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Manufacturability of Mechanical Structure Fabricated using Entry Level 3D Printer

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ABSTRACT

3D printing or also known as additive manufacturing (AM) processes fabricate complex mechanical structures by using deposition of the filaments layer by layer technique. AM process has a good capability to fabricate the complex structure compares to conventional machining. However, there is limited design guideline for AM even for the most used AM technique which is fused deposition modeling technique (FDM). Thus, in this paper, various mechanical structures such as overhangs, bridges, wall thickness, hole diameter and vertical wire diameter were fabricated to study the manufacturability of the design structure fabricated by entry level 3D printer using polylactic acid (PLA) material. The parts manufactured were then measured to evaluate the dimensional accuracy and deviations between 3D computer-aided design (CAD) and nominal data. Based on the results, design guidelines for each respective mechanical structure have been recommended.

Keywords: *Design for Additive Manufacturing (DFAM), Additive Manufacturing (AM), Design Guideline, Fused Deposition Modeling (FDM)*

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Introduction

3D printing or additive manufacturing (AM) is a process of manufacturing the physical parts layer by layer using the strand of deposited filament. The process ranged from object geometry through digital information. The parts are fabricated through the adjustment of parameter settings such as layer thickness, the path pattern, path angle and others. In the AM process, before the part is being fabricated, there is a certain issue in design for assembly (DFA) and design for manufacturing (DFM) that need to be considered. Two important factors that need to consider when designing the part for development are the design and manufacturing, where the technical teams need to consider the manufacturability factors because it will affect the design feasibility for the final products. However, there is always a gap between design and manufacturing operations, which leads to the increase of the production time and costs. During the early stages of product development, the concepts of DFM and DFA were developed to ensure the manufacturability can be implemented so that the production cost can be minimized [1]. Thus, in order to identify the problem of DFM and DFA, the proper design guideline that referring to the specific manufacturing process is usually being developed, but the other factors such as the dimensional accuracy, geometric tolerance, and the raw materials need to be considered too [2].

The aim of this research is to develop the DFM design guideline for AM because this process has great potential to become a mainstream manufacturing process due to its technology advancement [3]. Since the AM process is different compared to the conventional method, thus it has the advantage of fabricating a complex part easily due to the layer by layer manufacturing process. Currently, a number of AM technology are being used in the industry such as fused deposition modeling (FDM), streolithography (SLA), selective laser sintering (SLS), direct metal laser sintering (DMLS) and others [4]. FDM is one of the leading AM processes which is used by a domestic consumer and low-cost industry to fabricate plastic parts instantly. However, there is certain feature that has difficulty to fabricate using the FDM method, which is an overhang, and it needs some optimization and improvement in terms of the process parameter and design manufacturability. Hence, the proper development of design guideline for basic features in FDM is discussed in this study.

FDM has a limitation in printing unsupported structure such as the overhangs due to the layer by layer technique. In FDM, parts are being built layer by layer in horizontal and vertical, thus for each layer, there must be a support base before newly layered being deposited. Features that are not supported are known as unsupported overhangs and it happens because the outer layers are hanging. Overhangs structure are usually failed to print because there are no supports under the hanging parts. It produces the unwanted effects such as falling out filament, sagging and the part is totally destroyed and cannot be used [5,6,7]. Apart from that, the process has other limitations such as limited thickness, roundness and other. This study focuses on the FDM technique used in AM. However, there were lack of literature review regarding the design guideline for FDM. Thus, the study reported by the previous researchers on other AM technique were being discussed. The staircase effect is the most crucial issue to discuss in the AM technique due to the adhesion layer, and other findings showed the direct relationship between the staircase effects towards the design manufacturability. This includes the flatness tolerances, cylindrical tolerances, layer thickness and built orientation [9,10,11]. Penga et al conducted a study on the fabrication of thin wall metal parts and explained the relationship between the built height and the accuracy of complex thin wall metal [12]. The benchmarking design was proposed to investigate the wall thickness towards the thermal warping. Moreover, the thermal distortion of the printed parts was also being discussed and analyzed [8,13,14].

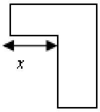
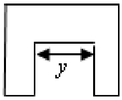
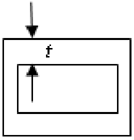
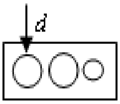
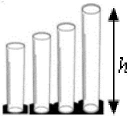
Klahn et al presented a list of criteria to take into considerations when designing for AM part and illustrated the redesign process on the various sample parts [15]. Seepersad et al fabricated the plastic material using laser sintering process and developed the design guideline to improve the manufacturability. However, the design guideline was not applicable to FDM due to the difference of the physical properties [16]. Furthermore, Adam et al developed the design rules which can be applied to laser sintering, laser melting and FDM process by investigating the complex features from three different elements consisted of the basic element, element transitions and aggregated structures. The basic element was an elementary geometrical shape or shapes that were easy to fabricate. Meanwhile, element transitions were the combination between basic elements and another feature to make the joints. Aggregated structure was the arrangement of two or more basic structure such as the overhangs. The details about certain features that were crucial for each type of process were provided and suggested in the guideline [17]. The establishment and development of AM technology inspired many researchers to develop a new approach specifically for AM. Ponche et al developed and proposed the idea of a new numerical chain-based design method to find the optimal geometry in terms of functionality. However it still considered on the manufacturing process parameters [18]. Several attempts have been made by researchers to improve the manufacturability through topology optimization process. Zhou et al did a study on the casting and manufacturing using the extrusion process and presented designs with increased in manufacturability [18]. The optimization process would also overcome the overhang constraint by a Heaviside project scheme and algorithm optimization using a sensitivity method [19,20,21].

