Proceedings of the 8th Annual World Conference
of the Society for Industrial and Systems Engineering,
Baltimore, MD, USA
October 17-18, 2019

A Qualitative and Quantitative Inspection Analysis of 3D Printed Prototype Parts

R. Alkhasawneh and D.L. Santos

Department of Systems Science and Industrial Engineering
State University of New York at Binghamton,
Binghamton, NY, USA

Corresponding author's Email: ralkhas1@binghamton.edu

Author Note: Rawan Alkhasawneh recently completed the Master of Science in Industrial and Systems Engineering of the SSIE Department at Binghamton University. Daryl Santos is a Professor in the SSIE Department and advised Rawan on her master's thesis, upon which this paper is based.

Abstract: Three-dimensional (3D) printing plays a vital role in the continual cycle time reduction of product development through rapid prototyping. Nonconformities in the printing process could slow down this phases of product development. In this research, quantitative and qualitative studies are carried out on prototypes that are 3D printed both with and without support material on different parts of the design. Fused deposition modeling, or FDM, is the method of fabrication used in this study. These prototypes are studied in a non-destructive manner. The qualitative investigation examined aesthetical issues on small prototypes printed with and without support material. The quantitative study investigated the specimens' bases to explore the effect of the item's design on the foundation pieces. The results show that, the smaller the pieces printed over the foundation, the closer to target value the foundation measures. Elements of the 3D printed items, not directly connected to support material, were not affected by using the support materials. Furthermore, for portions of the design with overhangs (parts that used support), no evidence was found of a geometrical effect of using support. However, the visual appearance of the items was affected. Aesthetical issues studied on the items were Sagging, Bulging, Z-Wobbling and Base Surface Imperfection. Results showed that using support material did alleviate the Sagging defect. However, all the other defects were exacerbated with the use of support material.

Keywords: FDM 3D Printing, Quality Inspection, Prototypes, Quality Control

1. Introduction

There are several current three-dimensional (3D) printing techniques, but fused deposition modeling (FDM) is the most common. In this technique, the FDM printer heats then extrudes thermoplastic filaments though a nozzle into a base commonly referred to as the bed. The printed items are built one layer at the time and layers are assembled over each other. In the printed item, each layer corresponds to a horizontal slice. Figure 1 shows an illustration of an FDM printer's parts. Numerous materials are used in 3D printing that differ in strength, details, textures, possible thickness, price, and many other factors. The final product, budget, and desired properties are some of the determining factors in choosing the appropriate material for each project. Some of the most widely available materials are polymers which are obtainable in diverse types of filaments. In this work, Polylactic Acid (PLA) is used since PLA can be obtained in many shades and styles which makes it ideal for the prototyping industry, not to mention, due to its wide availability and low cost.

Destructive testing is mainly employed to investigate quality issues with 3D printed items (Periera et al., 2017). Printing process settings and environment are typically studied to investigate each setting effect on the final item's conformance to design and fitness for use. Factors like tensile strength, printing flow speed, and product features, including shapes and edges, were a focus of many studies in the additive manufacturing research area (see (Gordeev et al., 2018), (Periera et al., 2017) and (Papon and Haque, 2018) for examples). However, prototyping using AM has not adequately been explored.

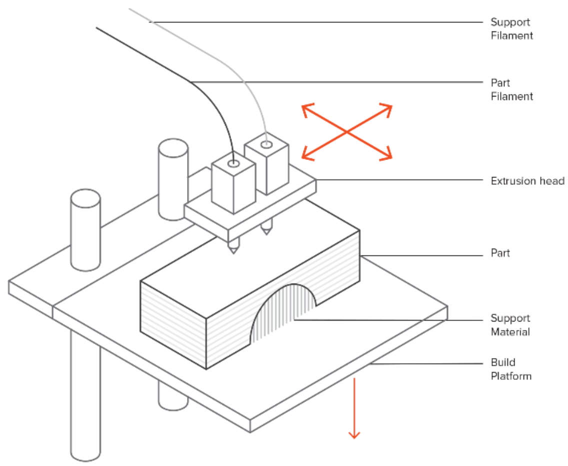

Figure 1. FDM Process Illustration [Source: Hudson, 2016]

1.1 Research Objective

Destructive testing causes wastage of good samples, not to mention, material, time and effort wasted to establish the test and print the items (Periera et al., 2017). Less destructive techniques should be explored to further study items functionality, without the wastage.

