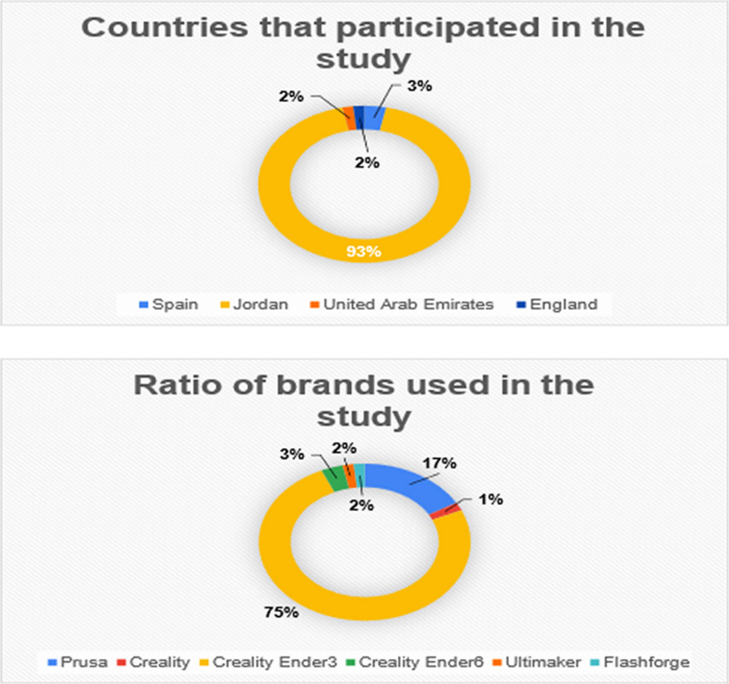

Fig. 5. Countries and brands used in the study

To carry through with this study, we have designed a sample file with known dimensions to be printed multiple times to measure the difference in the printed dimensions.

The CAD file is shown in the Figure 6.

This file was designed to measure 29 parameters, which are:

1. Height of the base (3mm)
2. Height of the step (3mm)
3. Height of the cylinder (5mm)
4. Base width (40mm)
5. Base length (40mm)
6. Cut edge length (8mm)
7. Thickness of thin wall (1mm)
8. Thickness of thicker wall (2mm)
9. Diameter of the big cylinder (12mm)
10. Thickness of the big cylinder wall (2mm)
11. Diameter of cylinder hole 1 (4mm)
12. Diameter of cylinder hole 2 (3mm)
13. Diameter of cylinder hole 3 (2mm)
14. Diameter of cylindrical column 1 (4mm)
15. Diameter of cylindrical column 2 (3mm)
16. Diameter of cylindrical column 3 (2mm)
17. Length of the edge of square column 1 (4mm)
18. Length of the edge of square column 2 (3mm)
19. Length of the edge of square column 3 (2mm)
20. Length of the edge of the square hole 1 (4mm)
21. Length of the edge of the square hole 2 (3mm)
22. Length of the edge of the square hole 3 (2mm)
23. Length of the base of the step (16mm)

24. Length of the edge of the face of the top of the pyramid (6mm)
25. Height of the pyramid with base step (8mm)
26. Height of square column 1 (5mm)
27. Depth of square hole 1 (3mm)
28. Distance between two steps (4mm)
29. The angle of the cut part (90 degrees)

