# Design Challenge I: Restrictive DfAM

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BENCHMARK ARTIFACT

EDSGN562 – DESIGN FOR AM

A single CAD design will print differently depending on parameters such as layer height, orientation, layer thickness, printer model, nozzle temperature, material type, etc...
In order to analyze the limitations of Fuse Deposition Modeling (FDM, specifically using a MakerBot Replicator 5th Generation), a part must be created to accommodate Design for Additive Manufacturing (DfAM) restrictions (i.e. bridging limit, minimum feature size, self-supporting angles, etc...).
For this Design Challenge, the two dependent variables studied are minimum feature size and minimum assembly clearance. Additionally, the two independent variables handled are orientation and geometry (see Figures 1, 2, 4, and 5).

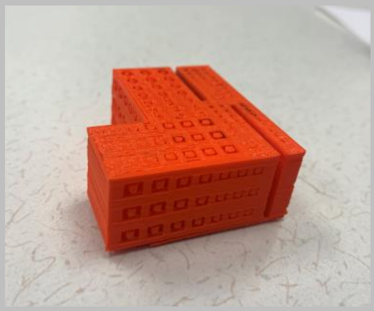

*Figure 1: Isometric View of Benchmark Artifact*

## Design

Both DfAM considerations should be printed on one part, but most independent variables (nozzle temperature, layer thickness, and other parameters that can be changed in the slicer's settings) will require more than one print. Picking geometry and orientation have allowed this to be made in one single print. The two different geometries implemented are squares and circles (cuts were used instead of extrusions to avoid the need for support material), whereas the two different orientations are XY and XZ/YZ (assuming that XZ and YZ are sideways printing and should behave similarly).
This benchmark part should be used for various AM processes. It will demonstrate the minimum feature size (1.35 to 0.15 mm, with 0.15 size reduction intervals, resulting in 9 features) and the minimum assembly clearance (0.8 to 0.05 mm, with 0.15 size reduction intervals, resulting in 6 features) before material fusing.
To evade wasting material, this design has been created to be as small as possible (50x45x19 mm), and cuts were made as need be.

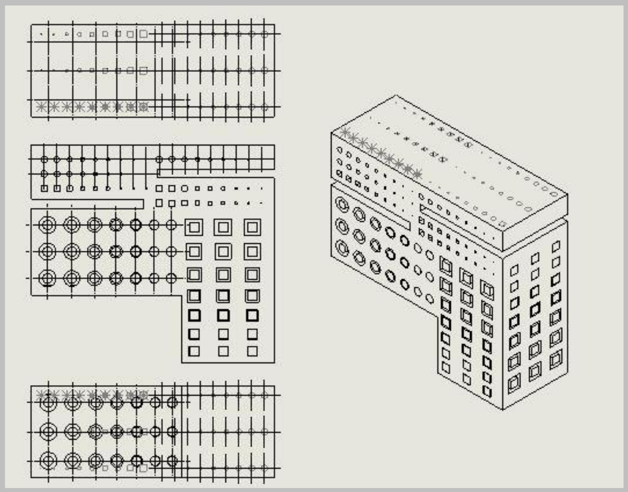

*Figure 2: CAD Drawing of Benchmark Artifact*

## Procedure

Having the printed features as cuts rather than extrusions makes it way harder to measure, especially because of their size. Since this benchmark part is to be printed and measured applying common methods (no microscopic analyses, 3D scanning, or other high-end processes), a simple way has been adopted. "Play-Doh" can mimic the features and reveal them as extrusions rather than cuts; placing the dough on a surface, applying a small force, then gently removing it will result in the imprint (Figure 3).
Using digital calipers, the features are then measured and compared with the CAD measurements, and pass/fail criteria are adopted. This part will be discussed in detail in the "Data Collection" section.

*Figure 3: Shape Imprints on "Play-Doh"*

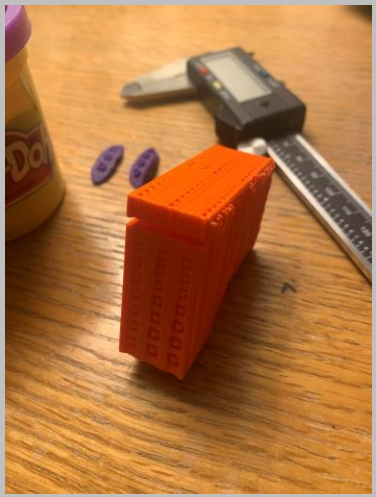

*Figure 4: General photo with the tools used*

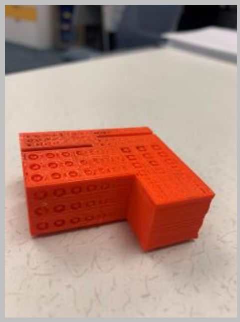

*Figure 5: Other Isometric View of the Benchmark Artifact*

## Data Collection

| | Minimum Feature Size (% error) | | | | |
|---|---|---|---|---|---|
| | 0.9mm | 0.75mm | 0.6mm | 0.45mm | 0.3mm |
| Circles (TOP PLANE) | 3.703704 | 11.11111 | 75 | 100 | 100 |
| Circles (SIDE PLANE) | 1.851852 | 2.222222 | 6.666667 | 14.81481481 | 60 |
| Squares (TOP PLANE) | 11.48148 | 19.55556 | 40 | 100 | 100 |
| Squares (SIDE PLANE) | 4.444444 | 6.666667 | 7.777778 | 14.81481481 | 55.55555556 |