Inspecting prototypes that are 3D printed using FDM technology is the main interest of this research. As this subject was not researched in its specificity, exploring geometrical and aesthetical issues in 3D printed prototypes is carried out. Specifically, the main research objective is to investigate the performance of the printing process for different shapes on the design. Furthermore, investigations will compare the quality of batches printed with the use of support material and batches printed without it and, to do so, with a non-destructive and reasonably priced approach.

2. Prior Related Studies

A detailed literature review focused on articles that study inspection of 3D printed parts is found in Alkhasawneh (2019). In that review, it was discovered that most assays are destructive and that they employ methods that generally study either tensile strength or porosity as the response variable(s). In summary, researchers mostly used fracture properties to compare between different factors affecting 3D printed specimens. Fracture properties require destructive testing to reach conclusions about those properties. Even though data and indications might be stronger using mechanical strength studies, those studies require the demolition of inspected items, rendering them a waste. Good news – the product is perfect; bad news – we destroyed it to find that out. Items that are 3D printed can take a long time, considerable expertise, and expensive materials, all of which makes destructive testing uneconomical and impractical.

Some researchers used mechanical properties, like porosity, to determine the effect of printing speed and item shape on the quality of 3D printed items. While testing porosity of 3D-printed items may be indicative of many quality issues, the process might be excessive for continual quality assurance and not sustainable in the long run. In this work, we are focusing on the aesthetic appearance and the conformance to specification for prototypes. Which makes porosity testing not sufficient to determine the prototype's performance. This led to a need to create a new non-destructive investigational method that can be simply applied to the 3D printed parts.

In this work, prototypes will be studied both geometrically and aesthetically. Data will be analyzed for shape related defects. Shapes are going to be studied for position related qualitative issues. Also, the effect of support material utilization on all design parts is to be examined. Lastly, items are to be analyzed for aesthetical defects. Sagging, Bulging, Z-Wobbling and Base Surface Imperfections are to be investigated for items printed with and without the use of support material.

3. Methodology

To inspect the quality of different shapes of prototypes, items were printed in two different parts that fit together to create a cube. The 3D printed design was chosen because it presents many of the parts that can, typically, be found in prototypes. The first part consists of a square Base with four Protrusions off the sides, those Protrusions are hollow in the middle with a triangular head (see Figure 2a). Further, it is expected that many prototypes encompass Arches, examples of which are presented in the second part (see Figure 2b). The Arch design consists of two pillars and a semi-circular overhang on top. The investigation of the Arches considers both the heights of the Arches and the aesthetic inspection of overhangs printed both with and without supporting materials. Each cube will be made of two (2) sides of Part A and four (4) sides of Part B. The dimensions of the parts are provided in Table 1.

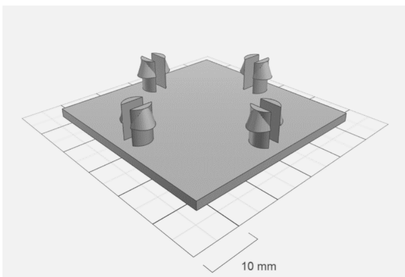

Figure 2a. 3D-printed Part A

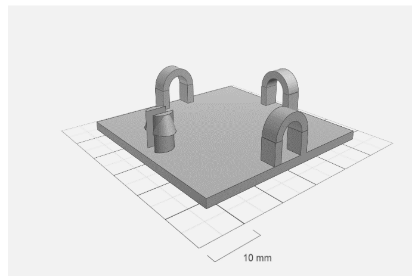

Figure 2b. 3D-printed Part B

Overhangs in the design introduce one of the problems that could emerge in a layer-over-layer printing. Each sheet consists of a molten PLA thread built on top of a lower previously printed sheet. Layers can build up to a 45˚angle (Hudson, 2016). However, designs that have overhangs beyond a 45˚angle will face the problem of sagging (Brockotter, 2017).

Table 1. Parts Design Measurements (mm)

Part	Base	Arch	Protrusion
A	46.00	n/a	10.00
B	46.00	12.00	10.00

3.1 Data Collection

The printed objects are measured in multiple positions and each measurement will be investigated. In this experiment, 14 items were printed of Part A and 28 items were printed of Part B. To make a cube we will need twice as much of Part B than Part A. Each cube consists of 4 pieces of Part B and 2 pieces of Part A. A sketch of all the Parts and their combination to form the final cube is shown in Figure 3.

