Spring 2018

# Repeatability Case Study of the 3D Printer in the School of Engineering and Applied Science Lab

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# REPEATABILITY CASE STUDY OF THE 3D PRINTER IN THE SCHOOL OF ENGINEERING AND APPLIED SCIENCES LAB

A Thesis
Presented to
The Faculty of the School of Engineering and Applied Science
Western Kentucky University
Bowling Green, Kentucky

In Partial Fulfillment
Of the Requirements for the Degree
Master of Science

By
Naif Albaiji

May 2018

REPEATABILITY CASE STUDY OF THE
3D PRINTER IN THE SCHOOL OF ENGINEERING AND APPLIED SCIENCES LAB

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I dedicate this thesis to my family, especially my mother, Laila Altaie, my father, Faleh, and my brother, Fawaz Albaiji. They have supported me since day one to ensure that I find my way to success. I also dedicate this work to the School of Engineering and Applied Science, my thesis committee, and my professors who have guided me.

ACKNOWLEDGMENTS

I would like to thank several people who inspired and helped me throughout my journey with this study and degree: Dr. Greg Arbuckle, Dr. Douglas Chelson, Dr. Bryan Reaka, Dr. Brent Askins and Dr. Daniel Jackson. I would also like to thank the Ogden College of Science and Engineering for giving me the opportunity to use their facilities and resources to finalize my thesis. I would like to thank the Royal Embassy of Saudi Arabia and the Saudi Arabian Cultural Mission (SACM) in the U.S for providing scholarship and support during my studies in the U.S.  I would also like to thank Mr. Amro Eissa, my advisor at SACM, for the guidance he provided and for his patience.

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Naif Albaiji May 2018 42 Pages

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3DP (three-dimensional printing) technologies have become more than just a tool to help companies with prototyping and designing in the pre-production stage. Some firms have already implemented 3DP technology to produce parts and end-use products. However, there are several challenges and barriers that this technology must overcome to replace traditional manufacturing methods. One of the most significant obstacles associated with 3D printing is its low level of accuracy in variable repeatability when it comes to making separate batches of the same product. There are several arguable reasons behind this variation. Some of the factors that can influence repeatability are the type of material, the design, the type of product produced, and the orientation, or the location of the build inside the building envelope. The goal of this study was to determine whether the location of the build inside the surface area of the working envelope can affect the properties (height, width, depth, and weight) of the product.

Western Kentucky University (WKU) provides students with a few 3D printers on campus. One of those printers, a Stratasys (model: BST 768/SST 768), is in the Senator Mitch McConnell Advanced Manufacturing and Robotics Laboratory. The researcher used this printer for the study to determine if the location of the printer influenced the final product. The conclusion of the research did reveal that the printing location does affect the quality of the final product.

## Introduction

3DP creates objects of different shapes by laying material down in a layered structure. Some examples of useful products that are being produced with 3DP include knee implants, tooth crowns, automotive parts and hearing aids. It is probable that the 3DP industry will grow into an $8.4 billion market by the year 2025, with significant contributors such as the aerospace, automotive and medical industries (Bhattacharjee, Urrios, Kang, & Folch, 2016). 3DP has emerged as a game-changer in the global business environment, mainly because of its ability to reduce lead-time (Petrick & Simpson, 2013). 3-Dimensional printing is also highly useful in creating customized products due to a fast and straightforward design-to-create manufacturing cycle.

Despite the many applications and services that 3DP offers, manufacturers are still not taking full advantage of the technology when it comes to end-use products due to several obstacles. Some of these barriers include the limited variety of materials and the variation in repeatability. Traditional manufacturing processes are still winning the race when it comes to mass production and end-use products. However, 3DP has an advantage when it comes to the pre-production stage, namely in the prototyping and designing phases.

In this case study, the researcher tested the 3-dimensional printer to determine whether the location of the build on the printing surface affected the measurements (height, width, depth, and weight) of the final products. The 3D printer, made by Stratasys (BST 768/ SST 768), is located at the Senator Mitch McConnell Advanced Manufacturing and Robotics Laboratory. Completion of this study required multiple steps: design, Gage R&R, measurement devices, and making the products.

First, the researcher designed a product using CAD (Computer Aided Design) software. The product has a simple design to minimize the possibility of error, especially in the measurement phase. The design, a one-inch cube, included specific markers to determine the orientation of the product. The design utilized a small sphere indentation on the top face and a planned vertex. The weight and volume of the indentations were calculated and deducted from the initial weight (See methodology section for more details).

Following the design phase, the researcher performed a Gage R&R study on the measurement devices used to measure the products. Testing the measurement devices ensured that they would not introduce any false data to the study. The Gage R&R method allowed the researcher to test repeatability and the reproducibility of the measurement devices (Pyzdek & Keller, 2014). Because there was only one operator recording measurements for this study, it was not necessary to test the reproducibility of the devices. Two instruments used during the study, a digital scale for weight and a digital caliper for height, depth and width. The researcher tested the caliper using three different cera gage blocks made by Mitutoyo, certifying the blocks on June 15, 2005. The sizes of the blocks are 1”, 1.2” and 0.9” or 25.4 mm, 30.48 mm and 22.86 mm, respectively. Additionally, the accuracy of the scale was tested using three different US currency coins: a penny, which weighs 2.5 g, a nickel, which weighs 5.0 g and a dollar, which weighs 8.1 g (Weight specifications are from the US Mint website).

First, the measurement devices were checked and readied. Then the researcher started building batches, containing five different products with the same specifications and assigned each product a different location on the working envelope of the printer.

Once the products were ready, the researcher took the measurements needed and recorded the findings.

The goal of this study was to determine whether the location of the build on the printing surface affects the final products. Based on William Gosset's theory, to have a valid study with a normal distribution, at least 30 different products were required. The researcher used five different locations in six different runs, which resulted in 30 parts. The five sections of the printing surface were named A, B, C, D, and E. Each sequence was assigned a numeral: 1, 2, 3, 4 and 5. The number of the run and the name of the location determined the name of each product. For example, the name of the product at location C in the third sequence would be C3.

