2.008 Team H
12/11/2024
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Yo-Yo Project Addendum Report

Introduction

Team H decided to model our yo-yo after the Spotify logo this semester. We also made a goal to put a speaker in our yo-yo to make it a more interesting design challenge for us. Based on these ideas, we created the CAD model shown in **Figure 1**.

Figure 1: Rendered image of complete yo-yo assembly modeled in Fusion. Pictured left is the yo-yo as it will be assembled and pictured right is an exploded view.

The yo-yo is symmetrical, so both sides have an injection molded body, the black piece in **Figure 1**, an injection molded green cap, and a clear thermoformed piece. These are the parts that we were explicitly required to make by the course guidelines. The cap is internally press fit into the body with the thermoformed piece seated on a lip on the press fit surface of the body under the cap. A full bill of materials can be found in Table 1.

Table 1: Bill of materials for one yo-yo of Team H's design.

Part	Quantity per yo-yo	Description
Body	2	Injection molded polypropylene (PP), press fits with cap and holds speaker
Cap	2	Green ends of toy, injection molded polypropylene (PP), internally presses into body
Thermoformed Piece	2	Clear plastic logo piece, sticks out through cap, polyethylene terephthalate glycol (PETG)
Speaker	1	Ordered from Amazon, button activated, recordable
10x24 Nut	2	Insert molded into body

Set Screw	1	⅝" set screw, holds 2 halves together
3D Printed Spacer	1	Custom part to prevent damage to bodies
String	1	Wrapped around center of yo-yo

Our team frequently divided labor to increase our efficiency as we moved through this project. It's worthwhile to note that while some people started out as the primary person in one role, many of the bigger jobs like machining and injection molding eventually became shared responsibilities for everyone on the team. In the design phase, everyone contributed to the CAD. The thermoformed part was designed by Molly and the mold was designed by Ruchitha. Drake made the cap, Sam and Hez designed the body, and Kayla designed the molds for both parts. The initial mold CAM was done by Sam. As we moved into manufacturing, work became less strictly assigned and everyone had a hand in many more areas. Initially, Sam and Hez did the machining on the CNC HAAS for our molds as they had experience in that area but others used their example and learnt to use the CNC. Ruchitha and Molly were the first ones taking on injection molding while Kayla and Hez worked out thermoforming parameters, and Drake made our shoulder bolts. When we did analysis, Molly, Ruchitha, and Kayla measured parts. Drake and Sam created the graphs. Finally, the whole team worked on the poster and report.

Manufacturing Results

Our yo-yo was designed to consist of the following components: an injection molded body and cap, a thermoformed feature to sit under the cap, and a speaker press fit in the body. An internal press fit was chosen between the body and cap. An exploded view of the yo-yo is provided in **Figure 2**.

Figure 2: Rendered image of yo-yo assembly exploded view modeled in Fusion.

The dimensions and geometry of the yo-yo were constrained by the speaker, namely the height and diameter of the body. Initially, design specifications for the critical press fit of the injection molded parts were as follows:

Body inner diameter: 2.510” +/- 0.005”

Cap outer diameter: 2.525” +/- 0.005”

Diameter interference: 0.015” +/- 0.005”

Length of press fit engagement: 0.205”

The length of engagement for the press fit interface was chosen based on a model of 0.001” interference per inch of diameter for aluminum, based on material properties such as Young’s Modulus. Because the plastic has a Young’s Modulus an order of magnitude lower (about 10x lower), we estimated an ideal length of engagement of 0.205”. The cross section of the body/cap press fit interference can be seen in **Figure 3**.

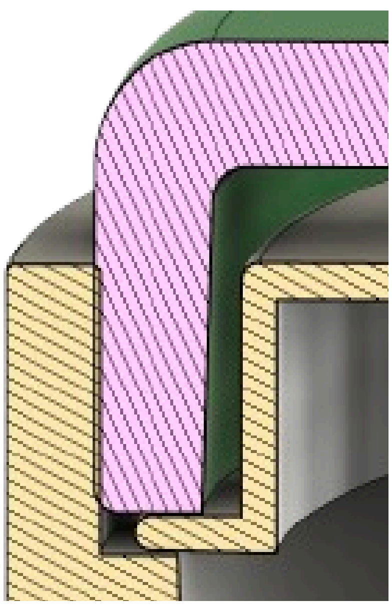

Figure 3: Cross-sectional view of the cap and body interface modeled in Fusion. Pictured left is a zoomed in view to feature the location of interference and length of engagement between the cap and body. Pictured right is a full yo-yo cross-sectional view.