A detailed GR&R study was conducted and, although not shown in this paper, confirmed that the system was acceptable to use to measure the key quality features studied in this work.

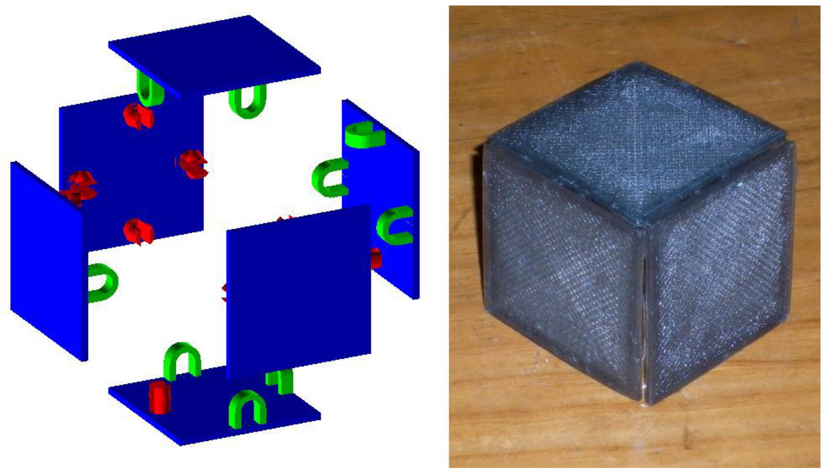

Figure 3. Soft sketch of assembly concept (left); Example of final assembled cube (right)

3.2 Part Measurements

Each part is measured for Base width on each of the Base's sides. This means that each sample will be made of 4 measurements. The deviation from nominal value is determined for each, considering the nominal value as 46.00 mm (target width). Each run will have 14 samples of size 4, which makes a short production run chart an ideal choice in this case. Normality of the data was tested and were found to be normal for each of the Part's Bases. Figure 4 shows the probability plot of Part A's Bases. Figure 5 and Figure 6 show probability plots of Part B's Bases without and with support, respectively. Notice that, in the probability plots, the P-Values are > 0.05 which justifies the assumption of normality.

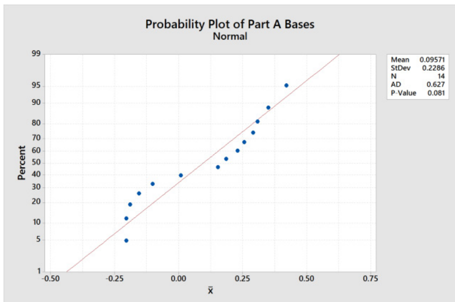

Figure 4. Normality Assumption Upheld – Part A Base Measurements

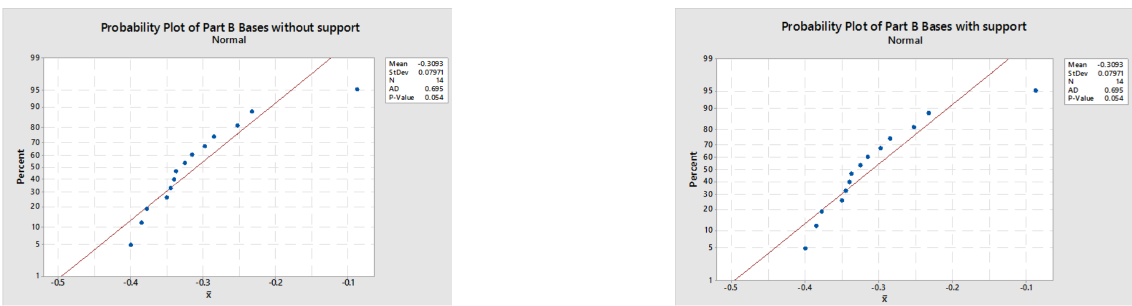

Figure 5. Normality Assumption Upheld – Part B Base Measurements; without support (left), with support (right)

ISBN: 97819384961-7-2

The deviation from nominal (DNOM) chart is chosen to be utilized to inspect the width of each side of the square Base. Justifying the use of DNOM chart depends on three important assumptions (Montgomery, 2013). First, the assumption that process standard deviation is approximately the same for all sides. Second, the sample size should be constant for all samples; in our case all samples are the same size of 4. Third, the nominal specification is the desired target value of the process; which is the case in our experiment.