**Problem Statement**

The usage, and applications, of 3DP are rapidly growing. However, there are some obstacles to overcome for this new technology to change the face of manufacturing. The main problem associated with this technology is its repeatability when it comes to the four areas mentioned earlier: height, width, depth, and weight. Using a Stratasys (BST 768/ SST 768) 3-dimensional printer, this case study tested one of the factors that can result in the lack of accuracy. The researcher experimented with the location of the build on the printing envelope to determine if it influenced the outcome.

**Significance of the Research**

Berman, B. (2012) anticipated that 3DP technology would be a critical factor in the third industrial revolution. However, to be part of this new revolution, this technology has many areas to improve upon, including types of material available, prices of printers and most importantly, the accuracy and repeatability. This research examined the variability in products when using different locations on the printing surface of the Stratasys 3-dimensional printer (BST 768/ SST 768). The focus of the study was the location of the build inside the printer. The researcher investigated the potential role of the locale in conjunction with the inconsistency of product dimensions.

**Purpose of the Research**

This study attempted to determine whether the location of the build in the 3D printer can result in vast variation in final product measurements. The areas that the researcher measured and considered were height, width, depth, and weight. The outcome of this study showed the variation between the products in a statistical way using the ANOVA test method.

**Research Questions**

Based on the problem statement highlighted in the previous section, this research attempts to answer the following research questions:

- Does the location of the build have any effect on the height of products?
- Does the location of the build have any effect on the width of products?
- Does the location of the build have any effect on the depth of products?
- Does the location of the build have any effect on the weight (mass) of products?

This research attempted to experiment with the 3DP available in the School of Engineering and Applied Science Laboratory (Stratasys BST 768/ SST 768) to answer these research questions.

**Assumptions**

a. The printer worked perfectly, and there was no variation in its performance during the study.

b. The material used in the printer was in decent condition.

c. The researcher cleaned the printer of any previous products and projects.

d. The researcher used the same measuring devices for each product.

**Limitations**

a. The printer is a few years old. There is no previous data available on the wear associated with the printer, and if it will affect the build.

b. Not having control over the temperature and humidity of the room caused some variation in the study.

c. The cost of the materials used limited the sample.

**Definition of Terms**

- 3DP- 3-Dimensional Printing. According to Petrovic et al. (2011), it is the evolved form of printing technology that can produce, as well as reproduce, sophisticated freestanding structures through additive layer fabrication process in one piece.
- Gage R&R- Gage repeatability and reproducibility, a statistical test to determine the variation in the measurement devises used in the study.
- ANOVA- Analysis of variance to test the variation between or within groups of products.

## Review of Literature

According to Lu and Reynolds (2008), the process of 3D Printing involves two stages. In the first phase, the data/designs transfer from software to the 3D printer. Then, in the second stage, the printer head works in all X, Y and Z directions to print the required product layer-by-layer. Lu and Reynolds further explain in detail that the printing process starts with designing the required product in CAD (Computer Aided Design) software. The operator then sends the design to the printer, which begins to print two-dimensional slices layer-by-layer that join to represent a 3D object. The printing process continues until completion of the job and the component, or product, is ready.

CAD systems allow designers to design and manipulate design data. Using the software, they can create three-dimensional figures, with variations in design, size or features, and send it for approval. Once the operator approves the design, the process moves on to the second stage. Petrovic et al. (2011) describes the second phase as the coating and fusing stage during which the printer creates the layers. The raw materials, and the energy source, for the second stage depend on the techniques used by the manufacturer. According to Kain et al. (2009), 3DP allows a high level of flexibility in manufacturing because of its ability to print customized designs and ability to alter the configuration at the last moment before printing. This flexibility provides the manufacturer with more control over the design, producing a highly detailed finished product.

3DP technology has been in the development and application phase since the 1980s. The development of cost-effective 3DP solutions has led to breakthroughs in dimensional printing technology. Scholars consider 3DP technology breakthroughs in manufacturing technology in a similar light to the recognition of the Internet, and personal computers as breakthroughs in information technology (Jenkins et al., 2015; Barnatt, 2016). However, in the last five years, owing to the development of 3DP technology, the potential for 3DP has increased to a tremendous degree and across several fields.

According to Marchese, Crane, and Haley (2015), the market size for 3D printers, services, and materials have reached approximately $44.2 billion. Application of this technology has extended to a range of industries, for example consumable goods, consumable food, building prototypes, and creation of spare parts and objects (Millsaps, 2016; Dillow, 2011).

**Additive Manufacturing (AM)**

Additive manufacturing, also known as AM, is the industrialized version of 3DP. AM refers to the layer-by-layer building of a product until the final product is ready. The technology uses several types of powder formed materials, including plastics, composites, and metals. It is a design-driven manufacturing process, offering a serial production as well as high degree of customization (Manners-Bell & Lyon, 2014). AM offers new possibilities for designing and manufacturing. It allows for the creation of exclusive products having complex geometries. Moreover, 3DP enables the creation of one-piece functional parts, which results in a reduction of time and cost (Campbell et al., 2011). According to Karagol (2015), there are several types of AM technology categorized by the type of raw material used. These include powder-based, solid-based and liquid-based 3DP.

**History of 3DP**

Charles Hull, an American engineer, developed the first 3D printer in 1984 (Paukku, 2013). The idea of the 3D printer came to Hull while studying photopolymers, i.e., plastics having the potential to harden with light. He conceived of building a device that could gradually create an object by hardening one thin plastic layer over another (Paukku 2013). He applied for a patent on the equipment, as well as the technology, terming the technology as stereolithographic.  Patenting the technology led to the development of the company ‘3D Systems', which is still one of the world's largest manufacturers of 3D printers. Stratasys is another major player in the industry, with a similar origin story. Scott Crump founded the company a year after inventing fused deposition modeling (FMD). According to Barnatt (2013), both 3D Systems and Stratasys are similar regarding scale.

Scholars also describe 3DP as rapid prototyping, because some manufacturers use AM to build scale models, prototypes, or parts, before sending them for mass production. Rapid prototyping does not refer to instant printing, but it does decrease the time compared to traditional manufacturing. Although AM can take hours, sometimes days, to manufacture an object, the conventional production is still considerably slower.  The development of prototype by hand or making a mold of the object, and then tooling machinery, and finally producing the required object takes a lot of time. 3DP, or AM, provides a more rapid solution. Gershenfeld (2005) suggests that building a prototype using 3DP is better for the manufacturer as the cost of mold, as well as tooling, can be avoided in case a change in design is required.