A shrinkage estimate was based on the following equation:

$D_{target} = D_{scaled} - (D_{scaled})(\%_{shrinkage})$

$D_{scaled} = (D_{target}) / (1 - \%_{shrinkage})$

From investigation of the shrinkage range for polypropylene (PP), which is typically 1-3%, we proceeded with an estimated 2% shrinkage for our scaled body and cap nominal diameters. This 2% shrinkage estimate agreed with course recommendations. As a result, our scaling factor for both parts was 1.0204. Therefore the scaled diameters were:

Body inner diameter: 2.561”
Cap outer diameter: 2.577”

This scaling factor was applied to the entire CAD model, including the press fit ring for the speaker in the body. Speaker diameters were measured to be a mean of 1.724” with a standard deviation of 0.0009”.

Machine parameters were recorded in the manufacturing spreadsheet to track adjustments and as references for further mold adjustments once parameters were finalized. The first set of successfully machined body and cap molds had the following geometry compared to the scaled CAD models of the respective molds:

Body cavity: 2.695” (actual) vs 2.714” (CAD)

Body core: 2.596” (actual) vs 2.51” (CAD)

Cap cavity: 2.601” (actual) vs 2.576” (CAD)

Injection molding with these initial molds allowed for confirmation of plastic shrinkage. The outer diameter of caps measured compared to the nominal diameter design specification resulted in 1.5% shrinkage.

Following these initial mold measurements and injection molding, modifications were made for better release of parts and for surface finish. An unintended draft angle on the cap cavity was discovered and re-machined.

Once injection molding parameters were established, 100 bodies and 100 caps were made with the new molds. Statistical process control on these parts gave the following results:

Body inner diameter: $\mu = 2.543$” , $\sigma = 0.005$”
Cap outer diameter: $\mu = 2.548$” , $\sigma = 0.003$”
Diameter interference: $\mu = 0.005$” , $\sigma = 0.007$”

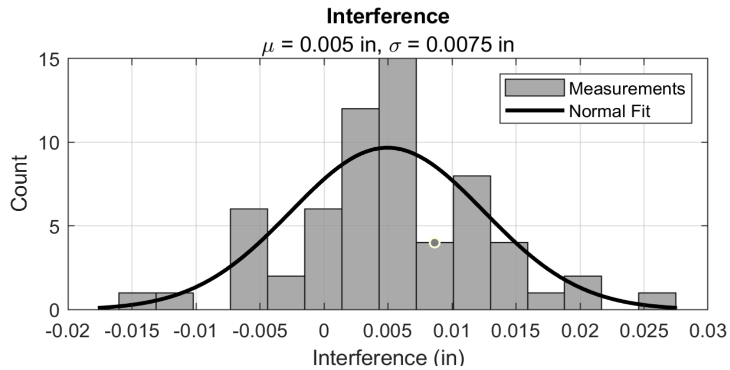

Figure 4: Interference data from the first iteration of 100 bodies and caps.

Graphical representation of the press fit interference of the initial 100 parts can be found in **Figure 4**. As the data shows, the interference was insufficient, with a mean interference of 0.005”. To achieve a better press-fit, the cap molds were modified by removing material – 0.008” increase of diameter – for a slightly larger cap. After this adjustment, 100 more caps were made and the injection molding parameters for the body were fine-tuned. Engineering analysis and statistical process control is presented below:

Body inner diameter: μ = 2.543” , σ = 0.006” , C_p = 0.28 , C_{pk} = -1.56

Cap outer diameter: μ = 2.562” , σ = 0.008” , C_p = 0.21 , C_{pk} = -0.75

Diameter interference: μ = 0.019” , σ = 0.006” , C_p = 0.28 , C_{pk} = 0.056

Figures 5 and 6 represent the spread of measurements for the body and cap diameters (**Figure 5**) and of the interference data with the new caps (**Figure 6**).