Meanwhile, Hietikko et al studied on the complex part to fabricate using AM technology and analyzed the data using finite element analysis (FEA) to identify the design that has the manufacturability value for AM process [22]. Although AM provided lots of potential and benefits, the insufficient availability of the design guideline for AM have been discussed comprehensively. In order to the understand the behaviour of AM, many researchers conducted studies on the formation of the first and single layer as it was the basis of 3D structure as explored in [23,24] since the formation process contributed to the strength and porosity [25]. However, these researches concentrated on the formation and design guideline for laser melting process. There is a lack of studies that focuses on FDM process. Thus, this study has made an attempt to focus on the development of design rules for FDM technique. This FDM design guideline which is developed in the study can be used as a standard reference on the capability of the process. This is because FDM has specific characteristics and limitation that were different from the other AM techniques. Some of the features based on certain quality characteristics are fabricated in order to analyze the manufacturability. The overhangs, bridges, supported wall thickness, hole diameter, and wire diameter were the selected features for this study.

Methodology

In this paper, a set of FDM design guideline was developed for thermoplastic material based on the relevant literature review. The specimens were fabricated using an entry level or also known as low cost 3D printer. The material that being used was polylactic acid (PLA) and five different features were studied. After the specimens were fabricated, each specimen was measured and compared with the CAD data and the printed parts. In order to identify the suitable element structure, the qualities of manufactured specimens were examined through the visual inspection and evaluated. All the samples tested dimension were taken according to the guide given in the following Table 1.

Table 1: Details description of the structures used in the study

Structure	Overhangs	Bridges	Wall thickness	Hole diameter	Wire diameter
Feature					
Guide	Length, *x*	Length, *y*	Thickness, *t*	Diameter, *d*	Height, *h*
Dimension range, mm	0.2 to 24	20 to 100	0.5 to 3.0	0.5 to 3.0	10 to 60

Development of design guideline

The nature of the AM build process gave rise to unique considerations when designing the parts. The support structures, surface finish, wall thickness and stair stepping needed to be examined when developing the design guideline and considered in the part design. Standard triangulation language (STL) is a format used to generate the information to produce these 3D models. In order to get the appropriate part design, the angle, deviation and also the roughness and smoothness of the part need to be controlled. From the STL file, the part can be successfully fabricated by using the 3D printer however there were also some issues regarding the DFM concept that needed to be taken into consideration. Thus, the design rule development was to provide the suitable ranges within the standard elements attributed. In order to examine the best value settings, standard elements were manufactured with different values. The parameter setting of the entry level 3D printer is listed in Table 2. The infill density is the percentage of a material that is deposited on the part fabricate while starting angle is the angle on nozzle pathway to extrude the filaments.

Table 2 : FDM process parameters of entry level 3D printer and specifications

Specifications	Parameters
Machine	Prusa 3D printer
Material	Thermoplastic, PLA
Layer thickness	0.18 mm
Infill density	70 %
Angle	45 degree
Speed	70 mm/s

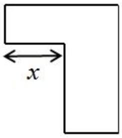
Results and Discussion

The visual inspection and comparison to nominal values were made after the part was fabricated. Generally, all of the specimens were successfully fabricated using a 3D printer but has limited manufacturability performance at certain dimension. The successfully built structures were being compared to the nominal structure measurement and recommendation is made on the results.

Overhang structure

Overhang structure is the structure that fabricated without any support and rafts. Thus, this part usually would fail when being printed. Rafts and support are very difficult to remove and would contributed to the waste in materials, thus it is not recommended to be used unless the functions are necessary. In this experiment, the overhangs structures were fabricated using a low cost 3D printer. The material used was thermoplastic material, PLA. The overhang structure tested have twenty-two different dimensions. After the part was fabricated, it was measured to compare the CAD and the printed parts. In order to identify the suitable length, the qualities of the manufactured test specimens were examined through the visual inspection and evaluated as shown in Table 4. The dimension of the overhang length was taken according to the guide of “x” as tabulated in Table 3.

Table 3: Details descriptions of the overhang feature

Overhang	Specifications
Feature	
Guide	Length, *x*
Dimension range, *x*, mm	0.2 to 24

The visual inspection of an overhang structure is tabulated in Table 4 after the part was fabricated. The successfully built overhang structure was compared to the nominal overhang length. The data was presented in the terms of dimensional accuracy by comparing the results from 3D CAD dimension and printed parts. Figure 1 shows the 3D CAD dimension and the successfully fabricated parts with good quality of the overhang structure at different length, *x* varied from 0.2 to 2 mm. Generally, the overhang can be fabricated using the low-cost 3D printer but restricted to a certain value of maximal length.