Analysis of Variance was done for each of the Parts. Sides of the square Base were tested to confirm the assumption of equal variance. Figure 6 shows the interval plot for all sides of Part A's Bases. It is clear from the chart that all sides' means were of close proximity to each other. The P-Value for the null hypothesis (all means are equal) is 0.999 at a significance level of 0.05. The assumption of equal variance can be confidently applied.

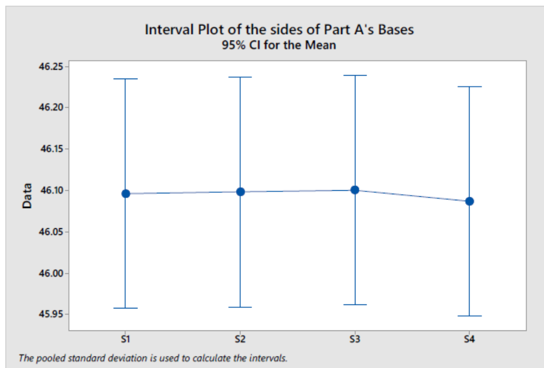

Figure 6. Interval Plot of Part A's Bases

Also, each of Part B's batches was tested for equal variance. With the same null hypothesis of equal mean for all sides. Figure 7 shows the results for Part B's Bases without (left) and with support (right). The equal variance hypothesis for Part B's Bases with support is accepted with a P-Value of 0.925 at a significance level of 0.05. However, Part B's Bases printed without support showed apparent variation in the means of the sides (see Figure 7, left). In the hypothesis testing, a P-Value of 0.001 with a significance level of 0.05, forces us to reject the null hypothesis. This means that for Part B's Bases printed without the use of support, Standardized $\bar{x}$ and R charts should be used instead of a regular DNOM.

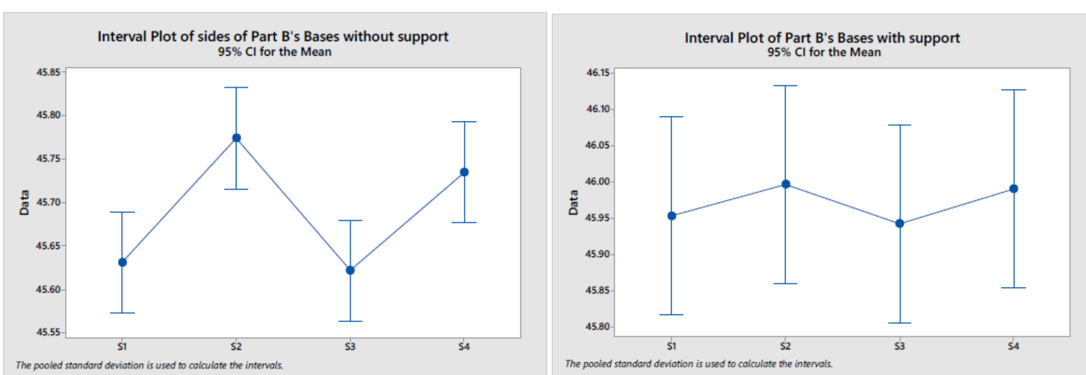

Figure 7. Interval Plot of Part B's Bases; without support (left), with support (right)

In addition to the base measurements, protrusions (4 on Part A, 1 on Part B) were also measured. Protrusions are studied because of the insight they provide into position-based printing stability. And, for Part B, it gives more insight on whether the utilization of support affects other parts of the design. Moving Range values were taken to assess the stability of the FDM process for printing the protrusions. The last feature measured was arch length. Only Part B has arches; 3 arches per part. MR values for these features were also used to assess stability of the process. To investigate, for each Arch on Part B, an MR-chart will be created. The comparison will take into consideration the position of each Arch relative to the Protrusion present once in Part B. And, the difference in performance between the two batches based on support material will also be considered.

3.3 Qualitative Inspection

To further the study into support material used in the 3D printing process, items were studied for the aesthetic appearance and visual imperfections. Every piece of Part B was visually checked and given a grade for each of the categories chosen for inspection. Sagging, Bulging, Z-Wobble and Base Surface Imperfection are the categories to be studied. All the inspections were done in a well-lighted area with a flash light directed at the parts inspected. Light was aimed directly toward the items and also in angles to make sure the reading was as consistent as possible.