**Diffusion of 3DP**

Although 3DP technology has been around for more than 30 years, the adoption rate has been low. In 2016, AM was approximately a $5.1 billion industry (McCue, 2016), while the overall manufacturing industry in 2012 was worth approximately $15 trillion (Lipson & Kurman, 2013). The overall worth of the industry highlights the low adoption rate of 3D technology.

According to Wohlers Associates (2013), the 3DP industry could be worth $10 billion by 2021. However, Wohlers is skeptical about the adoption of 3D printers at a consumer level. He predicts that the majority of people will never operate or purchase a 3D printer regardless of their happiness and satisfaction with customized 3D printed goods. The consumers will get the printing done by a retailer, but will not purchase a 3D printer for themselves (Lipson &Kurman, 2013). Similarly, according to Dougherty (2013), 3DP is like espresso makers and jet skis and should be considered a toy rather than a manufacturing tool. Marsh (2012) highlights several experts and researchers who believe 3DP will become a mainstream manufacturing technology by the year 2040. The unique characteristics of AM indicate a tremendous potential for mass production, reduced supply chain costs, and reduction in lead-time. By adopting 3DP, organizations can differentiate themselves from other manufacturers. 3DP allows companies to add variety in their products at almost zero extra cost.

The diffusion of 3DP accelerated from the start of the year 2014 mainly because of a couple of events that occurred in the 3DP industry. As a result, the potential of 3DP reached a new level. In 2014, the unpatented technology selective laser sintering (SLS) was developed. The unpatented technology was available for everyone to use, which resulted in new 3D printer manufacturers entering the market. In 2009, a similar thing occurred when there was a lapse in patenting FDM (fused deposition modeling). However, SLS is a more advanced 3DP technology as compared to other available technologies. SLS can produce ready-to-use metal objects. The lapse in patenting the SLS technology resulted in an efficient technological breakthrough. The 3DP market saw an unexpected inflow of affordable 3D printers based on SLS technology. This breakthrough made 3DP technology available to a higher number of SMEs who manufactured customized metal parts. Since the 3DP technology was expensive, these SMEs could not afford to purchase multiple printers for different locations. However, with the availability of the unpatented SLS technology, they were now able to afford the 3DP technology previously denied to them by cost.

Another event that enhanced the potential for 3DP was the entry of Hewlett Packard (HP) into the 3DP industry. HP is one of the biggest companies in 2D printing. The hope of greater diffusion of the 3DP technology increased because of the success of HP in the printing industry. The industry expected that the household name, HP, would make the 3DP technology feel more established among consumers. Also, HP is a more established company than both 3D Systems and Stratasys combined.  They have massive production facilities, which can reduce prices of the 3D printers and increase the adaptability of this technology.

**3D Printing Disrupt Manufacturing**

According to Petrick and Simpson (2013), manufacturers produced goods differently before the industrial revolution. The industrial revolution disrupted the industry and created something new called ‘supply chain.' As the industrial revolution did, Petrick and Simpson suggest that 3D Printing will interrupt manufacturing again. They highlight the example of a hammer.  Ordering one single customized product like a hammer will cost consumers a lot more using traditional manufacturing compared to additive manufacturing. This price gap will lean towards conventional production, as the firm produces more hammers due to the economics of scale. Petrick and Simpson then predict the future of production with the 3DP and its impact on consumers and manufacturers (Petrick& Simpson, 2013). They claim that two main rules will control manufacturing.

The first rule is ‘mass production;’ economies of scale for interchangeable parts produced at high volume. The second is ‘craft production;’ economies of one for highly customized products that can be built layer by layer. Petrick and Simpson also discussed the materials used in 3DP. These materials range from polymers, which are the most common, to ceramics and metals, which are the least common. Some limitations exist concerning the capabilities and variety of materials, the speed of the printers and lack of standards of the printers. Moreover, when building any part using a 3D printer, the finished piece will still need some final touches, and sometimes there is a variation when printing two similar components using the same printer (Petrick& Simpson, 2013).

**The Future of 3DP**

According to D’Aveni (2015), 3DP technology has come to a point where its usage is about to enter mainstream manufacturing. He further adds that approximately 12% of the large-scale manufacturing organizations have adopted 3DP technology to produce products in large volumes. However, for firms to consider this technology as a part of the mainstream manufacturing method, 3DP must achieve at least 20% saturation of the mainstream market. Managers should look for the potential of using 3D printers within their organization, assessing how the technology can strategically fit their institution's needs to utilize this technology to reap all the possible benefits fully. D'Aveni (2015) suggests that the future is manufacturing and that there is no doubt about it. He predicts that the technology will be competing with conventional methods of production within five years. However, organizations will have to explore how they can attain the maximum possible benefits from this technology to increase the percentage of usage in the mainstream market.

**Commercial 3DP**.

From the commercialization perspective, 3DP technology has been developing and achieving maturity. Nonetheless, the benefits of this technology have favored some specific situations and industries. Concerning the current research, it is essential to comprehend the reasons behind the adoption and implementation of 3DP into organizations' manufacturing strategy. It is important to understand how commercializing 3DP technology can influence supply chain costs. The following sections provide insight into the industries that have recognized 3DP as a modern and efficient manufacturing method.

**Prototyping**

Manufacturers have been using 3DP to create prototypes in the initial phases of this technology. According to Berman (2012), creating a prototype using 3DP is different from making a prototype from traditional methods, using clay and wood. 3DP technology allows making prototypes with different materials and moving parts. In fact, 3DP allows developing prototypes for different markets, using different materials, without making any costly change in the 3D Printer (Berman, 2012). Using 3DP technology for producing prototypes has several advantages. First, 3DP allows making two identical products, with slight variation, suggesting that economies of scale do not depend on serial production in a 3DP context (Berman, 2012). Moreover, manufacturers and designers can use cheap material, such as recycled paper, plastic, and resins to produce less expensive 3D prototypes. 3DP technology reduces the time and costs to develop a prototype because it does not require dies and tools (Berman, 2012). Supporting Berman's view, Bogue (2013) explains that a 3D printer can produce a prototype directly from the CAD design eliminating the requirement of costly specialized equipment. Berman (2012) cited an example of Black and Decker and highlighted that a prototype that usually took three to five days to produce, now required only a few hours using an on-site 3D printer. Bogue (2013) suggests that 3DP can help start-up companies, particularly in situations in which they want to do extensive market testing of their product before attempting a full-scale launch.