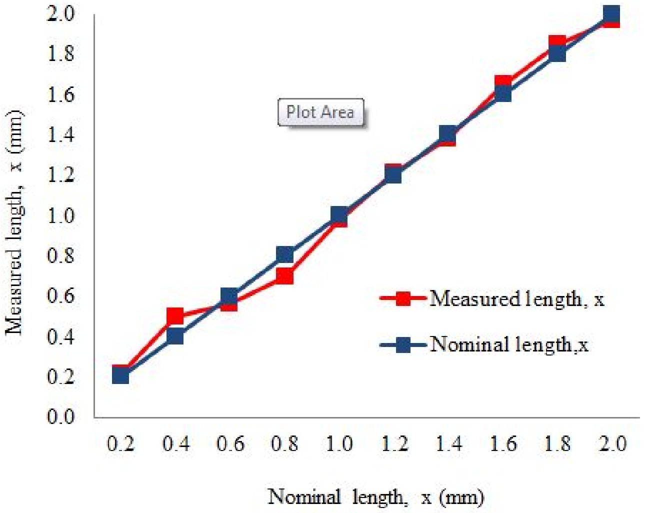


Figure 1: Length of successfully fabricated overhang structure, *x*

Table 4: Visual inspection of overhang quality

Overhang length, mm	**Quality**
0.2	Successfully fabricated
0.4	Successfully fabricated
0.6	Successfully fabricated
0.8	Successfully fabricated
1.0	Successfully fabricated
1.2	Successfully fabricated
1.4	Successfully fabricated
1.6	Successfully fabricated
1.8	Successfully fabricated
2.0	Successfully fabricated
2.2	Sagging
4.0	Sagging
6.0	Sagging
8.0	Sagging
10.0	Sagging
12.0	Sagging

14.0	Serious fall out
16.0	Serious fall out
18.0	Serious fall out
20.0	Serious fall out
22.0	Serious fall out
24.0	Serious fall out

Based on Figure 1, the overhang length does not deviate much as compared to the CAD data. The graph indicates only the successfully fabricated overhang by the range of 0.2-2mm. Meanwhile, for the rest, the measurements could not be properly taken due to the poor quality from fabricated parts because the parts have sagged and agglutinated filament was formed underneath the layers. For the overhang structure, the hanging part should be short enough to ensure the manufacturability and the filaments did not fall out from its starting position. Thus, there were some recommendations on the suitable length of the overhang structure being proposed in this study. Table 5 and Table 6 describe the general guideline on the quality images of 3D printed overhang.

Table 5: Recommended length of overhang structure

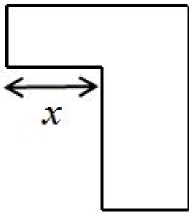
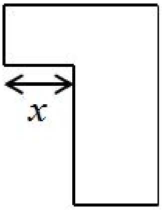
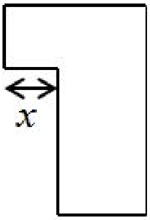
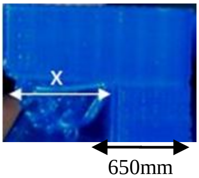
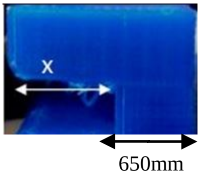
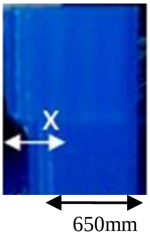
Design	**Not recommended**	**Acceptable**	**Recommended**
Feature			
Range, mm	$x \geq 14$	$2.2 \leq x \geq 13$	$x \leq 2$

Table 6: Visual images of the 3D printed overhang structure

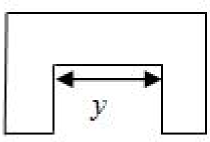
Design	**Not recommended**	**Acceptable**	**Recommended**
Feature			
Quality	Serious fall out	Sagging	Successfully fabricated

Overhang structure can be printed with good quality if the parts having 45 degrees angle. This happened because at 45 degrees, the newly printed layers were supported by the existing layer that act as a support for the angle. If the printer needed to print more than 45 degrees angle, support was required to ensure the newly printed layer did not bulge downwards. Apart from the overhang quality mentioned in the table above, curling was also happened to overhang structure. Curling occurred because of the newly printed layer became increasingly thinner at the edge of an overhang which resulted in difference cooling area causing the parts to deform upwards, forming curling effects. The proper adjustment of the parameter was recommended in order to reduce the defect of overhang part. Some adjustment setting of FDM parameters such as speed (mm/s) and temperature (C) were necessary so that the proper fabrication of hanging part can be successfully fabricated with an only minimal defect on the parts. However, it is possible to print the overhang structure with successfully fabricated quality with minimal overhang length of $x \leq 2$. When the length $x \geq 2$, the quality of fabricated parts does have some defect such as serious fallout and sagging. It depends on the requirement of the 3D printer user to choose which quality that they desire for the functionality of the final product.