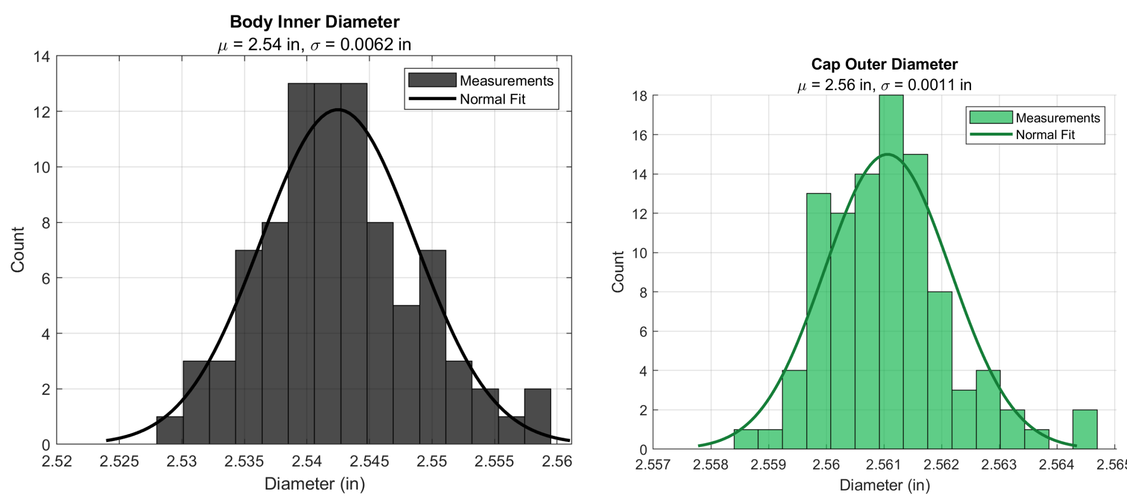

Figure 5: Shown on the left is data for the yo-yo bodies. Shown on the right is data for the yo-yo caps.

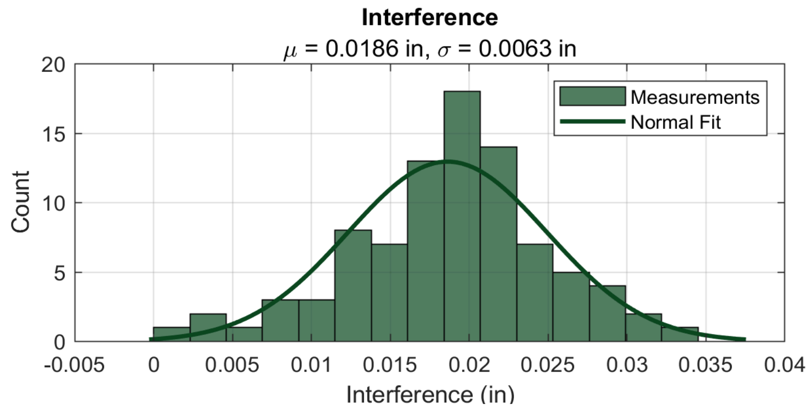

Figure 6: Interference data from the final iteration of 100 bodies and caps.

Measurements for the speaker press-fit are not presented, but also had adequate interference despite the slight draft angle that was added for part to release off of the mold due to longer length of engagement between the body's ring and the speaker.

The press-fit between the body and the cap exceeded the design specification of 0.015" +/- 0.005" but proved to be successful during drop testing. The final diameters of the body and cap also fall outside the original design specifications for nominal diameter as a result of mold modifications to achieve adequate interference.

Design, Manufacturing, and Assembly Journey

Our manufacturing journey began with the foundational stage of designing the yo-yos in Fusion360 CAD software. During this stage, we finalized the design of the yo-yo and determined the appropriate dimensions for a press fit between the cap and body and a press fit internally for a speaker. After the initial design phase, we moved to machining our yo-yo molds. This stage involved using CAD to design the molds and CAM software to program the CNC milling machines. Examples of the molds can be seen in **Figure 7**. We were able to speed up the milling process significantly by optimizing feed rates and spindle speeds on the machine.

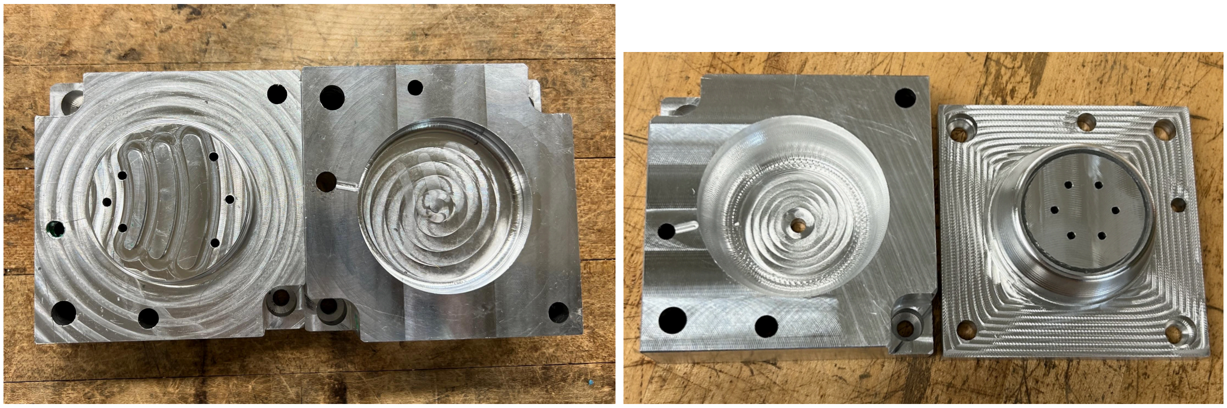

Figure 7: Injection Machine molds for the cap (left) and the body (right)

Simultaneously, we designed the mold for our thermoformed part (**Figure 8**) and quickly manufactured the 100 parts needed. With the molds complete, we moved to injection molding our 100 bodies and caps. After a few design iterations, we completed our parts and moved to finally assembling our 50 yo-yos.