**Aircraft Industry**

One industry that has been utilizing the 3DP technology the most is the aircraft industry (Campbell et al., 2011; Bogue, 2013), particularly with the use of metal as the 3DP material (Petrick& Simpson, 2013). The aircraft industry used 3DP to produce low volume, customized products not readily available. In their work, Campbell et al. (2011) cited an example of an environmental control system duct produced using 3DP technology for the F-18 fighter aircraft.  The aircraft manufacturer uses 3DP technology to save time, and reduce the number of parts involved for environmental control system duct from sixteen to one.  The complicated component produced did not need assembly.

Airbus also commercially utilizes the 3DP technology (Bogue, 2013). In fact, the A380 is the first commercial plane to use parts manufactured using 3DP. The benefit for the A380 was that 3DP technology allowed development of lighter components within short lead times (Airbus, 2014). Thus, Airbus was able to reduce material usage, while still ensuring the quality of the parts, and improved their lead-time. According to Airbus (2014), in comparison to the traditional manufacturing technique, 3DP allowed them to reduce 30% percent to 55% of the component's weight, as well as reduce 99% of the raw material requirement. The most notable advantage of 3DP for Airbus was that the company can now produce cost-effective out-of-production spare parts in a very short lead-time (Airbus, 2014). Ehrenberg (2013) highlighted that Airbus is working on the development of a 3DP facility to print entire wings of their planes and is planning to produce whole planes using 3DP by 2050.

**Medical Industry**

Another industry that has been increasingly using 3DP is the medical industry. This industry is developing medical appliances like orthopedic implants and hearing aids through 3DP technology. According to Campbell et al. (2011), Phonak and Siemens use laser sintering to produce customized hearing aids. Using a 3D scan of the ear canal, they can create a customized hearing aid that perfectly fits the ear of the patient. Titanium is used to print the hearing aids. 3DP is also useful in the production of human prosthetic bones to replace bones that have suffered damage from illness or injury (Bogue, 2013). More importantly, any geometrical or complicated design can be developed in CAD to be printed on a 3D printer later making this technology particularly ideal for the prosthetic medical industry. Li et al. (2007), suggests that using porous implants with perfect geometrical design can enhance the integration of implants with the newly grown bone. There are many tremendous opportunities to expand 3DP technology within the medical industry.

**Locations Difficult to Access**

Another area where 3DP has a considerable advantage regarding manufacturers is in locales that are very difficult to access. For instance, sites like military or navy facilities, or naval aircraft carriers in the middle of the sea. Deploying 3D printers in such aircraft carriers will reduce the vulnerability of supply chains. Stinson (2014) argues that if any component is required which is not available in the inventory, it can be printed on demand using the 3D Printer. Stinson further adds that the US Navy has a 3D printer installed on the USS Essex and considers the technology as the future of logistics. 3DP can reduce the number of supplies and spare parts kept in supply as healthcare providers can easily print as per requirement directly on the naval ship. Osborn (2014) contends that printing parts at the destination will reduce lead-time from months to moments. The potential of this technology at locations that are remote or difficult to access is limitless. Osborn (2014) further adds that logistics in the future will have the following characteristics: decreased costs, improved readiness, less frequently shipping parts, and increased the speed of execution. Better logistics will eventually lead organizations to produce products as complicated as printed unmanned aerial vehicles that have microprocessors, communication capabilities, sensors, and electronics embedded in them. In summary, organizations have been embracing 3DP as a method of manufacturing products. The technology has been used to produce prototypes, components in medicine and aircraft industry and to manufacture at the point of destination in remote, or difficult to access locations.

**Previous Studies**

Previous studies are insufficient in researching and discussing whether the location of the build in 3DP influences the final products. However, some scholars have discussed other reasons for variation and quality when it comes to finished products. Ollison and Berisso (2010) researched if the orientation of the build effects the outcome using ZCast build material with a ZCorp 310 printer. It turned out that the direction was a factor that had a significant influence on their final product.

**Sample Size Validity**

There are many arguments about the size of samples needed when conducting statistical research. According to William Gosset's rule of thumb, to have a valid study with normal distribution levels, researchers need at least 30 samples. Box (1987) discussed how and why this theory started. First, he began with a brief history of how Gosset and Fisher came up with the rule of thumb that requires at least 30 examples. One of the reasons that the rule of thumb of 30 became popular is that computers were not able to be utilized statistically, so tables were used to determine the cut-off points. The author also talked about the misconception of the rule of thumb. Having 30 samples ensures that the researcher has enough examples to have a study that contains a normal distribution.

**ANOVA Studies**

ANOVA is a set of statistical formulas used to calculate the variance of several parts or products (Miller Jr, 1997). Biologist Ronald Fisher first introduced the ANOVA test. ANOVA works by testing the means of the groups and then creating the t-test to determine the statistical significance of the scores calculated. At least 30 samples are necessary to have a valid ANOVA test with a normal distribution. (Miller Jr, 1997)

# Methodology

## Procedure

The goal of this study was to determine whether the location of the build on the 3D printer's envelope influences the accuracy of the products when using a Stratasys BST768/SST768 3D printer. The researcher designed, printed and measured multiple products built on different locations of the printing surface.