Bridge structure

Bridges are defined as the flat sections that span for some area. A bridge is an overhang structure that is connected to another part of a surface with no support needed in the middle. The 3D printer can fabricate this part without support, but to certain length limitation. In order to print this type of overhang structure, the key factor that needed to be considered is the speed of printing (mm/s). The process started after the supports being printed, which then the printer would have stretched thin strands filaments between them, and it would all became parallel to each other. At this point, the sagging of filament was likely to occur and its most usual places of defects happened. In order to identify the suitable span distance for the bridge, the dimension of the span distance was taken according to the guide of "*y*" as described in Table 7.

Table 7: Descriptions of bridge feature

Bridge	**Specifications**
Feature	
Guide	Length, *y*
Dimension range, *x*, mm	20-100

The bridge parts have five differences span (length), y. The hanging components ranged from 20 to 100 mm. The inspection for printed part was based on the bridge quality and comparison between the CAD data and nominal data. The deviations were being evaluated. Similar to overhangs, the 3D printer generally can fabricate the bridge structure with a maximal range of span dimension. Table 8 shows the bridges quality based on the visual inspection and by referring to the overhang quality. Sagging happened when the nozzle extruded and deposited the filament as it strands from the end to the end of the support. The tendency of the filament to drop was higher especially at the middle area of the span.

During printing, the process started when the first couple of strands marked out of the edges of the bridge. Then, the nozzle went back and forth between the supports, which it dragged a strand of filament each time it was passed between them. At this stage, there was no real structure of the span developed and it was just a network of fine strands. For overhangs, speed was a very important process parameter. Thus, depending on the printer speed, there might be one or two strands of filament that dropped down. These defects happened when a filament strands became too hot or not under enough tension. When the temperature was too high, the structure may produce a noticeable sag. Thus, the adding loose strands from the sagging of filaments can easily be broken off and affected the finished parts. Once all of the parallel strands have been layered, the nozzle would then went back over to print a zig-zag layer across and it was depending on the setting of the 3D printer itself. The zig-zag patterns described 45-degree starting angle or known as raster angle. If the angle assigned was 90 degrees, thus the patterns would be changed into only straight line patterns. In this process, zigzagging across fine strands can produce unwanted bends and sagging since the filaments were falling out. However, this also would depend on the length of the bridge span. When the filaments were extruded, it was layered down above the bending strands and may force them to bend or even broke as it pulled across them. Some recommendation has been made in order to propose the acceptable value range for bridge fabrications in Table 9. Meanwhile, the visual image of bridges quality is shown in Table 10.

Table 8: Measured length, *y* with respect to the quality of bridges

Span length of bridges, *y* (mm)	**Quality**
20.0	Successfully fabricated
40.0	Successfully fabricated
60.0	Sagging
80.0	Serious sagging
100.0	Serious sagging

Table 9: Recommended length of bridge structure, *y*

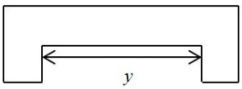
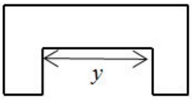
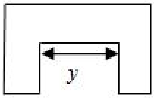
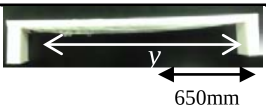
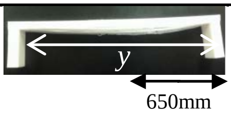
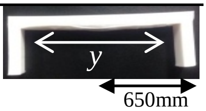
Design	**Not recommended**	**Acceptable**	**Recommended**
Feature			
Range, mm	$y > 80$	$40\leq y \geq 80$	$y < 40$

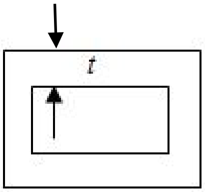
Table 10: Visual images on the bridge quality fabricated parts

Design	**Not recommended**	**Acceptable**	**Recommended**
Feature			
Quality	Seriously sagging	Sagging	Successfully fabricated

Wall thickness

In the AM process, the wall thickness is differentiated between two categories which are supported wall thickness and unsupported wall thickness. In this study, the supported wall thickness was experimented in order to know the range value of the thickness that can be fabricated using low-cost 3D printer machine. A supported wall thickness means that the wall was connected to other walls on two or more sides. The study showed that a supported wall smaller than 0.5 mm was detached away and damaged from its support during the printing process. The descriptions on the supported wall thickness were being explained in Table 11.

Table 11: Descriptions on supported wall thickness features

Supported wall thickness	**Specifications**
Feature	
Guide	Thickness, *t*
Dimension range, *x*, mm	0.5-3.0

In injection moulding, wall thickness is one of the most important aspect to consider when designing the part. The basic wall needed to be kept uniform in order to provide an even flow of the melts during the injection. By providing the uniform wall thickness, it would ensure even cooling and shrinkage distributed to control the part warpage and reduced the molded stress [26]. In FDM, the wall thickness should be consistent to avoid warp because FDM extruded very small amounts of molten material in a heated environment. However, it would not extrude all of the molten materials at once. Thus, the warping effect is one common problem in this case. Maintaining a uniform wall thickness would solve many of the plastic material manufacturing problem because when plastic melted, it flowed into the areas that have least resistance. If the parts have both thick and thin wall sections, the melting would flowed into the thick wall area first, thus caused the thin wall area to not fill in and pack properly, which would lead to high possibility for the part to warp.