*Figure 6: Pass/Fail with Minimum Feature Size*

| | Minimum Assembly Clearance (% error) | | | | |
|---|---|---|---|---|---|
| | 0.65mm | 0.5mm | 0.35mm | 0.2mm | 0.05mm |
| Circles (TOP PLANE) | 4.615385 | 10 | 13.33333 | 100 | 100 |
| Circles (SIDE PLANE) | 7.179487 | 4.666667 | 8.571429 | 15 | 100 |
| Squares (TOP PLANE) | 1.538462 | 6.666667 | 47.61905 | 100 | 100 |
| Squares (SIDE PLANE) | 4.615385 | 9.333333 | 11.42857 | 13.33333333 | 346.6666667 |

*Figure 7: Pass/Fail with Minimum Assembly Clearance*

Each dependent variable has been printed a total number of three times for each case (i.e. minimum feature size circles have been printed 3 times on the top orientation and three times on the side orientation) to establish a mean and a standard deviation.

The percentage error formula is shown below:

$$error\% = \frac{CAD\ measurement - Mean\ of\ real\ measurements}{CAD\ measurement} \times 100$$

It is chosen to be 15%; the reason behind this number is because human error, in addition to errors from the dough being malleable, is very common. When the feature has an error higher than 15%, it fails, otherwise, it is considered as a pass. This method has been applied because relating to results with the naked eye can be misleading and can differ from one person to another.

Figures 6 and 7 show the results obtained using this pass/fail criteria (green shows that the structure has printed successfully under the criteria whereas red demonstrates the opposite). This experiment is a two-level, full-factorial design (with n being equal to 2). In this study, y (also called the dependent variable, or DfAM restriction) will be divided into two parts, one for each restriction. Each y value will have two x values (also called independent variables, or parameters that should affect the print). Explanation and results will be shown in the "Statistical Analysis" section.

## Statistical Analysis

In this study, we will assume that residuals have constant variance, are independent, and are normally distributed. "ANOVA: Two-Factor with replication" is then used to formulate both F and P values.

Figures 8 and 9 represent those results.

| ANOVA | | | | | | |
|---|---|---|---|---|---|---|
| *rce of Varia* | *SS* | *df* | *MS* | *F* | *P-value* | *F crit* |
| Sample | 0.012675 | 1 | 0.012675 | 16.71429 | 0.003494 | 5.317655 |
| Columns | 0.138675 | 1 | 0.138675 | 182.8681 | 8.58E-07 | 5.317655 |
| Interactior | 0.012675 | 1 | 0.012675 | 16.71429 | 0.003494 | 5.317655 |
| Within | 0.006067 | 8 | 0.000758 | | | |
| | | | | | | |
| Total | 0.170092 | 11 | | | | |

*Figure 8: ANOVA for Minimum Feature Size*

| ANOVA | | | | | | |
|---|---|---|---|---|---|---|
| *rce of Varia* | *SS* | *df* | *MS* | *F* | *P-value* | *F crit* |
| Sample | 0.013333 | 1 | 0.013333 | 53.33333 | 8.36E-05 | 5.317655 |
| Columns | 0.168033 | 1 | 0.168033 | 672.1333 | 5.26E-09 | 5.317655 |
| Interactior | 0.0147 | 1 | 0.0147 | 58.8 | 5.92E-05 | 5.317655 |
| Within | 0.002 | 8 | 0.00025 | | | |
| | | | | | | |
| Total | 0.198067 | 11 | | | | |

*Figure 9: ANOVA for Minimum Assembly Clearance*

Having the F-value bigger than F-critical and p-value $< 0.05$ means that there are different results between the two parameters and that we can reject the null hypothesis (Both minimum feature size and minimum assembly clearance satisfy this hypothesis).

## Reflection

Changing either orientation or geometry resulted in different final structures. It is concluded that this 3D printer has a better side orientation resolution and accuracy (Figure 10 summarizes it).

Those results comply with the knowledge of AM I processes, and I think that designing a successful benchmark artifact would be very efficient for designers in analyzing DfAM concerns.

I believe that the measurement part implemented in this study is very prone to error. First, "Play-Doh" is not to be used for scientific research, measurements should be done using professional equipment, especially when they are extremely small. Another idea (if expert equipment is not available) is using dough that can be heated for hardening (like clay), to result in stiff extrusions.

For future research, I would like to have more than 2 DfAM restrictions in my model, which could significantly improve this study.

Note: All the slicer parameters were kept to default on the MakerBot Desktop slicer except for an extruder temperature of 200°C and an addition of rafts and supports. This print, being small successfully printed in a short amount of time using very minimal material (Figure 11).

| | | Top Plane | Side Plane | Individual Best | Overall Best |
|---|---|---|---|---|---|
| Minimum Feature Size | Circles | | | Better on Side Plane | Cicles on Side Plane |
| | Squares | | | Better on Side Plane | |
| Minimum Assembly Clearance | Circles | | | Better on Side Plane | Squares on Side Plane |
| | Squares | | | Better on Side Plane | |

*Figure 10: ANOVA for Minimum Assembly Clearance*

| | |
|---|---|
| Amount of material used | 18.57g |
| Print Time | 2hrs, 6 mins |

*Figure 11: Amount of material used and print time*