In the designing phase, the researcher designed and determined the size and the material of the product. The design was small and simple, setting the design dimensions at X = 25.4 mm, Y = 25.4 mm and Z = 25.4 mm. The design allowed the researcher to print more than one product in a single run while minimizing time and cost. The total weight of the initial design was 20.5 g based on the calculation of the material's density. The researcher subtracted the weight of the indentations used as markers from the total weight to get the exact volume of the product.

$$W_{TC} - W_I = W_{FC} \quad (1)$$

$$W = D \times V \quad (2)$$

$D$ of ABS plastic = 1.25 g/cm$^3$

$$V = (X)\,(Y)\,(Z) \quad (3)$$

$W_{TC}$ = the total weight of the initial cube

$W_I$ = the weight of the indentation

$W_{FC}$ = the final weight of the cube

$W$ = weight

$D$ = density of the material

$V$ = volume

$V = (25.4)\ (25.4)\ (25.4) = 16.4$ g

$W_{TC} = (1.25)\ (16.4) = 20.5$ g

To calculate the cut of the corner which was shaped as a triangle, the researcher calculated the base and height first to get the area of the triangle.

$$A^2 + B^2 = C^2 \qquad (4)$$

$(0.25)^2 + (0.25)^2 = C^2$

$.0625 + 0.625 = C^2$

$.125 = C^2$

$C = 0.3535533" = 8.98$ mm

To calculate the area of the triangle:

$$A = (1/2)\ (B)\ (H) \qquad (5)$$

$A$ = area

$B$ = base

$H$ = height

$A = (1/2)\ (4.49)\ (4.49) = 10.08\ \text{mm}^2$

To get the weight of the cut piece:

$$(A)\ (H_c)\ (D) \qquad (6)$$

$H_c$ = height of the cube

$(10.08)\ (25.4)\ (1.25) = 3.2$ g.

To calculate the area of the circle:

$$A = (4)\ (\text{pi})\ (\text{R})^2 \qquad (7)$$

$R$ = radius

$A = (4)\ (3.14)\ (1.587)^2$

$A$ = 31.66919069 / 2 = 15.8345953 mm$^3$

$W$ = (15.83459) (1.25) = .0197893 g

The total estimated weight of the product was:

20.5 – 3.2 – 0.019 = 17.281 g.

Before proceeding with the printing stage, the researcher performed a Gage R&R study of the measurement devices. Gage R&R is usually helpful to test the repeatability and reproducibility of measurement devices. In this study only one operator recorded the data, making reproducibility unnecessary. Therefore, the researcher conducted a study of Gage repeatability to make sure that the devices were accurate and would not introduce any false data into the study.

To measure the four different areas tested in this study (height, width, depth, and weight), the researcher needed to use two devices: a digital caliper to measure the height, width, and depth and a digital scale to measure the difference in weights. To record the weight of the products, the researcher used a Mettler Toledo digital scale provided by the Biology Department at WKU. The maximum capacity of the scale is 220 g, with a readability of 0.1 mg, and a minimum weight of 82 mg.

After conducting Gage repeatability on the measurement devices, the researcher initiated the first run, building five different products in five separate locations on the working envelope of the Stratasys BST768/SST768. The size of the envelope is 203 x 203 x 305 mm (8 x 8 x. 12 in). After the products printed, the researcher removed them, and then cleaned the printing surface. After that, the parts were identified based on the number of the run and the location of the build. For example, the section on the top right corner of the second set is A2. A is the name of the area, and 2 identifies the second series. Upon completion of the first series, the researcher started the second run following the same procedure. The researcher performed six different runs with five products in each series for a total of 30 parts to have a normal distribution. After the production of the batches, the researcher recorded the necessary measurements for the ANOVA test. This test is a statistical tool to help observe the variance in a set of parts, or products.

After recording the data, the researcher divided the parts into five different groups (group A, B, C, D, and E). Group A will have all the products built on location A; group B will have all the products produced in group B, etc. Since the researcher used each location six times, each group had six products. The researcher performed an ANOVA test on each product measuring height, width, depth, and weight.

Creating groups simplified the process of recording the data into Excel speeding up the development of an ANOVA test for each location. After conducting the ANOVA test, the experiment yielded an F score and a P score. The F score determined if the means between the groups was significantly different. The P score showed the calculated probability of finding the projected side of the hypothesis.

**First step: Design**

Before getting to the designing phase, the researcher had to choose the dimensions of the product. The preferred size of the product was X: 25.4 mm, Y: 25.4 mm Z: 25.4 mm. These measurements were selected to allow the researcher to print multiple products in one run, to reduce time, and to reduce the overall cost of the experiment. Determining the size of the product made it easier to decide which measuring devices to consider. Also, the simple design reduced the error of the measurement phase. The product had a circle (3.175mm diameter) and 2mm deep indention on the top and a cut (6.35 mm) on one of the corners (see figures 1, 2 and 3). These two indentations were utilized to help the researcher determine the orientation of the product. Based on the given information of the used material, the weight of the product should have been 17.281 g. The printer Stratasys (BST 768/ SST 768) used ABS plastic in this experiment.

*Figure 1*. Top of the product.

*Figure 2*. Bottom of the product.

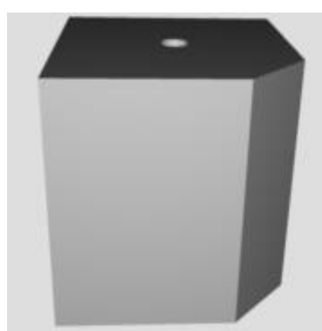

*Figure 3*. Top and side of the product.

**Second step: Gage R&R**

Once the design stage was ready, the researcher tested the measurement devices. After choosing the measurement devices for the properties measured (height, width, depth, and weight), Gage repeatability was conducted to check if the measurement devices were ready for the measurement step. The research lacked having Gage's reproducibility tested with the measurement devices due to a single operator recording the data. The researcher used a digital caliper to measure the height, width, and depth. This study also used a digital scale to measure the weight of the products. To test the repeatability of the caliper, the researcher used three different cera gage blocks 1", 1.2" and .9". The measurements convert to mm 25.4 mm, 30.48 mm and 22.86 mm. The researcher performed the test using three different US currency coins, a penny which weighs 2.5 g, a nickel which weighs 5.00 g and a dollar which weighs 8.1 g, using specifications on the US Mint website, was used to check the repeatability.