Table 12: Quality descriptions on the supported wall thickness

Wall thickness, mm	**Quality**
0.5	Major defect and damaged
1.00	Minor defect
1.50	Minor defect
2.00	Successfully fabricated
2.50	Successfully fabricated
3.00	Successfully fabricated

Based on the observation during thin wall printing, it showed that the thin wall would detached away while printing process occurred. Thus, the proper wall thickness was recommended in Table 13 and visual images on the wall thickness fabricated parts is shown in Table 14. The comparison data between the nominal thickness and actual thickness (*t*), is described in Figure 2. Since the thickness of 0.5 mm was damaged, thus the only dimension that can be measured is between 1.0 to 3.0 mm. For rectangular boxes or supported wall thickness below than 0.5 mm, it would warp or detach away from the support. While, for the part that having thickness below than 0.1 mm, the part would not be able to print using the low cost 3D printer. For wall thickness, it was better to design the part with consistence support and thick as it would prevent the part from damage or shrinkage just like the injection moulding process that being described before.

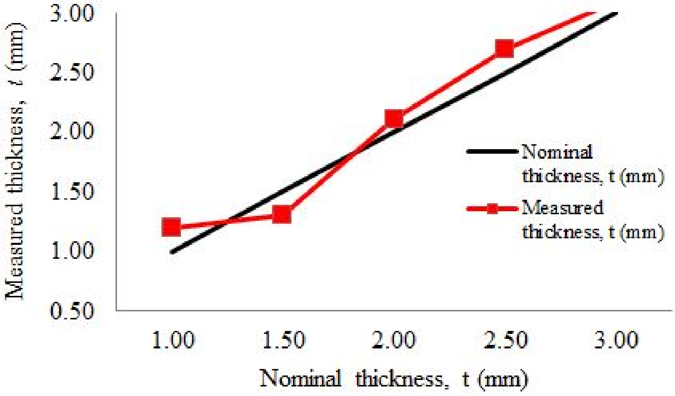


Figure 2: Measured length of successfully fabricated wall thickness, *t*

Table 13: Recommended thickness of wall thickness structure, *t*

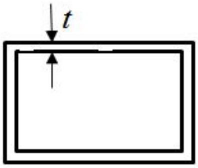
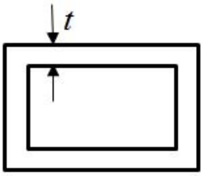
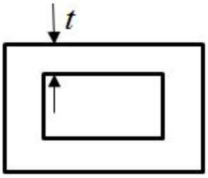
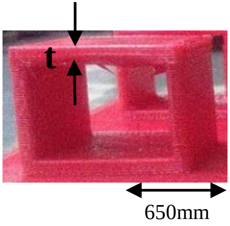
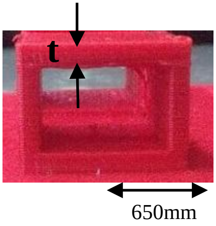
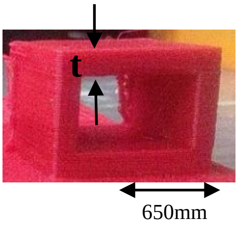
Design	**Not recommended**	**Acceptable**	**Recommended**
Feature			
Range, mm	t ≤0.5	1.5≤ t ≥2.00	t ≥2.0

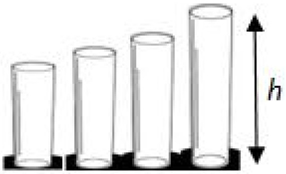
Table 14: Visual images of wall thickness structure, *t* quality

Design	**Not recommended**	**Acceptable**	**Recommended**
Feature			
Quality	Major defect	Minor defect	Successfully fabricated

Vertical cylinder or vertical wire diameter

Bakar et al [27] analysed FDM performance by measuring the surface roughness and dimensional accuracy on a few selected features. One of the experimented features was a cylinder. The results showed that horizontal surface of the cylinder was better than the vertical cylinder. It created a good surface roughness because the thin layer would produce a smoother surface compared to the thick layer. In this experiment, the vertical wire diameter (thin cylinder) was fabricated in order to identify the manufacturability of the design whether it can be successfully fabricated or not if the design has a different height. The specifications on the features are being tabulated in Table 15. The design consists of same diameter, but it has a different height started from 10-60 mm. The diameter assigned was 5 mm for all of the six features.