Figure 8: Thermoform mold CAD (left) and final version (right)

The design and manufacturing of our 50 yo-yos was no smooth journey. We encountered our fair share of obstacles along the way; however, our engineering judgment guided us through the troubleshooting process for many of these issues.

The most prominent obstacle we faced this semester was the press fit between the cap and body of the yo-yo. Halfway through the semester, it came to our attention that there was a draft angle on the mold for the cap. We discovered this issue when testing our initial injection molded parts for the manufacturing review and noticed odd behavior on the fit. When the body and cap were squeezed, the cap would pop off, indicating a single-point contact, or a draft angle on the cap.

We were unsure of how this design flaw made its way into the mold, but regardless, we returned to machining the mold for the cap and eliminated the draft angle. With our new caps, we manufactured approximately 50 to measure and test our press fit. After collecting a confident amount of measurements, we discovered that our interference was centered around 0.005", much too small for a reliable press-fit. The distribution of this data can be found in **Figure 4**. Moving back to the CNC mill, we machined the cap mold to be larger such that our press fit was more robust. Our final iteration included a distribution centered around 0.019". This distribution can be found in **Figure 6**.

With the project now complete, it is easier to reflect on the design decisions we made throughout the semester and determine what worked and what did not. A decision we made as a team which we believe served us well was setting lofty goals and timelines, but also setting fixed dates to drop a feature if needed. For example, we knew the inclusion of a speaker inside our yo-yo would be a challenge, so we decided on a date that, in the case that the speaker was causing too many issues, we would drop it from the final iteration. Giving ourselves hefty design challenges is important, but making sure they don't disrupt other requirements is crucial.

In the same vein, keeping designs simple can alleviate unnecessary workload while maintaining an elegant solution. With the inclusion of a speaker, we knew that our work would already be cut out for us, so the remainder of the yo-yo was kept relatively simplistic. This design decision made the rest of the process smooth while also challenging ourselves.

Designing the yo-yos for a seamless assembly process was also imperative to our project. From the early stages in CAD, we made choices that eased our workload later on when it came to the assembly phase of the project (DFA). **Figure 3** demonstrates one of these early design decisions – we included a small lip on the interior of the yo-yo body to support the thermoformed piece and the yo-yo cap. Moreover, we made a decision to integrate the spacer of the yo-yo into the injection molded body to eliminate another assembly step and part. Not only did this design feature aid in assembly, but it also solved another challenge of creating enough space internally for the speaker and over-molded nut.

Scaling Up Production

Scaling production to one million yo-yos requires planning to ensure efficiency, low costs, and robust sustainability goals. The process begins with material selection. Durable, low-shrinkage plastics are ideal for yo-yo manufacturing, like polypropylene or ABS. While ABS is more durable than PP, yo-yos do not require the durability of ABS. Additionally, PP is less expensive, easier to recycle, and more energy efficient due to its lower melting point (160-170°C vs 200-250°C). Given that cost of material is a massive portion of the manufacturing cost, choosing the cheapest material that meets the design requirements can reduce the per-unit cost. For the metal component and the speaker, bulk purchasing would reduce our per-unit cost. Our small batches of washers and speakers were expensive and purchased through Amazon. Working directly with suppliers for order quantities in the millions could drop per-unit cost by several orders of magnitude. Additionally, polyester strings are lightweight and durable, adding to product durability without significantly increasing costs.

Scaling up production introduces costs we didn't face with a small production scale. Tooling costs would be a significant part of the price as our aluminum molds, though durable enough to make it through our process, would need to be replaced many times over a 1 million part production run. We would also encounter significant overhead costs. Our labor this semester was free, as was shop space and utilities. Running a shop with multiple injection molding machines would require employees to run and maintain the machines, and consume energy melting the thousands of kilograms of plastic.