Categories were chosen according to industry standard for plastic materials manufactured through 3DP ("Correct Plastic Part Defect from Injection Molding, 3D Printing", 2018). Each was graded according to the standard associated with it as will be described in the following subsections.

3.1.1 Sagging

Sagging in 3D printing is the sinking of the printing material and bulging downward. In the inspection, each Arch was looked at directly to determine whether the inner curvature creates a semi-circle, if it showed parts that bulge downward, then the Arch will be considered a sag. Figure 8 shows one of the sagging Arches in our experiment. Looking at the picture, it can be noticed that the vertical lines have some sag and the inner semi-circle does not have a perfect curvature. Sagging was given a score of 0, 1, 2 or 3. The score given to each piece represents the number of Arches that show sag in them in any extent.

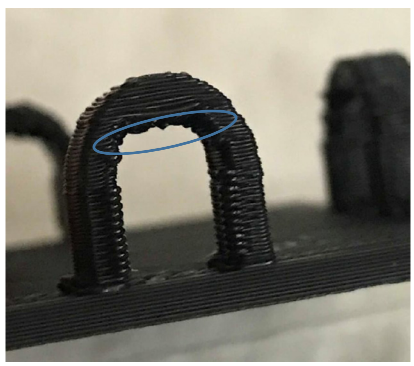

Figure 8. Sagging in 3D Printed Arches

3.1.2 Bulging

Bulging is identified when the printed specimen has excessive material protruding off the surface, that is, not within what the design entails. It was graded on a score of 0, 1, 2 or 3 based on the degree of their presence. A score of 0 means that there is no bulging and the Arch surface is in a perfect condition. A score of 1 means that bulging was present only once, 2 moderate bulging (up to 2 Bulges), and 3 excessive (3 or more Bulges were detected). Figure 9 shows an example of Bulging on the surface of the Arch. As can be seen, this item has excessive Bulging all over the Arch.

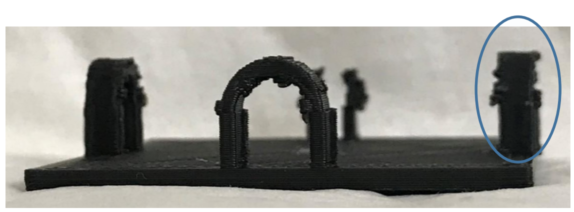

Figure 9. Bulging in 3D Printed Arches

ISBN: 97819384961-7-2

3.1.3 Z-Wobble

The Z-Wobble is a defect that in a 3D printed item shows horizontal lines across the z-axis. In our prints, those lines do exist in some of the items as seen in Figure 10. There are two main areas presenting this kind of defect, the Base and both projections (Arches and Protrusions). The Z-wobble defect on the Base appear to be in a good condition. However, the projected parts show worse quality in this regard. In the inspection done, the items were given a Yes or No score based on the presence of the Z-Wobble on projections only. Because, all the parts showed a good quality on the Base.

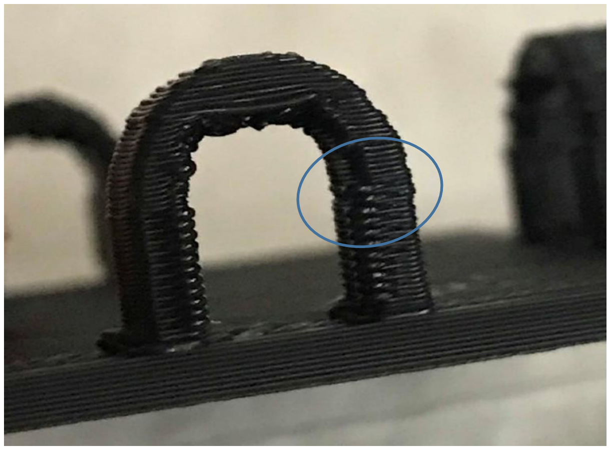

Figure 10. Z-Wobble in 3D Printed Arches

3.1.4 Base Surface Imperfections

3D printed items often time show lines and gaps on the surface of the top layer. This is because items are printed in a layer-over-layer technique and the material undergoes melting and cooling. In the scoring of the items, the Base surface is the focus of this check; as other parts of the item are inspected in the previous steps. Items were given a score of 0, 1, or 2. A score of 0 was not achievable in our material as it represents a surface that is very smooth and in 3D printing this is only achievable with post treatment (Armstrong, 2017). A score of 1 is earned when the items only shows lines on the surface. A score of 2 is given when the surface contains other imperfections in addition to the lines. Figure 11 shows an example of the surface finishes of an item of our project with a score of 2; mainly this is due to the presence of unexpected smooth part in the lower right corner.