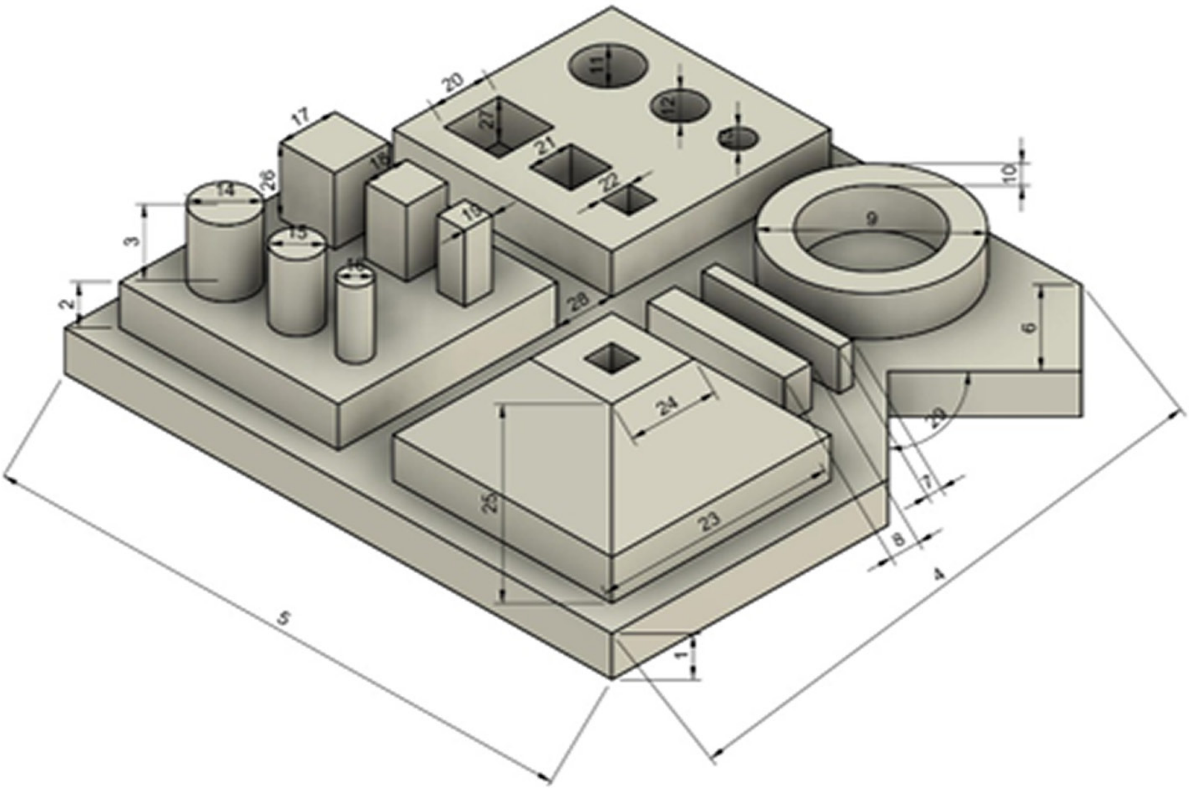

Fig. 6. CAD model with annotations

Due to the complexity of analyzing 29 parameters, we opted to categorize them into five parameters as per the following:

- Height (H): 1,2,3,25,26,27
- Length (L): 4,5,6,17,18,19,20,21,22,23,24,28
- Thickness (T): 7,8,10
- Diameter (D): 9,11,12,13,14,15,16
- Angle (A): 29

The file was then exported into STL Format, and shared with the participants by uploading it into an open-source platform for 3D printable designs, with specific slicing settings that will be used to prepare the g-code.

A. Slicing Settings

The second step after obtaining the STL file of the design is to insert it into slicing software. The slicing software used for this study is an open-source slicing software called Ultimaker Cura. The slicing process enables the FDM 3D printer to accurately recreate the digital model in a physical form by slicing the 3D model into layers and generating a tool path that will be followed by the 3D printer.

In the slicing software, various parameters are set, including layer height (the thickness of each layer), print speed, infill density (the internal structure of the object), and support structures (if needed). The chosen slicing settings were based on the standard profile which determines the following:

- Resolution (layer height): 0.2 mm
- Infill: 20%
- Nozzle diameter: 0.4mm
- Top/Bottom thickness of 3D-printed part: 0.8 mm
- Wall thickness of 3D-printed part: 0.8 mm
- Infill pattern: Grid
- Print speed: 60 mm/s
- Printing temperature: 200
- Bed temperature: 60
- Adhesion: none

Following the insertion of the slicing parameters, the software will generate the tool path that the printer will follow. To do that, we need to specify the model of the printer we will be using. For each layer, the slicing software generates a tool path that specifies the exact movements of the printer's extruder nozzle. The tool path includes information such as where to start and end each layer, how to fill the interior with infill material, and where to add support structures if required. Once the slicing process is complete, the slicing software generates a file, typically in G-code format. This file contains the instructions for the 3D printer, including the specific movements, temperatures, and other parameters needed to create the object layer by layer. The generated G-code file is transferred to the 3D printer, which follows the instructions to deposit the filament material layer by layer, gradually building the physical object based on the sliced layers. After slicing, the software shows the following data:

- Printing time: 54 minutes
- Weight of material used: 6 grams (1.92 meters long)
- Number of layers: 55 layers