For large scale production, multi-cavity molds will be essential. These molds create multiple parts in a single cycle, increasing the production rate. For instance, an 8-cavity mold operating at 40 second cycle times will produce 720 parts per hour. This means one machine running 24/7 could manufacture 17,280 parts per day. Each yo-yo needs two caps and bodies, assuming a factory with six injection molding machines (half for caps and half for bodies), 103630 injection molded parts could be produced each day. Parallelizing the molds like this increases the complexity of machining the molds, raising their cost, but it is the only effective way to increase production to make 1 million yo-yos in a reasonable time. Another option would be to use more machines, but that is impractical. Machines are a massive investment up front, take up floor space, and require employees to operate them. Parallelizing the molds saves on all of those costs in exchange for a small increase in tooling cost.

We would redesign the yo-yos to be more space efficient for mass manufacturing. The current bodies are massive, barely fitting in the molds. This means we have a large shot size, high packing pressure, and long cooling time. These factors drive up material cost, put extra wear on the molds and machines, and slow down production rate with cooling time. With a high production value we could source more compact speakers, or potentially design our own to package them smaller. This would mean we could shrink the yo-yos significantly, making them faster and easier to manufacture, and even save on the molds as smaller molds need less stock. On the scale of millions of parts, even single cents per yo-yo saved can add up, so it's critical to optimize the design of our yo-yo beyond what we did for this class.

A final consideration would be storing and shipping the product. We had issues storing our yo-yos in LMP due to their large size, which would be amplified at large scales. We'd need to ensure that orders to ship our yo-yos matched our production rate to prevent backlogs of supply that would be expensive to store. Yo-yo demand is likely predictable enough that we could have a stable equilibrium with our suppliers with few demand shocks, meaning we would not need significant stores ready to ship out.

Cost Analysis

Cost of Tooling

$$C_1 = \frac{C_t}{N}\left[Roundup\left(\frac{N}{n_t}\right)\right]$$

where N is the total production volume, C_t is the cost of one set of tooling, and n_t is the number of parts each tool set can make. See **Figure 9** for mold price estimates.

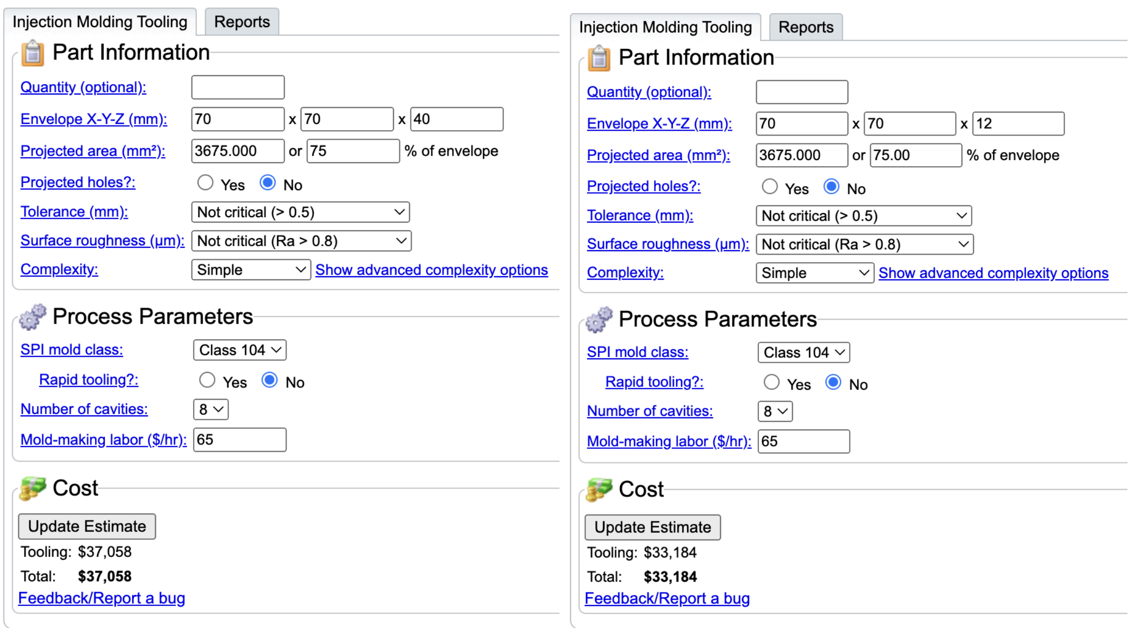

Figure 9: Estimate for the cost of tooling for the body molds (left) and the cap molds (right) based on the number of cycles they would undergo.