**Table 1. Gage Repeatability Measurements (Caliper)**

| Attempt | Size (25.4mm) 1” | Attempt | Size (30.48mm) 1.2” | Attempt | Size (22.86mm) 0.9” |
|---|---|---|---|---|---|
| 1 | 25.15 | 1 | 30.48 | 1 | 22.83 |
| 2 | 25.4 | 2 | 30.48 | 2 | 22.86 |
| 3 | 25.4 | 3 | 30.48 | 3 | 22.86 |
| 4 | 25.4 | 4 | 30.48 | 4 | 22.85 |
| 5 | 25.4 | 5 | 30.45 | 5 | 22.88 |
| 6 | 25.61 | 6 | 30.48 | 6 | 22.89 |
| 7 | 25.4 | 7 | 30.48 | 7 | 22.86 |
| 8 | 25.4 | 8 | 30.48 | 8 | 22.87 |
| 9 | 25.4 | 9 | 30.48 | 9 | 22.86 |
| 10 | 25.35 | 10 | 30.48 | 10 | 22.86 |
| Average | 25.391mm | Average | 30.477mm | Average | 22.862 |

Placing the average of each set in the following formula calculates the accuracy of the caliper.

$$A = Xbar_m - X \tag{8}$$

$A$ = accuracy

$Xbar_m$ = average

$X$ = actual size

Caliper accuracy of the first set = 25.391 – 25.4 = -0.009 mm

Caliper accuracy of the second set = 30.477 – 30.48 = -0.003 mm

Caliper accuracy of the third set = 22.862 – 22.860 = 0.002 mm

The previous Gage study indicated that the caliper would not cause any variation or error in the study.

**Table 2. Gage Repeatability Measurements (Scale)**

| Attempt | weight<br>Penny<br>2.50g | Attempt | weight<br>Nickel<br>5.00g | Attempt | weight<br>Dollar<br>(coin)<br>8.10g |
|---|---|---|---|---|---|
| 1 | 2.50 | 1 | 5.00 | 1 | 8.12 |
| 2 | 2.50 | 2 | 5.01 | 2 | 8.11 |
| 3 | 2.53 | 3 | 5.00 | 3 | 8.09 |
| 4 | 2.49 | 4 | 4.99 | 4 | 8.10 |
| 5 | 2.50 | 5 | 4.98 | 5 | 8.12 |
| 6 | 2.50 | 6 | 5.01 | 6 | 8.08 |
| 7 | 2.49 | 7 | 5.00 | 7 | 8.10 |
| 8 | 2.51 | 8 | 5.01 | 8 | 8.10 |
| 9 | 2.49 | 9 | 4.99 | 9 | 8.09 |
| 10 | 2.49 | 10 | 5.01 | 10 | 8.09 |
| Average | 2.50g | Average | 5.00g | Average | 8.10 |

The same formula was used to determine whether the scale was in good shape.

Scale accuracy of the first set = 2.5 – 2.5 = -0.00 g

Scale accuracy of the second set = 5.00 – 5.00 = 0.00 g

Scale accuracy of the third set = 8.10 – 8.10 = -0.00 g

**Third step: Printing**

After testing the measurement devices, the researcher determined the location of the build inside the printer working envelope. Five different locations were used to determine whether the location will influence the accuracy of the build.

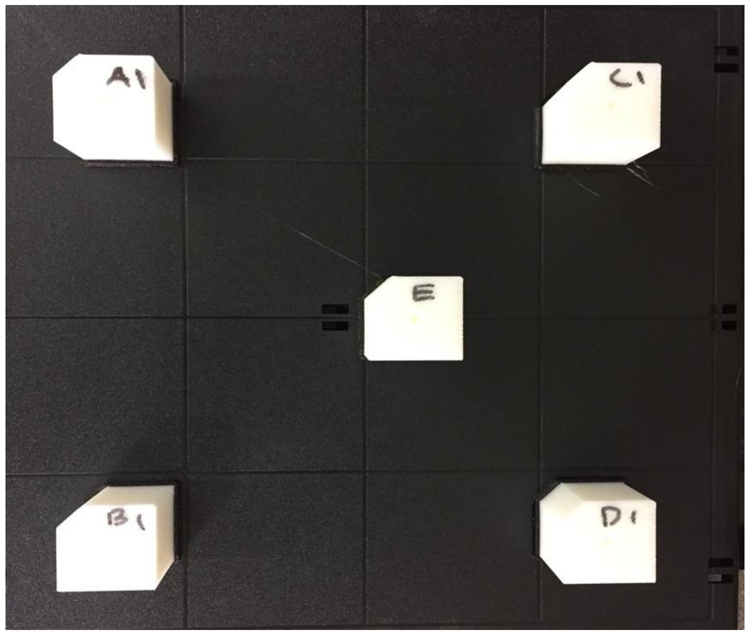


*Figure 4*. Top of the building table inside the 3D printer.

It was decided to name each product after its location (A, B, C, D, and E). This step helped the researcher to determine which product came from which site to group them when conducting the ANOVA tests. The organizational placement of each letter is as follows: A is in the top left corner, B is in the bottom left corner, C is in the top right corner, D is in the bottom right corner, and E is in the middle. Since the researcher performed five different runs, each product had a name consisting of a letter and a number. The alphabetical character indicated the location and the number determined the series. For example, the name of the product in the top left corner of the second run would be A2. The researcher took the products out after each run, cleaned the printing surface, named and numbered each product after each cycle until the 30 products were ready. A pocketknife and a cleaning station helped in removing the supporting material from the surface of the parts. The researcher also recorded the modeling material remaining in the printer as well as the supporting material before and after the build. Time of each run was careful kept ensuring that each cycle used the same amount of material, and had the same build time.

**Fourth step: Measurement**

In this stage, the researcher had all 30 products cleaned and ready for the measurement phase. To reduce human error, the researcher measured the products randomly and then recorded the measurements in a separate sheet before plugging in the numbers into Excel for the ANOVA tests. To avoid variations, the researcher started recording the data using the same devices on the same day and in the same place.