Table 15: Descriptions on the vertical wire diameter height, *h*

Vertical wire diameter	**Specifications**
Feature	
Guide	Height, *h*
Dimension range, *x*, mm	10-60

Vertical wire diameter or also known as vertical pins often printed in FDM process when the assembly and alignment of the parts are required. Considering that these features are often functional, it is important to consider the size and diameter of the vertical pin so that FDM able to print the parts accurately. Based on the experiment, the 3D printer managed to print up to 50 mm tall before the features started to curl. The factors that may influenced the fabrication of vertical pins were height and its diameter. In this experiment, the variable being tested was the height of vertical pins, whereas the diameter was constant for all of the six parts. The diameter assigned has a smaller diameter which was 5 mm. The 3D printer able to print the part up to 50 mm tall before the part started to curl. This happened due to several factors related to its diameter and its height. When fabricating smaller diameter, the surface area was small. Thus, the nozzle was focused onto the area while heat loss to the surrounding was slower that made the part difficult to harden. This occurred due to the solidifications process of the melted filament. When the filament extruded and formed the layer, the solidifications time needed to be faster to ensure that the layer can be hardened easily. When the existing layer has hardened, the new layer able to be fabricated and formed without defect however it constricted only to a certain maximal length.

Generally, from this experiment, the vertical pins with a small diameter can be printed up to 50 mm height. During the process of 3D printing, the fan located at the nozzle would focused on the existing layer and increased its rapid cooling, that could made the layer hardened easily. Once the height reached up to 50 mm, the part could not be printed properly due to poor solidification of the printed components. As the part height continued to increase, the cooling process getting slower and the existing layer was still soft, thus the new layer could not properly adhere to the bottom layer that led the part to curl at the end. In this case, an additional external fan is recommended. By providing the external fan, it would support the cooling process around the printing area and increase the rate of solidification process for the part printing. Furthermore, it is not recommended to print the vertical wire diameter with small area. This would result in a weak connection between the new layer and existing layer that can lead the part to break and detach from the platform due to the bad adhesion factors. The quality characteristics of the vertical cylinder was illustrated in Table 16 whereas some recommendations were provided in Table 17. Meanwhile in Figure 3, the graph indicated the height comparison between the CAD data and actual data.

Table 16: Quality characteristics on the vertical cylinder

Wall thickness, mm	**Quality**
10	Successfully fabricated
20	Successfully fabricated
30	Successfully fabricated
40	Successfully fabricated
50	Successfully fabricated
60	Curling and damage

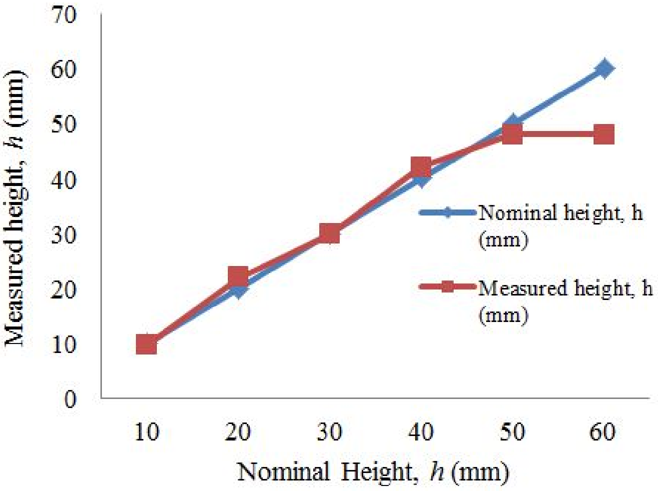


Figure 3: Measured CAD and nominal comparison of vertical cylinder height, *h*

Table 17: Recommended height of vertical cylinder, *h*

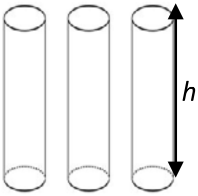
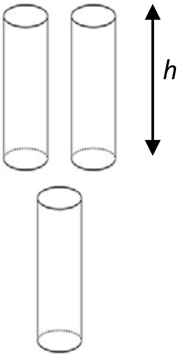
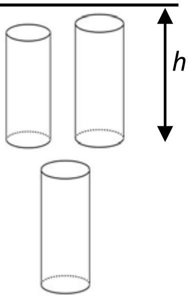
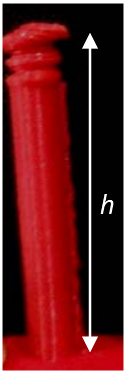
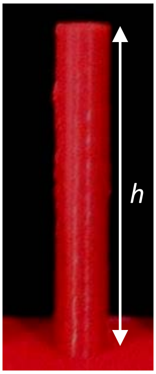
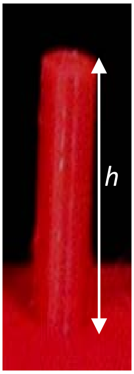
Design	**Not recommended**	**Acceptable**	**Recommended**
Feature			
Range, mm	h>50	50 ≤ h >10	h <10

Table 18: Visual images of vertical cylinder fabrication by referring to the height, *h*

Design	**Not recommended**	**Acceptable**	**Recommended**
Feature			
Quality	Curling and damage	Successfully fabricated	Successfully fabricated

Small hole diameter

Plastics expands and contracts when it is heated and cooled due to the thermal expansion and contraction of the material of plastic itself. This phenomenon will cause the dimension variation in parts fabricated using a

3D printer. Thus, the small hole diameter was the part experimented in order to test on the dimensional accuracy variations. The hole diameter was fabricated using two build orientation from xy plane and zx/zy plane. Both of the plane lay on the vertical and horizontal axis. Based on the results of the experiment, the proper fabrications of the small hole happened when it lay at the horizontal axis. The brief descriptions provided in Table 19. The dimensional variations may be caused by the filament deposition correlated to the layer thickness that was assigned to the parameter settings.