$$C_{1,\,body} = \frac{\$37{,}058}{2{,}000{,}000}\left[Roundup\left(\frac{2{,}000{,}000}{100{,}000}\right)\right] = \$0.37058/part$$

$$C_{1,\,cap} = \frac{\$33{,}184}{2{,}000{,}000}\left[Roundup\left(\frac{2{,}000{,}000}{100{,}000}\right)\right] = \$0.33184/part$$

$$C_{1,\,average} = (C_{1,\,body} + C_{1,\,cap})/2 = \mathbf{\$0.35121/part}$$

Cost of Equipment

$C_2 = \frac{1}{\dot{n}}(\frac{C_m}{Lt_{wo}})$, where ṅ is the production rate of one machine [parts/year], C_m is the purchase cost of one machine, L is the fraction of time during which equipment is productive and t_{wo} is the lifetime of equipment [years].

$$C_2 = \frac{1}{1{,}051{,}200\ parts/year}(\frac{\$25{,}000}{0.70 \cdot 10\ years}) = \mathbf{\$0.003397/part}$$

Cost of Material

$C_3 = \frac{mC_m}{(1-f)}$, where m is the part mass [kg], C_m is the material cost per unit mass [$/kg], and f is the scrap fraction. See **Figure 10** for an estimate of price for polystyrene. The price of polypropylene from the 2.008 Canvas.

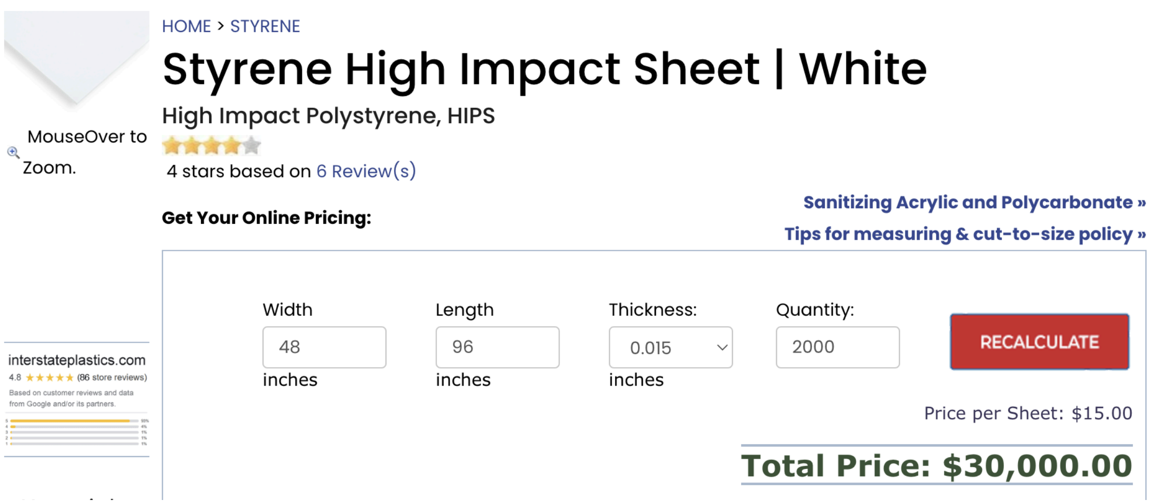

Figure 10: Estimate for the cost of polystyrene sheets needed for thermoforming.

$$C_{3,\,IM} = \frac{0.180\ kg/part \cdot \$1.98416/kg}{1-0.05} = \mathbf{\$0.375946/part}$$

$$C_{3,\,Thermoform} = \frac{\$30{,}000}{2{,}000{,}000} = \mathbf{\$0.015/part}$$

Cost of Overhead

$C_4 = \frac{C_{oh}}{\dot{n}}$, where C_{oh} is the total cost of overhead [$/hr], and ṅ is the production rate [parts/hr]

C_{oh} = Worker wages + Energy costs + rent = $35/hr +$40/hr (estimates cost of energy) + $15/hr (assuming $10,000/month for rent)

$C_4 = \frac{\$90/hr}{292\ parts/hr}$ = **$0.308219/part**

Total cost per part =
$C_{1,\,average} + C_2 + C_3 + C_4 + \ cost\ of\ speakers\ (\$3)\ =\ \$4.038772/part$

Manufacturing 1,000,000 yo-yos would cost approximately $4,000,000.

Spotify pays artists approximately $0.004 per stream, so for our Spotify yo-yo factory to be entirely funded by revenue from songs we would need **1.009 billion streams.** That equates to one person listening to Sabrina Carpenter's Espresso non-stop for **5,603 years!**

Appendix

Figure 1: Rendered image of complete yo-yo assembly modeled in Fusion. Pictured left is the yo-yo as it will be assembled and pictured right is an exploded view.

Table 1: Bill of materials for one yo-yo of Team H's design.