The slicing settings were included in the open-source platform where the file was shared and it was used by the participants when printing the sample file. Figure 7 shown the Cura Slicing Software

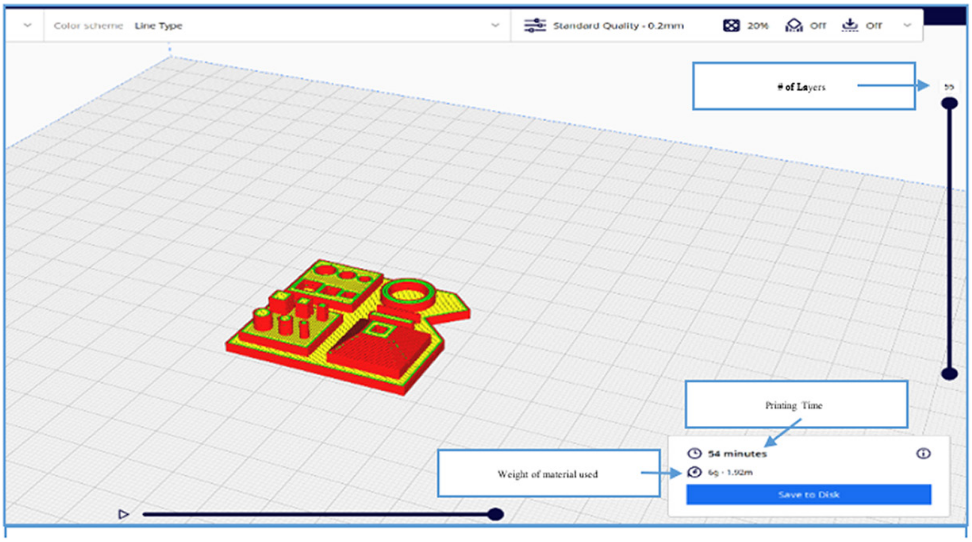

Fig. 7. Cura slicing software

B. Filament (PLA)

The filament chosen for this study is PLA. It is a biodegradable, aliphatic polyester generated from renewable resources such as maize starch or sugarcane [7] [8]. PLA is known for its ease of use in 3D printing. It has a relatively low printing temperature compared to other materials, which means it requires less heat and energy during the printing process. PLA also has minimal warping, making it easier to achieve successful prints without the need for a heated build plate. PLA exhibits good layer adhesion, allowing for strong and durable prints. It has a low shrinkage rate, which helps in maintaining dimensional accuracy and reducing the likelihood of print defects. The temperature chosen for printing PLA was based on the manufacturer's recommendation, which was 195°–220°C, hence the chosen temperature is 200°C. PLA can be printed without a heated build plate; however, in this study, a bed temperature of 60°C was chosen. Figure 8 shows the PLA filament and printing settings from the manufacturer.

Fig. 8. PLA filament and printing settings from the manufacturer

C. Measurement

The measurement tool that was used for this study is a digital caliper. Digital calipers provide precise measurements with high accuracy. They have a resolution of up to 0.1 millimeters, allowing for detailed and accurate measurements of various dimensions on the printed part. This is important for verifying if the printed object matches the intended design specifications. Calipers can measure different types of dimensions, including outer diameter, inner diameter, depth, and thickness. This versatility makes them suitable for measuring a wide range of 3D-printed parts, regardless of their geometry or complexity, and perfect to measure the dimensions of the sample CAD model used in this study.

A protractor was also used to measure the angle present in the CAD model.

3.1 Analysis

After data collection, we categorized the collected data into five different categories: height, thickness, length, diameter, and angle. Each category was studied individually.

A. Height

The height category consisted of the following parameters as numbered from the CAD illustration: 1, 2, 3, 25, 26, and 27. To be able to correctly analyze the data, we need to convert it to a unified unit of measure. To do so, we measured the difference between the inputted data and the designed value for each of the 60 entries. Then we took the average of all entries that fell under the height category. The specification limits were calculated based on the standard tolerance of FDM technology, which is usually accounted for when designing movable parts, the known tolerance is ± 0.3%.

The calculation in detail for one entry in the height category is provided below, and the same method has been followed for all other entries in the rest of the categories.