**Table 3. Products Measurements**

| Number of the product | Weight | Width | Depth | Height |
|---|---|---|---|---|
| A1 | 15.12 | 25.30 | 25.41 | 25.42 |
| A2 | 15.14 | 25.33 | 25.33 | 25.42 |
| A3 | 15.13 | 25.30 | 25.30 | 25.43 |
| A4 | 15.12 | 25.35 | 25.33 | 25.45 |
| A5 | 15.12 | 25.31 | 25.42 | 25.45 |
| A6 | 15.12 | 25.32 | 25.35 | 25.46 |
| B1 | 15.14 | 15.14 | 25.33 | 25.45 |
| B2 | 15.13 | 15.13 | 25.27 | 25.49 |
| B3 | 15.12 | 15.12 | 25.25 | 25.49 |
| B4 | 15.12 | 15.12 | 25.30 | 25.43 |
| B5 | 15.12 | 15.12 | 25.30 | 25.45 |
| B6 | 15.11 | 15.11 | 25.36 | 25.48 |
| C1 | 15.09 | 25.34 | 25.27 | 25.46 |
| C2 | 15.11 | 25.36 | 25.39 | 25.46 |
| C3 | 15.11 | 25.35 | 25.32 | 25.46 |
| C4 | 15.11 | 25.32 | 25.30 | 25.45 |
| C5 | 15.10 | 25.34 | 25.30 | 25.44 |
| C6 | 15.10 | 25.35 | 25.32 | 25.44 |
| D1 | 15.12 | 25.31 | 25.40 | 25.45 |
| D2 | 15.13 | 25.30 | 25.30 | 25.47 |
| D3 | 15.12 | 25.28 | 25.41 | 25.45 |
| D4 | 15.13 | 25.30 | 25.33 | 25.45 |
| D5 | 15.11 | 25.27 | 25.35 | 25.47 |
| D6 | 15.11 | 25.30 | 25.35 | 25.46 |
| E1 | 15.12 | 25.45 | 25.27 | 25.45 |
| E2 | 15.14 | 25.47 | 25.25 | 25.47 |
| E3 | 15.13 | 25.43 | 25.32 | 25.42 |
| E4 | 15.12 | 25.41 | 25.30 | 25.48 |
| E5 | 15.13 | 25.42 | 25.28 | 25.46 |
| E6 | 15.13 | 25.45 | 25.29 | 25.46 |

## Findings

After recording the measurements, the data was transferred to Microsoft Excel to start the ANOVA tests. The goal was to examine the variance within the groups, as well as between groups. ANOVA tests are also used to determine the F and P scores; those scores determine how statistically significant the variation was.

**Table 4. Weight ANOVA**

| **Group A** | **Group B** | **Group C** | **Group D** | **Group E** |
|---|---|---|---|---|
| A1= 15.12 | B1=15.14 | C1=15.09 | D1=15.12 | E1=15.12 |
| A2=15.14 | B2=15.13 | C2=15.11 | D2=15.13 | E2=15.14 |
| A3=15.13 | B3=15.12 | C3=15.11 | D3=15.12 | E3=15.13 |
| A4=15.12 | B4=15.12 | C4=15.11 | D4=15.13 | E4=15.12 |
| A5=15.12 | B5=15.12 | C5=15.10 | D5=15.11 | E5=15.13 |
| A6=15.12 | B6=15.11 | C6=15.10 | D6=15.11 | E6=15.13 |
| Sum= 90.75 | Sum= 90.74 | Sum=90.62 | Sum= 90.72 | Sum= 90.77 |
| Mean=15.125 | Mean=15.1233 | Mean=15.1033 | Mean=15.12 | Mean=15.1283 |

**Table 5. Weight ANOVA Calculations**

| *Source* | *SS* | *df* | *MS* | *F* | *P* |
|---|---|---|---|---|---|
| Between groups | 0.0023 | 5 | 0.0005 | 6.0526 | 0.0008 |
| Within groups | 0.0019 | 25 | 0.0001 | | |
| Totals | 0.0042 | 30 | | | |

Since the degrees of freedom for the weight ANOVA are 5 and 25 with the confidence level of alpha 0.05, the critical value of F would be 2.60. The ANOVA calculations are showing that the P-value = 0.0008 and F value = 6.0526 which means the difference is statistically significant. The initial calculated weight in the methodology section was 17.281 g, which is almost two grams more than the actual average weight.

**Table 6. Width ANOVA**

| **Group A** | **Group B** | **Group C** | **Group D** | **Group E** |
|---|---|---|---|---|
| A1=25.30 | B1=25.27 | C1=25.34 | D1=25.31 | E1=25.45 |
| A2=25.33 | B2=25.32 | C2=25.36 | D2=25.30 | E2=25.47 |
| A3=25.30 | B3=25.34 | C3=25.35 | D3=25.28 | E3=25.43 |
| A4=25.35 | B4=25.31 | C4=25.32 | D4=25.30 | E4=25.41 |
| A5=25.31 | B5=25.31 | C5=25.34 | D5=25.27 | E5=25.42 |
| A6=25.32 | B6=25.30 | C6=25.35 | D6=25.30 | E6=25.45 |
| Sum= 151.91 | Sum=151.85 | Sum= 152.06 | Sum=151.76 | Sum=152.63 |
| Mean=25.3183 | Mean=25.3083 | Mean=25.3433 | Mean=25.2933 | Mean=25.4383 |

**Table 7. Width ANOVA Calculations**

| *Source* | *SS* | *df* | *MS* | *F* | *P* |
|---|---|---|---|---|---|
| Between groups | 0.0800 | 5 | 0.0160 | 43.8647 | >0.0001 |
| Within groups | 0.0091 | 25 | 0.0004 | | |
| Totals | 0.0891 | 30 | | | |

Since the experiment had the identical number of groups and parts, each ANOVA study had the same degrees of freedom (5 and 25) and the corresponding critical value of F, which is 2.60. The ANOVA calculations of the width showed the value of F to be 43.8647 and a P value of >0.0001. These values are considered statistically significant.