Part	Quantity per yo-yo	Description
Body	2	Injection molded polypropylene (PP), press fits with cap and holds speaker
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String	1	Wrapped around center of yo-yo

Figure 2: Rendered image of yo-yo assembly exploded view modeled in Fusion.

Figure 3: Cross-sectional view of the cap and body interface modeled in Fusion. Pictured left is a zoomed in view to feature the location of interference and length of engagement between the cap and body. Pictured right is a full yo-yo cross-sectional view.

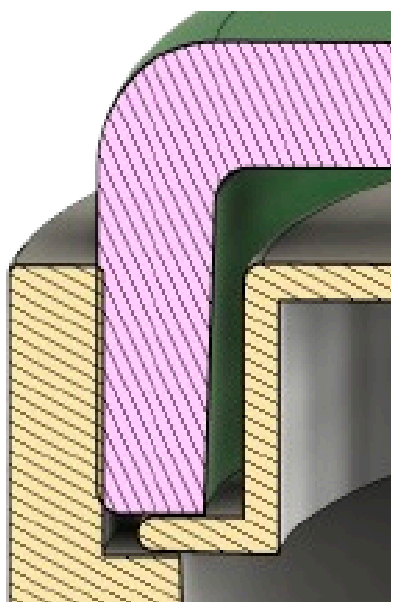
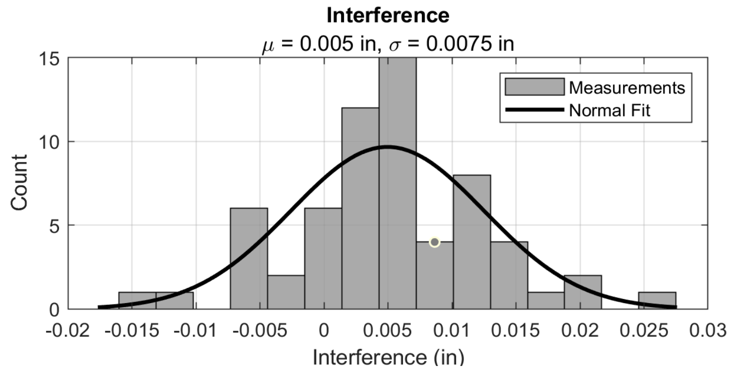


Figure 4: Interference data from the first iteration of 100 bodies and caps.



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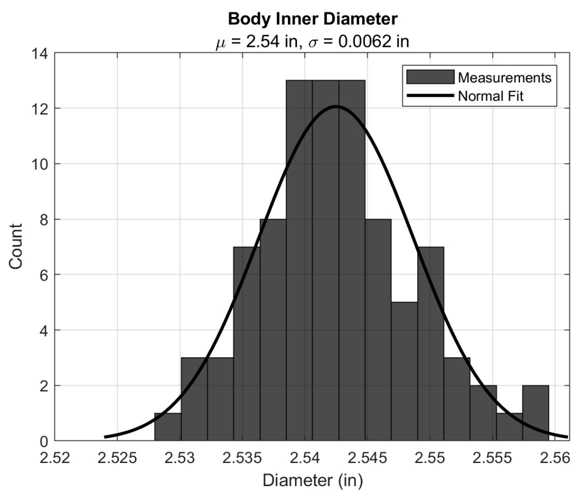


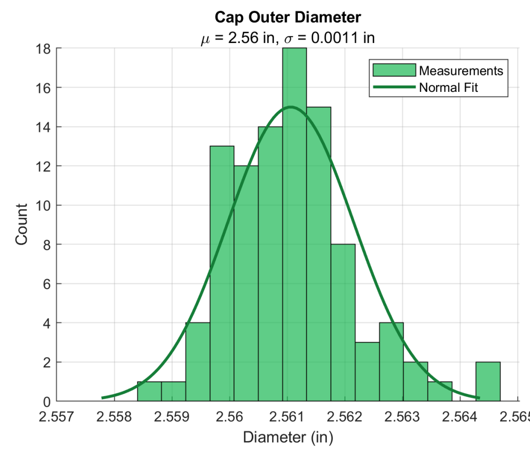


Figure 6: Interference data from the final iteration of 100 bodies and caps.