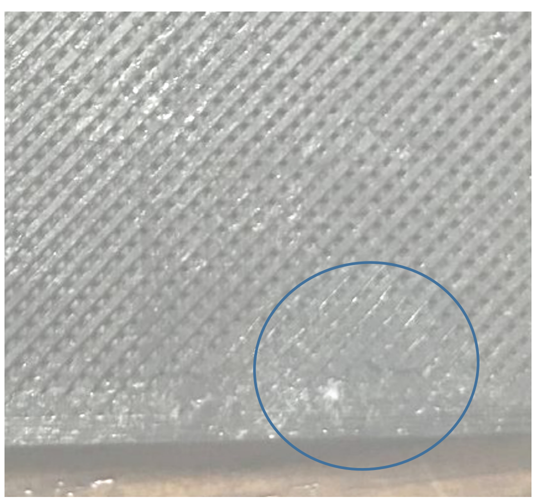

Figure 11. Surface Finish Imperfections – Brightness Adjusted to show Detail

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4. Results

This section will summarize some of the findings found in Alkhasawneh (2019) that are too numerous to place here. With size restrictions considered, the various ANOVA charts, GR&R analyses, and control charts will not be presented. In lieu of these, a summary, by feature inspection type, will be presented.

4.1 Bases – Inspection and Analysis

One interesting finding may inform us on how the design affects the foundation (base) of the parts. With respect to Part A, on average, the bases of Part A are slightly larger than their target value (46.00mm). On the other hand, for Part B, the bases tend to be slightly smaller than their target value (also, 46.00mm). As a result of this, we feel that the weight and shape of the overall design affects the printed value of the foundation portions (bases) of the item. To confirm such a conclusion, the average width of the Base's sides was calculated. Notice in Figure 2a, that Part A has 4 of the same type of projections off the surface. Part B (Figure 2b) has two different types of projection. Table 2 shows the average measurements for each side of the square Base, rounded to the hundredth digit. Notice that, for Part A, all sides have very close measurements of width regardless of the side number.

Table 2. Average Width of Bases per Side (mm)

Part\Side	1	2	3	4
Part A	46.10	46.10	46.10	46.09
Part B Support	45.95	46.00	45.94	45.99
Part B No Support	45.63	45.77	45.62	45.74

Side 1 on each of the Part B batches, refers to the side with the Protrusion projection. Notice that Side 1 and Side 3 are on the opposite borders, which means they should give similar values. Here, Side 2 and Side 4, gave higher values (closer to target) than Side 1 and Side 3 on both of Part B's averages. This supports the assumption that, in a 3D printed specimen, characteristic of printed items is affected by the portions printed over them.

Table 2 provided evidence that the use of support does improve the performance of the printing process for other elements of the design. Comparing the width of the Base of specimens printed without support material to those printed with support. The later measured closer to target value, on average.

4.2 Protrusions – Inspection and Analysis

Protrusions are present on all parts. Part A has 4 Protrusions, whereas Part B only has 1. As earlier discussed, Individual and Moving Range Charts (I-MR) of each Protrusion were created; though they are not included here. All charts appear to be in-control, and, no significant difference between the charts are identified.

All the charts showed a similar pattern. This indicates that there is consistency in reading all Protrusions of the same item. For instance, the readings on all individual Protrusions were dropping between Observation 1 and Observation 5 (as will be shown when this paper is presented at the conference). And there is an increase on all the 6th observations. Each item was numbered, and each observation comes from the corresponding item; this indicates that all Protrusions, regardless of their positions, showed similar characteristics for each item. To clarify, the 5th observations all show a similarity of readings lower than those of the 6th observations on all tested parts.

For Part B, I-MR Charts indicated the process to be in control and no other issues or major observations were found and this is irrespective of using supports or not. This indicates that elements of a 3D printed item, not directly connected to supported elements (as Arches are) will not be affected by using support. The printing process performance of such elements is independent of other non-adjacent elements.