1. $Average\,DV\ \ for\,Category = \frac{\sum_{i=1}^{n} DV(i)}{n}$
2. $Average\,AV\ \ for\,Category = \frac{\sum_{i=1}^{n} AV(i)}{n}$
3. $Tolerance = \pm Average\,DV\ \ for\,Category * K$

Where,

- i: parameter number
- DV(i): Design value for parameter i
- AV(i): Actual value measured for parameter i
- n: Number of parameters
- K: Known tolerance of FDM printing, which is 0.3%.

For example:

In the height category, we have six parameters, numbered in the CAD illustration as 1, 2, 3, 25, 26, and 27. The calculation is performed for each entry as shown in Table 1.

Table 1. The calculations for each entry (height)

Parameter	Parameter Name	Parameter Number (i)	DV	AV	Average DV for Category	Average AV for Category	Tolerance
1	Height of the base	1	3	2.95	4.5	4.558333333	± 0.0135
2	Height of the step	2	3	3			
3	Height of the cylinder	3	5	5			
25	Height of the pyramid with a base step	4	8	8			
26	Height of square column 1	5	5	5.2			
27	Depth of square hole 1	6	3	3.2			

The above steps are repeated for all 60 entries to get the average data in the height category to begin analysis.

- Mean = $\frac{\sum_{i-0}^{60} x}{60}$ = 4.539027778, where x is the average AV.
- Variance for each entry was calculated as:

$$\text{variance} = (x - \text{mean})^2$$

- Sum variance = $\sum_{i=0}^{60}$variance = 2.223957176
- Standard deviation = $\sqrt{\frac{\text{sum variance}}{n-1}} = \sqrt{\frac{0.057305793}{59}} = 0.024854897$
- Sigama was chosen to be 3.
- UCL = mean + 3* standard deviation = 4.613592467
- LCL = mean – 3* standard deviation = 4.464463088

A.1 Control charts

The control chart was then graphed in order to see if the collected data was within the limits of control and specification. As seen from the above graph, all entered data falls within both the control limits and specification limits. Another observation noticed is that eight consecutive points are below the mean, which might indicate an out-of-control process; however, since these entries refer to different 3D prints printed on different machines, this does not indicate anything or provide any statistical input.

A.2 Histogram

To study the frequency of data repetition, we graphed it in a histogram. The histogram shown below, illustrates a shape quite similar to a normal distribution (bell shape). Figure 9 shows the height category histogram for all the 60 entries:

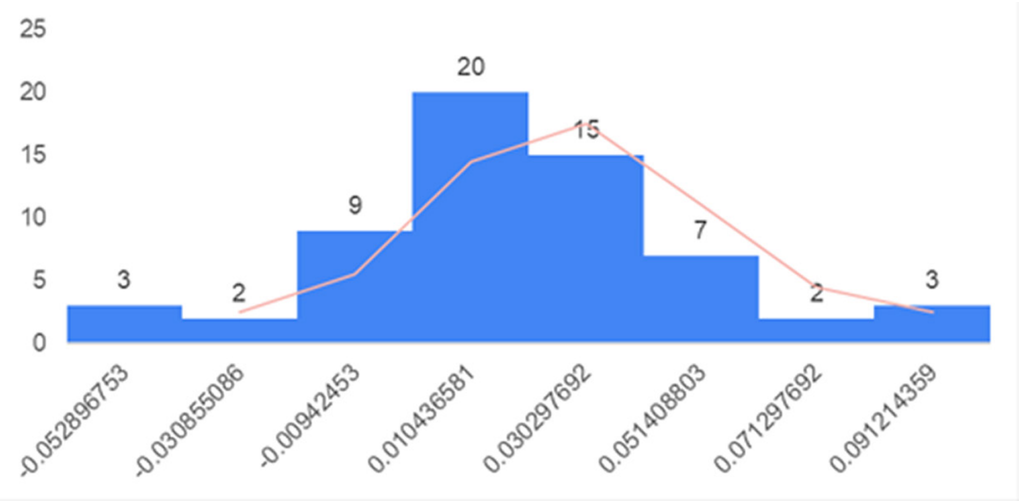

Fig. 9. Height category histogram for all 60 entries

We can see from the above illustration that the data is mostly centered on the middle. We can also notice that the data was spread out over eight intervals. There are no outliers noted in the above graph.