Table 19: Descriptions on the small hole diameter, *d*

Vertical wire diameter	**Specifications**
Feature	
Guide	Diameter, *d*
Dimension range, *x*, mm	0.5-3.0

Depending on the orientation of the design, the recommended minimum diameter was 1.5 mm. However, the hole diameter printed at the x, y plane (vertical axis) may not be similar to the horizontal axis because the diameter will close more holes other than the zx/xy (horizontal axis) planes. Two formula or equations to modify the dimension of the hole diameters were discussed below by researchers from the University of Texas. The equations provided as follow:

$$y= 1.0155x + 0.2795 \text{ (Vertical axis)} \tag{1}$$

$$y=0.9927x + 0.3602 \text{ (Horizontal axis)} \tag{2}$$

“x” was the value for diameter assigned while “y” was the value of adjusted diameter for the CAD model. If the value of “x” assigned was x=4, the actual value of fabricated hole diameter was 4.3415 mm, having the deviations from nominal diameter and measured diameter by 0.43415 mm. This value of deviations is still acceptable in 3D printer fabricated parts since the acceptance tolerance from 3D printed part is ±0.5 mm.± 0. 5 mm. However, in this experiment, the dimension of the hole diameters was measured practically and the results then being compared. The quality of fabricated parts evaluated in Table 20 and the measured diameter, *d* and are presented in Figure 4 and Figure 5 for vertical and horizontal diameter respectively.

Table 20: Quality evaluated on the vertical and horizontal axis of small hole diameter

Small hole diameter, *d*	**Quality on vertical axis**	**Quality on horizontal axis**
0.5	Damage	Successfully fabricated
1.0	Damage	Successfully fabricated
1.5	Near to close	Successfully fabricated
2.0	Fabricated	Successfully fabricated
2.5	Fabricated	Successfully fabricated
3.0	Fabricated	Successfully fabricated

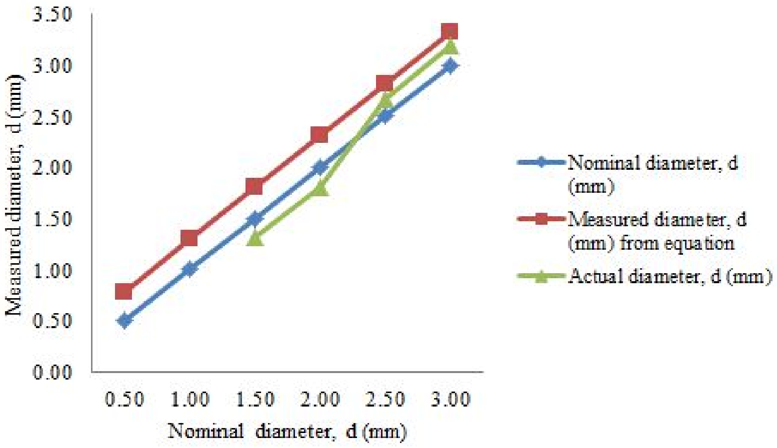


Figure 4: Comparison on the CAD data with theoretical and measurable diameter of small hole diameter, *d* for vertical axis plane

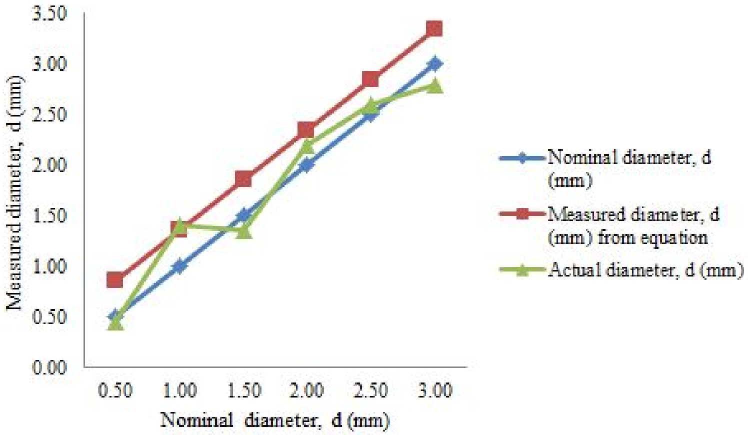


Figure 5: Comparison on the CAD data with theoretical and measurable diameter of small hole diameter, *d* for horizontal axis plane