4.3 Arches – Inspection and Analysis

To inspect the Arches, the data were taken based on Arch position relative to the only Protrusion on Part B. Arches were numbered as A1, A2, and A3 moving clockwise from the Protrusion. Each Arch position was inspected separately and

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plotted into I-MR charts. Arches printed without the use of support were inspected first. All charts appear to be in statistical control with random, chance causes of variability present. Similar results were found on arches measured with the use of support.

Based on the I-MR results for both cases, it can be inferred that the employment of support material for items with similar dimension does not geometrically affect the items. Arches length measurements still fell within control limits. So, in the next section, items will be inspected visually to determine the effect of support material on the visual appearance of the item. In this research, items were tested for rapid prototyping, which makes visual appearance an important factor of products' appeal and perceived quality.

4.4 Qualitative/Aesthetic Inspection

Items were inspected for the four aesthetic issues chosen (Sagging, Bulging, Z-Wobble and Base Surface Imperfection). To get a general sense of the extent of what each defect's presence is in those batches, Pareto charts were employed. Notice that 14 items were tested in each batch and the number of defects represents the number of items that contain that type of defect in any extent.

Figure 12 shows the defects occurrence in the original batch (without support). Sagging and Base Surface Imperfections were present in all the items. Bulging was present in 10 out of 14 items and Z-Wobble was only spotted in one of the items.

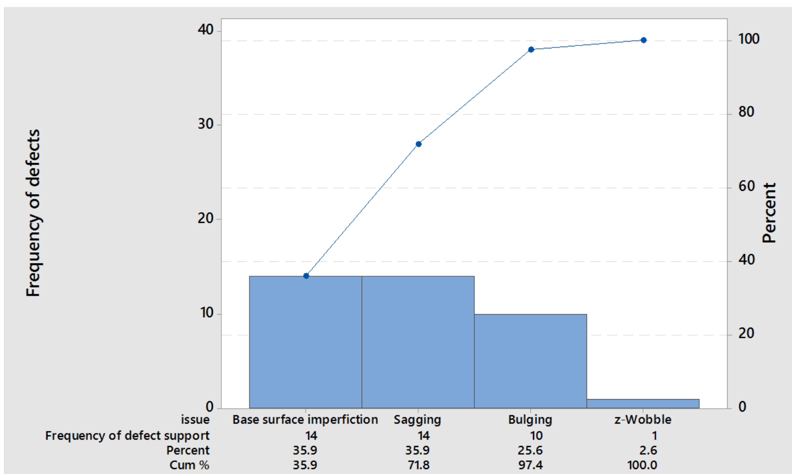

Figure 12. Pareto Chart of Defects – Without Support

After the support was used (Figure 13), all items still showed Base Surface Imperfection as well as Bulging and Z-Wobble. Sagging, on the other hand, appears to be less present in supported items, with only 9 items showing this defect.

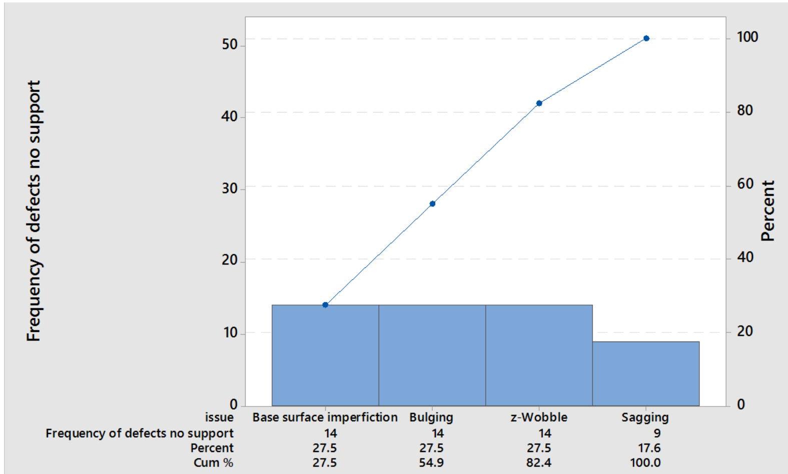

Figure 13. Pareto Chart of Defects – With Support

We can conclude that, generally, Base Surface Imperfection was not affected by the use of support. Sagging was expectedly less in items with support; the employment of support was meant to offer a foundation for the Arch to build on and spare the item from Sagging. Bulging was exacerbated when support was used, this is because material cools down stagnantly (Sagging is lowered) so material in the liquid state might shift and bulge. Finally, Z-Wobble appeared to be dramatically increased when support was used. This indicates that support material affected the stability of the printing nozzle.