B. Length

The height category consisted of the following parameters as numbered from the CAD illustration: 4, 5, 6, 17, 18, 19, 20, 21, 22, 23, 24, and 28. Following the same methodology for the height category, the following measurements were calculated:

- Mean = –0.00482
- Sum variance = 0.01897
- Standard deviation = 0.01793

- UCL = 0.04897
- LCL = –0.05861
- USL = 0.07052
- LSL = –0.07052

B.1 Control charts

The control chart was then graphed in order to see if the collected data was within the limits of control and specification. The above graph shows us one entry outside both specification and control limits, which is the 2nd entry. After going back and examining the collected data, we notice that there is truly a difference between inputted data and the designed value (See Table 2). This error could go back to an uncalibrated machine or a human error in taking the measurements.

Table 2. The calculations for each entry (length)

Parameter #	Input Data for Entry #2	Designed Value	Difference
4	39	40	–1
5	39	40	–1
6	8	8	0
17	3.5	4	–0.5
18	2	3	–1
19	1	2	–1
20	4	4	0
21	3	3	0
22	1.5	2	–0.5
23	15	16	–1
24	6	6	0
28	4	4	0

B.2 Histogram

The histogram was also plotted for the length category as shown below in the Figure 10.

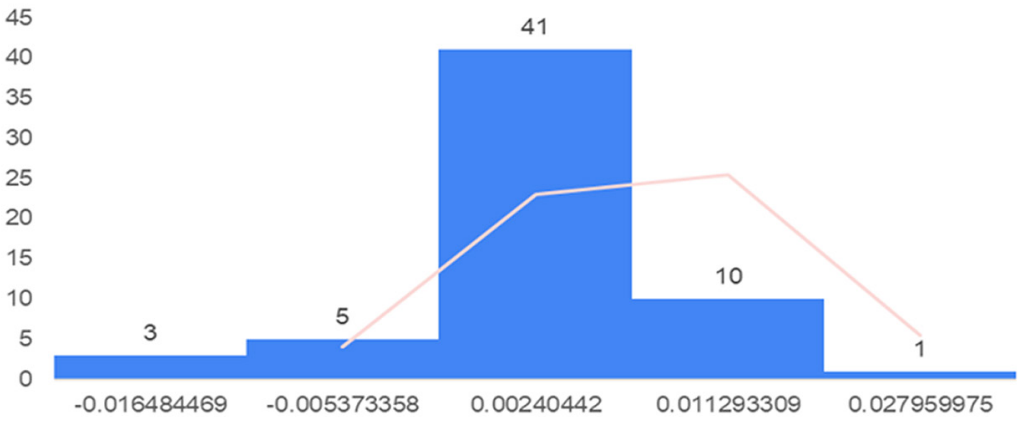

Fig. 10. Angle category histogram for all 60 entries

From the histogram, we notice that the data is mostly centered. The data was also spread around five bars.

C. Readings from one brand (Creality Ender 3)

After observing the collected data, we noticed that out of 60 entries, 45 of them were printed with Creality Ender 3. Therefore, we conducted the same analysis but over the 45 entries alone.

F.1 Height

From the next control chart drawn for the 45 entries printed on the same machine, we notice one significant difference, which is how close the control and specification limits are to each other. Figure 11 shows the height category control chart for Ender 3 prints.