Both of the figures above showed inconsistency for the hole diameter fabrications. For vertical axis hole diameter, generally, it can be fabricated but starting only from the diameter of 2.0 mm. While for hole diameter d ≤2mm, the hole was prone to close where the extruded filament agglutinated around the layer, made the hole covered which caused the hole to not be properly constructed as desired. Thus, the recommendation to design small hole diameter would be on the horizontal axis. If the design requirement needed to be fabricated on the vertical axis, the larger diameter needed to be assigned. For vertical axis holes, low cost 3D printer or FDM itself will often print the feature with undersized measurements. The reduction in diameter occurred because of the process of printing the holes. As the nozzle starting to print the diameter of a vertical axis hole, the new layer would compress the existing layer to improve the layer adhesions. Thus, the compressing force from surround or circle shapes would turned into a flat shape due to the compression matters. From this, it is not only help to improve adhesions but at the same time would increase the width of the extruded filaments and it resulted in decreasing the diameter of the hole printed parts. The undersized could also happened due to the parameter settings for the features and it was depending on the 3D printer from the user. The slicing software, the size of holes and materials also needed to be considered. Hence, drilling the holes may be accepted if a high level of accuracy is required. The specimens of dimensional accuracy taken for both orientation of small hole diameter are showed in Figure 6, 7 and 8.

Table 21: Recommendation diameter for small hole features, *d* in vertical axis

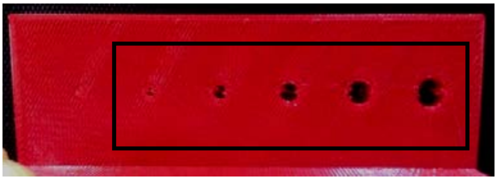
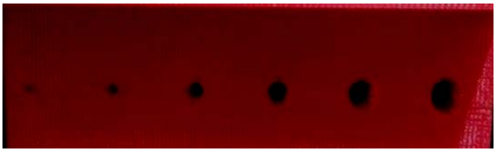
Vertical small hole diameter	**Recommendation**
Fabricated parts	
Dimension range, *d*, mm	0.5-3.0
Recommendation value, *d*	≥1.50
Not recommended, *d*	≤1.40

Table 22: Recommendation diameter for small hole features, *d* in horizontal axis

Vertical small hole diameter	**Recommendation**
Fabricated parts	
Dimension range, *d*, mm	0.5-3.0
Recommendation value, *d*	≥1.00
Not recommended, *d*	≤0.50

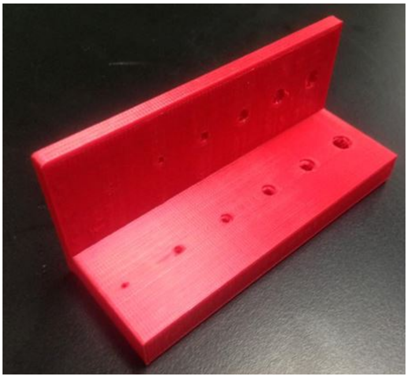


Figure 6: Specimens for small hole diameter in horizontal and vertical view

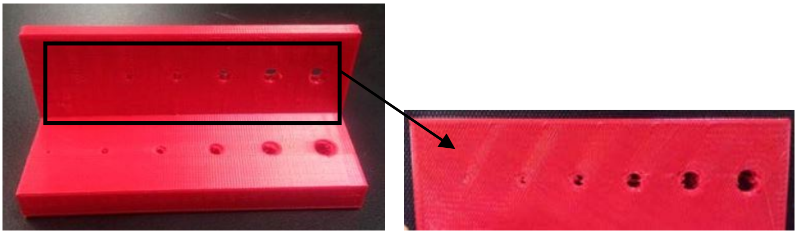


Figure 7: The vertical view of the small hole diameter fabricated parts

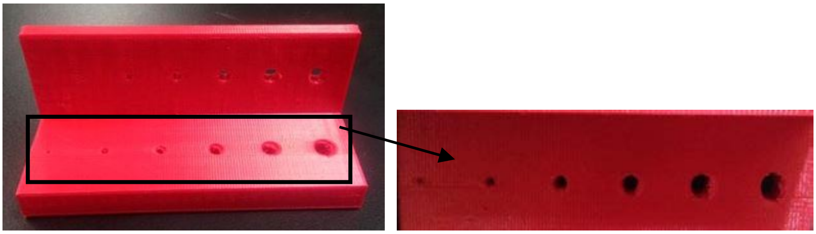


Figure 8: The horizontal view of the small hole diameter fabricated parts

Conclusion

FDM operates by extruding the thin layers of a molten thermoplastic layer by layer until the part is produced. FDM can produce a part with short manufacturing time but still maintain the good quality of the product, the system has become increasingly used to manufacture the products in the industry. In this paper, some FDM design considerations are discussed. These include overhangs, bridges, wall thickness, hole diameter and vertical wire diameter. The size and orientations were also discussed for small hole diameter. Since AM is increasingly being used as a mean to produce mechanical parts, the proper design guideline is the best alternative to provide to the user so that this technology can always be useful and to avoid laborious trial and error by designers. Each build of the design was inherently different because of the design parameters. In order to utilize FDM technology to its utmost potential, the designers need to fully understand the capabilities and limitations of the process. Producing a design guideline for the part using FDM allows creativity and flexibility and reduces the waste material. To conclude, several drawbacks must be keep in mind when designing part for FDM so that the manufacturing time can be minimized and the materials are not wasted. Many other design structures can be analyzed comprehensively in the future so the proper FDM design guideline can be developed and established.

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