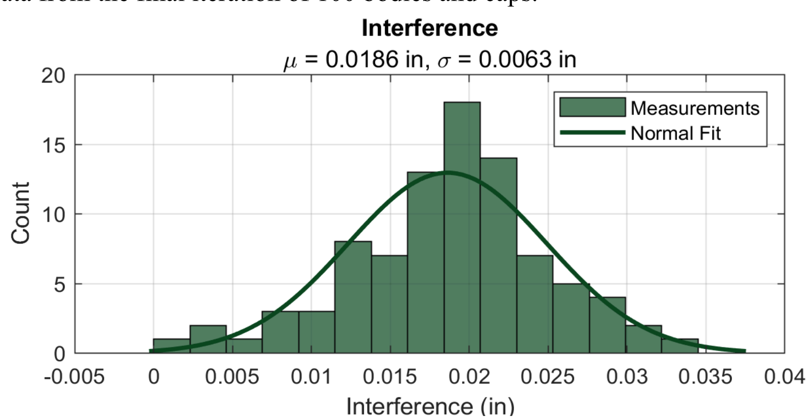
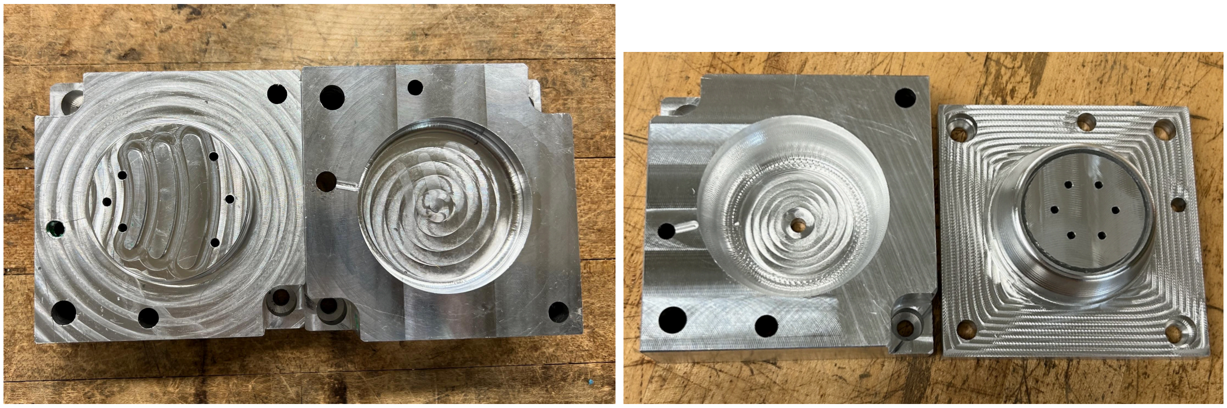


Figure 7: Injection Machine molds for the cap (left) and the body (right)



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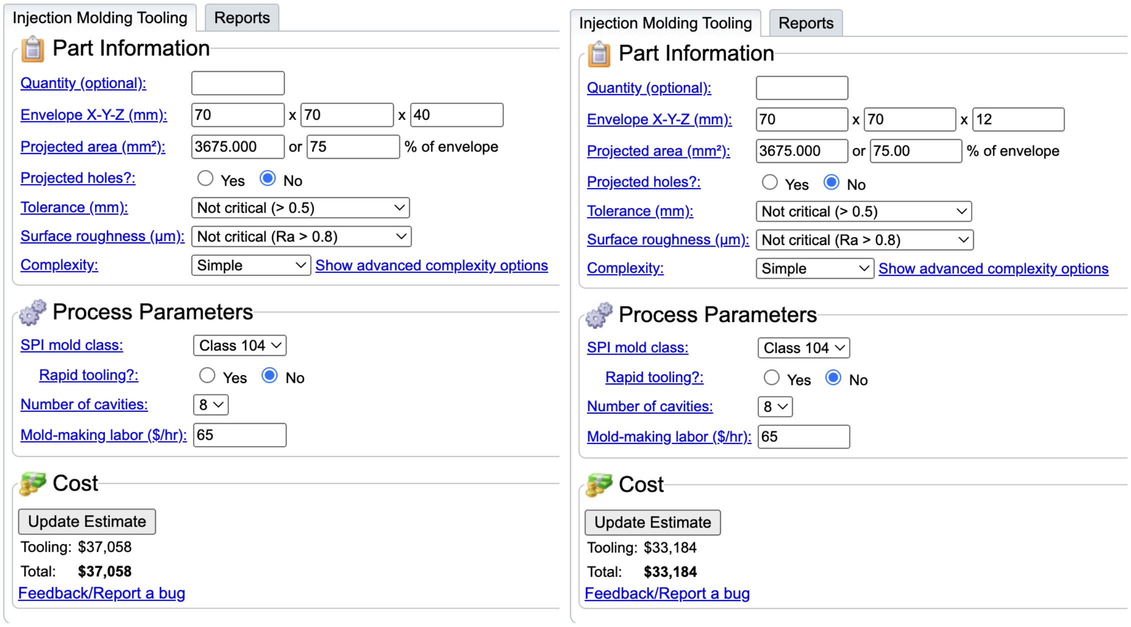

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