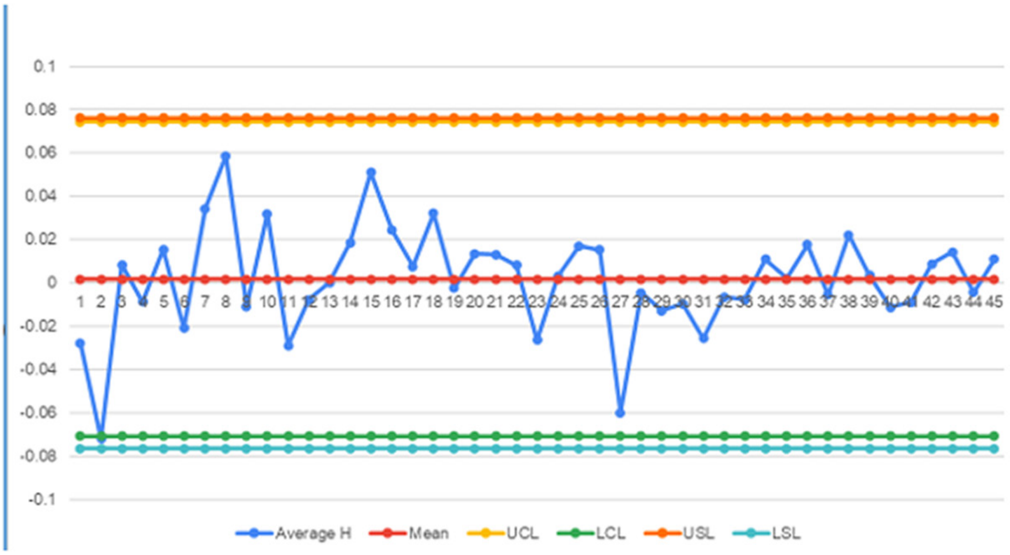

Fig. 11. Height category control chart for Ender 3 prints

We also notice the absence of the seven-point run, which indicates that the process is in control. The process capability tool (CP) was used to evaluate the process variability to present specification, and it is a ratio calculated by dividing the difference between upper and lower specification limits over the upper and lower control limit, and there are three possible ranges as follows:

- CP = 1: means the process variability just meets the specifications.
- CP < 1: This means the process variability just is outside the specifications and the process is not capable of producing within specification.
- CP > 1: This means the process variability is tighter than specifications and the process exceeds capability.

Therefore, the results of our research with regards to the height category on a single machine (Creality Ender 3), we find that (USL-LSL)/(UCL-LCL) is equal to (1.05), and it is to be considered that the process exceeds the capability but only in a slight measure. Figure 12 shows the length category control chart for Ender 3 prints.

F.2 Length

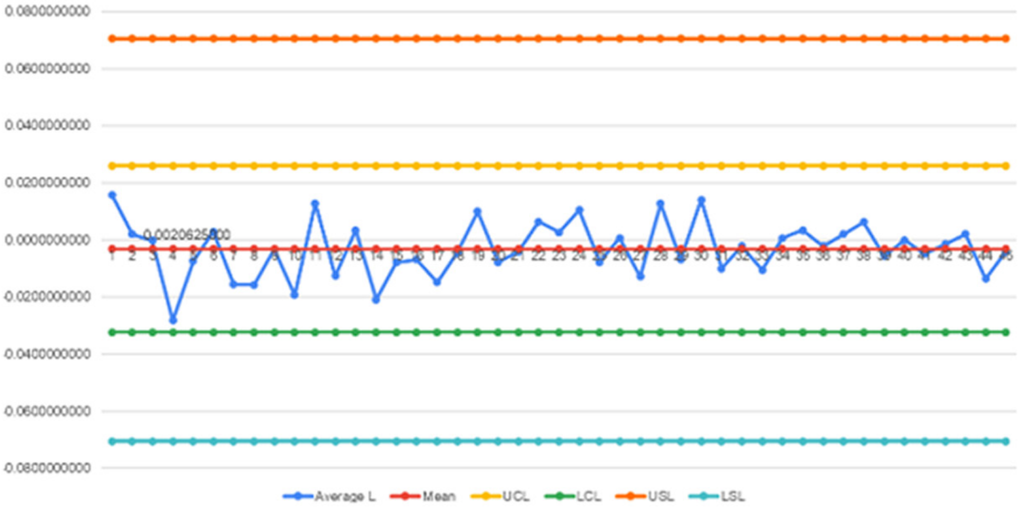

Fig. 12. Length category control chart for Ender 3 prints

From the above control chart, we notice the absence of an out-of-control entry, unlike the graph from the entire data set.

The CP was also calculated to be 2.42, which means the process exceeds the capability significantly in terms of achieving the length specified in the design. We also notice the absence of the seven-points run which indicates that the process is in fact in control. Figure 13 shows the thickness category control chart for Ender 3 prints.