**Table 8. Depth ANOVA**

| **Group A** | **Group B** | **Group C** | **Group D** | **Group E** |
|---|---|---|---|---|
| A1=25.41 | B1=25.33 | C1=25.27 | D1=25.40 | E1=25.27 |
| A2=25.33 | B2=25.27 | C2=25.39 | D2=25.30 | E2=25.25 |
| A3=25.30 | B3=25.25 | C3=25.32 | D3=25.41 | E3=25.32 |
| A4=25.33 | B4=25.30 | C4=25.30 | D4=25.33 | E4=25.30 |
| A5=25.42 | B5=25.30 | C5=25.30 | D5=25.35 | E5=25.28 |
| A6=25.35 | B6=25.36 | C6=25.32 | D6=25.35 | E6=25.29 |
| Sum=152.14 | Sum=151.81 | Sum=151.90 | Sum=152.14 | Sum=151.71 |
| Mean=25.3567 | Mean=25.3017 | Mean=25.3167 | Mean=25.3567 | Mean=25.2850 |

**Table 9. Depth ANOVA Calculations**

| *Source* | *SS* | *df* | *MS* | *F* | *P* |
|---|---|---|---|---|---|
| Between groups | 0.0252 | 5 | 0.0050 | 3.2158 | 0.0223 |
| Within groups | 0.0392 | 25 | 0.0016 | | |
| Totals | 0.0645 | 30 | | | |

As mentioned previously, since all the ANOVA tests share the same degrees of freedom and the same F critical value, the depth ANOVA calculations indicate that the F and P values are statistically significant. The test showed that the F value at 4.0198, which is higher than the critical F value (2.60).

**Table 10 height ANOVA**

| **Group A** | **Group B** | **Group C** | **Group D** | **Group E** |
|---|---|---|---|---|
| A1=25.42 | B1=25.45 | C1=25.46 | D1=25.45 | E1=25.45 |
| A2=25.42 | B2=25.49 | C2=25.46 | D2=25.47 | E2=25.47 |
| A3=25.43 | B3=25.49 | C3=25.46 | D3=25.45 | E3=25.42 |
| A4=25.45 | B4=25.43 | C4=25.45 | D4=25.45 | E4=25.48 |
| A5=25.45 | B5=25.45 | C5=25.44 | D5=25.47 | E5=25.46 |
| A6=25.46 | B6=25.48 | C6=25.44 | D6=25.46 | E6=25.46 |
| Sum=152.63 | Sum=152.79 | Sum=152.71 | Sum=152.75 | Sum=152.74 |
| Mean=25.4383 | Mean=25.4650 | Mean=25.4517 | Mean=25.4583 | Mean=25.4567 |

**Table 11 height ANOVA Calculations**

| *Source* | *SS* | *df* | *MS* | *F* | *P* |
|---|---|---|---|---|---|
| Between groups | 0.0024 | 5 | 0.0005 | 1.5431 | 0.2126 |
| Within groups | 0.0077 | 25 | 0.0003 | | |
| Totals | 0.0101 | 30 | | | |

On the other hand, the height ANOVA calculations indicated that the value of F at 1.5431 is lower than the F critical value (2.60). The ANOVA test also calculated the P value which was 0.2126. These values are considered statistically insignificant.

## Conclusion

The goal of this experiment was to determine whether the location of building products inside the 3D printer at the School of Engineering and Applied Science Laboratory affected the parts. The areas that the researcher focused on are height, width, length, and weight. The idea was to print multiple components in different locations using the same design and specifications then check if there is a variation between them. Based on William Gosset theory, and to have a normal distribution, the researcher had to build at least 30 parts.

To answer the questions of the study, the researcher had to go through a few steps. First, the design of the product was as simple as possible to ease the process of the build when it comes to time and materials. Keeping the design simple also helped in reducing the human error when taking measurements. The parts were set to be a simple one-inch cube all the way around (25.4 mm) with a cut on one of the sides and a small sphere cut on the top. Those two indentations were utilized to help the researcher to determine the orientation of the parts.

Before starting the printing phase, the researcher identified ABS plastic as the type of the modeling material used in the experiment. The density of this material is 1.25 $g/cm^3$, the estimated weight for each part was 20.5 g. However, after calculating the weight of the indentations and subtracting it from the total weight of the cube, the final initial weight was 17.281 g. Moreover, the researcher named and numbered every part made right after each set. Five different locations were used in six sets to produce 30 pieces. Each section has a name consisting of a letter and a number.  The alphabet character determines the position of the component inside of the printer and the numeral character identifies from which sequence the part originated. For example, the product D3 means that this product came from location D of the third run.

To start the printing phase, the researcher had to transfer the design from the CAD software to the printers' software and determine the location and the number of parts needed for each run. The printer took 4 hrs. and 21 min. to complete each cycle. Few obstacles arose removing the supporting material from the actual parts removing the necessity of having a cleaning station. However, in some cases, the researcher used a pocketknife to remove some of the supporting materials from the pieces and the printing surface.

Before recording measurements, the researcher conducted a Gage R&R study to make sure that the measuring devices would not introduce any falls data into the study. The research needed Gage repeatability, as only one operator recorded the measurements. After conducting the Gage repeatability study, it turned out that the measuring devices were in good shape and ready for the measurement phase.

The researcher recorded the measurements needed, height, width, depth, and weight, in the same place at the same time to prevent any uncontrolled variation. After recording the measurements, the researcher noticed some variations in the properties tested, especially in weight. The calculations of the final estimated weight came out as 17.281 g; however, the actual weight of the parts was fluctuating from 15.10 g to 15.12 g. The way the head inside the printer works could be the reason behind the variation in weight as some air could enter between the layers of the products.

The researcher then transferred all the recorded data into Microsoft Excel to start the ANOVA test. Four different ANOVA studies examined the height, width, depth, and weight. Since the experiment has the same number of parts and groups, the four ANOVA tests shared the same degrees of freedom (4 and 25) and the same F critical value (2.60). The results of the ANOVA tests showed that the calculated F and P values are statistically significant for the width, depth, and weight. On the other hand, the calculated P and F value for the height were statistically insignificant.

**Suggestions for Further Research**

A few recommendations can be made to revalidate the data gathered from this study.  The researcher noticed some of the proposals during the testing and some after the experiment. The first suggested change had to do with the printing surface inside the Stratasys 3D printer used in this test. The manufacturer of the printer recommends changing the printing surface after each use no matter how big or small the project is. Using the same printing surface for each cycle could have introduced some variation into the study and could be avoided in the future.

Another suggestion that would be helpful for further research is to anchor the printer. The researcher noticed that the printer was vibrating during the printing phase. The printer weighs 136 kg (300 lbs.) and is on a small table that is not attached to the ground. Setting the printer on a bigger, more substantial and more stable table would help prevent this issue from reoccurring.

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