5. Conclusions and Future Work

In this section, some of the pertinent conclusions, along with suggestions for future work are provided.

5.1 Conclusions

This research aimed to identify and study possible problems in 3D printing small prototypes using FDM technology and PLA filaments. The research objective was to identify geometrical and aesthetical quality issues of prototypes and to propose a non-destructive assay technique. Also, to explore the effect of using support material on different parts of the design was of interest. To accomplish this task, two different parts were 3D printed, with different projections. These projections are often found in 3D prototyping. The parts can come together to create a simple cube by locking together Arches and Protrusions. Those projections are printed over a square box base referred to in this research as the Base. The parts were studied for any geometrical shortcomings as well as for aesthetic imperfections. No strong evidence was found for geometrical consequence of using support material on prototypes. However, aesthetically, this research was able to identify 3 defects that can be exacerbated using support. And, although the items were not geometrically affected, the aesthetical flaws can affect the visual and mechanical performance of the prototypes.

Through the 3D printing process, some parts were printed with the aid of support material, and others were not. All shape types were printed under the same settings (bed temperature, extrusion temperature, printing speed, cooling rate, etc.). It was found that for the Base, the printing process performance did not show satisfactory results. This is believed to be because of a rapid cooling rate. It is recommended that for the foundation pieces, slower cooling rate should be considered. However, it was found that the performance of foundation pieces was directly connected to portions they bolster. The smaller the parts over the Base, the closer to target value the Base would measure. This can be generalized to foundation pieces in prototypes.

The Protrusion is another portion of the design that was considered. The analysis aimed to study the process performance for smaller pieces (10 mm length), not directly printed on the printing bed. It was found that the process performed was the best for such parts. Further, those pieces gave insight on the effect of using support material on portions that did not directly utilize support. Protrusions were the only portion of the items that did not tangibly touch the support material. It was concluded that for such parts, the process performance is not affected geometrically using support for neighboring portions. This may be because the printing process performed similarly with and without support. Items showed similar pattern of variability on the I-MR charts and had similar central tendencies.

Arches were the next portion of the design to be studied. This investigation aimed to study the geometrical effect of using support material on overhangs. The investigation took both supported and non-supported batches and compared the process performance for each. It was found that the use of support did not affect the geometrical aspect of the prints. This was concluded by comparing I-MR charts of each Arch with and without support; all charts were in control and performed similarly. However, the visual appearance of Arches printed with support material appears to be changed.

Visual appeal and aesthetic issues were studied to identify perceived effect of using support on prototypes. Defects studied are Sagging, Bulging, Z-Wobbling, and Base Surface Imperfection. It was concluded that the use of support material has a great merit in reducing Sagging in Arches and overhangs. This was determined because in non-supported Arches, more than 72% of the tested items showed Sagging defect in 2 or more of the 3 possible Arches. Whereas, after support material was utilized, the percentage dropped to only 14.2% of the inspected items. However, all other studied defects were affected negatively. For Bulging defect, all items printed without support had 1 or no bulges on their Arches. After support, however, ~93% of the items had 2 to 3 bulges per item. Furthermore, even though, items printed without the use of support were almost void of Z-Wobbling; all items printed with supporting material showed this defect. Finally, items inspected for Base Surface Imperfection, showed more imperfections after support was used versus those printed without it. So, decision making regarding the use of support should take into consideration all the aforementioned factors.

5.2 Future Work

Research in 3D printing can take many routes, analytical inspection was used in this research. Due to both the findings of this effort, along with information gleaned during the literature review process, here are some suggestions for future work:

- Researchers might look further into the effect of support materials on items of different sizes. The effect of items size on the performance of the printing process is an important factor to be studied especially in the overhanging parts of prototypes.
- Different printing material can act in diverse ways when used in the printing process. So, items can be tested and compared for discrepancies in performance depending on the printing material.
- Further study of the foundation portions of prototypes should be conducted. Parts of the items that are 3D printed initially and the rest of the item are built on top of, the foundation pieces. This is to identify appropriate machine setting for ultimate quality improvement for the overall prototype.
- Moving and mechanical parts of prototypes could be studied to identify issues occurring in such portions of the design.

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ISBN: 97819384961-7-2