F.3 Thickness

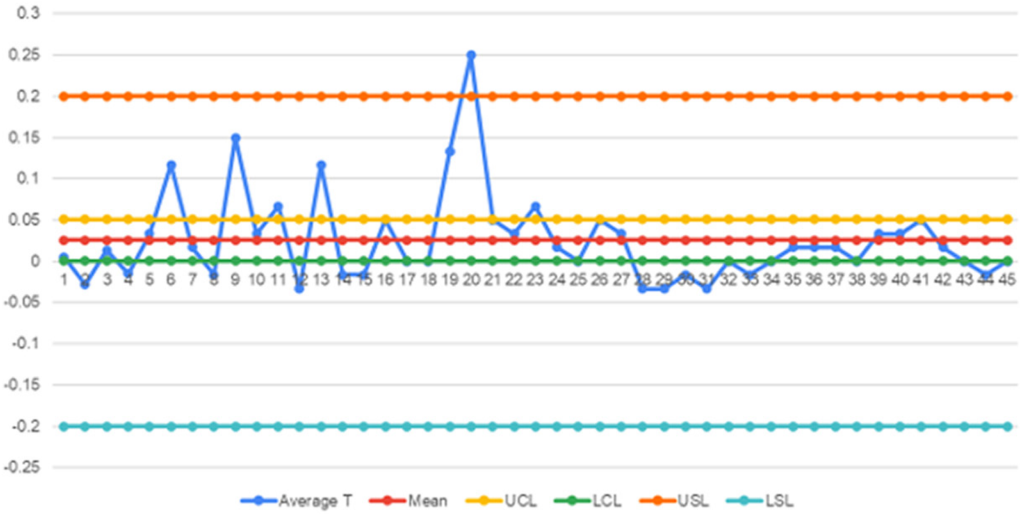

Fig. 13. Thickness category control chart for Ender 3 prints

From the above, we notice the presence of one entry out the specification limits, the data belongs to entry 37 from the dataset and upon investigation, and we found that one of the parameters from the thickness category was measured at 1.7 when the designed value was 1, which shows a significant deviation from the standard. This error is more likely a result of faulty measurement or data collection. We also notice the absence of the seven-points run which indicated that the process is in control. When the CP was calculated, we found the value to be 7.97, which indicates that the process exceeds the capability by a significant amount. Figure 14 shows the diameter category control chart for Ender 3 prints.

F.4 Diameter

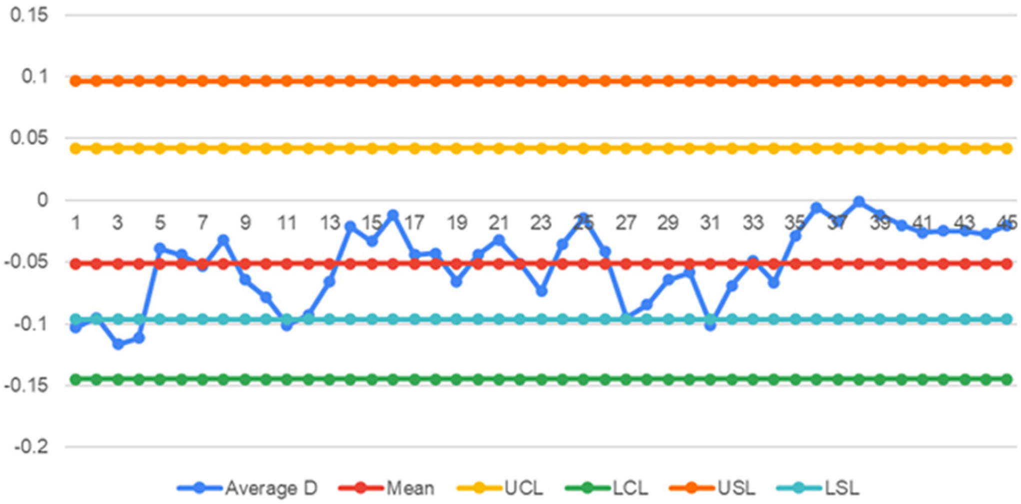

Fig. 14. Diameter category control chart for Ender 3 prints

From the above, we still notice that the lower control limit is outside the lower specification limit, which may indicate that the values might be slightly off the standard. We also notice that towards the end of the graph, we have 12 points above the mean but they do not cross the upper specification or control limits, so they do not indicate an out-of-control process. When the CP was calculated, it was found to be 1.03, which means the process exceeds the capability just by a very minimal amount.

F.5 Angle

From the next graph, we notice that the control limits are set outside the specification limit, which fortifies our initial observation that the measuring tool used was unable to provide accurate measurements in comparison with the tolerance. When the CP was calculated, the value was 0.15, which means that the process is not able of producing within the specifications. This is justified by the previous explanation since visual inspection shows that the angle was printed with minimal deviation from the designed value. Figure 15 shows the angle category control chart for Ender 3 prints.

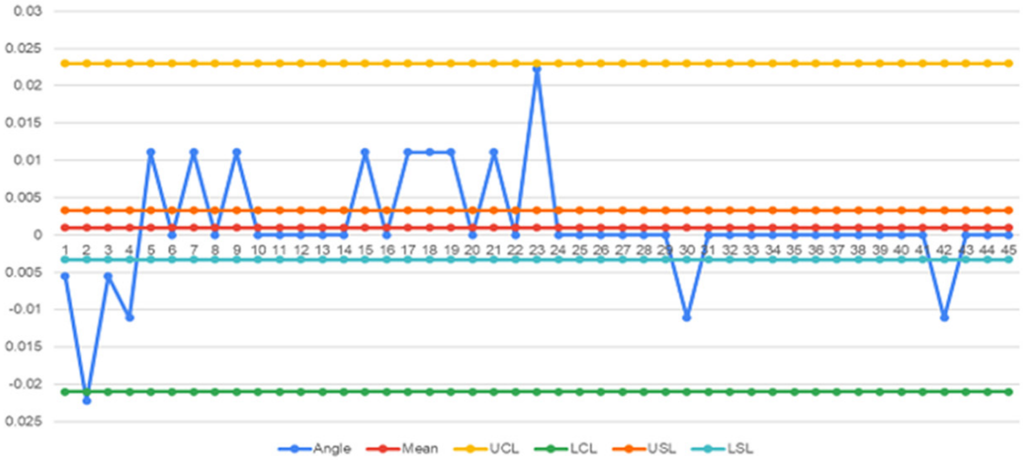

Fig. 15. Angle category control chart for Ender 3 prints

4 CONCLUSION

The paper explores the possibilities of 3D printing as a precise manufacturing method for creating items that meet specific requirements. It highlights the significant advancements in 3D printing technology, particularly in terms of high precision and dimensional accuracy. The technique can produce intricate and complex objects with small tolerances, surpassing previous limitations with advanced software algorithms, improved materials, and precise control systems. The study specifically focuses on FDM 3D printing and discusses how its precision has improved due to developments in software tools and design optimization algorithms. FDM has been shown to be a reliable and cost-effective way to produce parts that meet specifications, especially for prototypes and low-volume production. It allows for quick design changes and iterations, reducing the time and expenses associated with traditional manufacturing techniques. The versatility of FDM enables the fabrication of functional parts with various mechanical qualities, making it applicable in diverse applications.

Visual inspection is essential in assessing the quality of 3D-printed items, and while slight differences may be observed with quality analysis tools, FDM printing can still produce parts that meet specifications effectively. The paper emphasizes the importance of control charts and process capability in maintaining product quality within desired parameters. Control charts allow for real-time monitoring and analysis of process variation, enabling businesses to identify and correct deviations from expected specifications. Process capability indices, such as CP, provide numerical assessments of a process's ability to consistently produce within the intended range, guiding organizations in making process modifications and improvements. The study acknowledges the inherent uncertainties in measurement equipment such as protractors and calipers, which can influence the overall reliability of dimensional accuracy assessments. However, despite these limitations, the research demonstrates the capability of the FDM 3D printing process to produce parts within desired specification limits, making it a widely adopted technology across various industries.

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6 AUTHORS

Alaa Aljazara, King Abdullah II School of Engineering, Princess Sumaya University for Technology, Amman, Jordan (E-mail: ala20218128@std.psut.edu.jo).

Nadine Abu Tuhaimer, King Abdullah II School of Engineering, Princess Sumaya University for Technology, Amman, Jordan (E-mail: nad20218167@std.psut.edu.jo).

Ahmed Alawwad, King Abdullah II School of Engineering, Princess Sumaya University for Technology, Amman, Jordan (E-mail: ahm20218171@std.psut.edu.jo).

Khalid Bani Hani, King Abdullah II School of Engineering, Princess Sumaya University for Technology, Amman, Jordan (E-mail: kha20218160@std.psut.edu.jo).

Abdallah D. Qusef, Princess King Abdullah II School of Engineering, Princess Sumaya University for Technology, Amman, Jordan (E-mail: a.qusef@psut.edu.jo).

Najeh Rajeh Alsalhi, University of Sharjah, UAE; Education Department, College of Arts, Humanities, and Social Sciences, University of Sharjah (E-mail: nalsalhi@sharjah.ac.ae).

Aras Al-Dawoodi, College of Computer Science and Information Technology, University of Kirkuk, Kirkuk, Iraq (E-mail: aras.ghazi86@uokirkuk.edu.iq).