Massachusetts Institute of Technology

2.008: Design and Manufacturing II

Call Me Maybe

Lab F

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Call Me Maybe: Introduction to Team F1

This is the final report for *2.008: Design and Manufacturing II*, an upperclassmen Course 2 (Mechanical Engineering) class offered at MIT. This course covers a number of manufacturing techniques common in modern factories. We learned about processes from sheet metal bending to injection molding to pcb fabrication. The cumulative project in the 2.008 is the design and 'mass' manufacturing of a custom Yo-Yo. The only requirements for the 2.008 Yo-Yo are based on the types of parts you need to include; three injection molded parts and one thermoformed part. Other than that teams are free do as they please. In our case we decided to design out YoYo after a rotary phone, including not only the look, but the basic functionality of a classic rotary phone. A photo of our team, fonly named **Call Me Maybe** (after the song *Call Me, Maybe?*), is below:

Figure 1: Libsack, Pina, Owen, Wu, Epstein, & Damerla

Team Signatures: Proof of Involvement

Revanth Damerla	Date
Lindsay Epstein	Date
Travis Libsack	Date
Elliot Owen	Date
Kyle Pina	Date
Kerrie Wu	Date

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1 The Rotary Phone Yo-Yo

Team *Call Me Maybe* was inspired by old fashion rotary phones for the design of they Yo-Yo [Figuer 1.1]. Our YoYo is made up of two symmetrical halfs that are made up of five main components: the base, dial, fingerstop, retaining ring, and number pad [Figure 1.2]. Our YoYo also includes a spring and bearing to help mimic the spring-back action of rotary phones. During the ideation and design of our YoYo we thought that creating a finished product with an interesting mechanical property (ie. the rotating front) would make the design process more difficult and demanding, but the final product much more interesting.

The major design considerations we took into account when designing our YoYo included: critical press-fit dimensions, YoYo mass and moment of inertia, and the YoYo string gap. We accounted for each of these in the designs for our molds. For example, the core mold for our Base included critical dimensions for the Finger Stop press fit, bearing press fit, and a ledge for steel shims we over-molded into our YoYos.

Our YoYo was also designed to be assembled in a specific way. Each of our components fits into the YoYo assembly process in a specific order. Each half of the YoYo is made from a Base, Dial, Number Pad, Retaining Ring, Finger Stop, Bearing, Spring, and 10-32 nut. The steel shim and 10-32 were injected into our base when manufacturing parts. The bearing was later press fit into the Dial of our YoYo. For more information on the assembly of the YoYo you can refer to *Section 3: YoYo Assembly*

The final design of the YoYo can be seen on the following page. The first image on the next page is an exploded view of of YoYo. This shows a side view of each of the components from our YoYo. Below the initial exploded view you'll see and isometric view of both a fully assembled and expolded YoYo – we included these to help one better understand how the YoYo fits together. Finally we have a nice product shot of our YoYo at the bottom of the page.

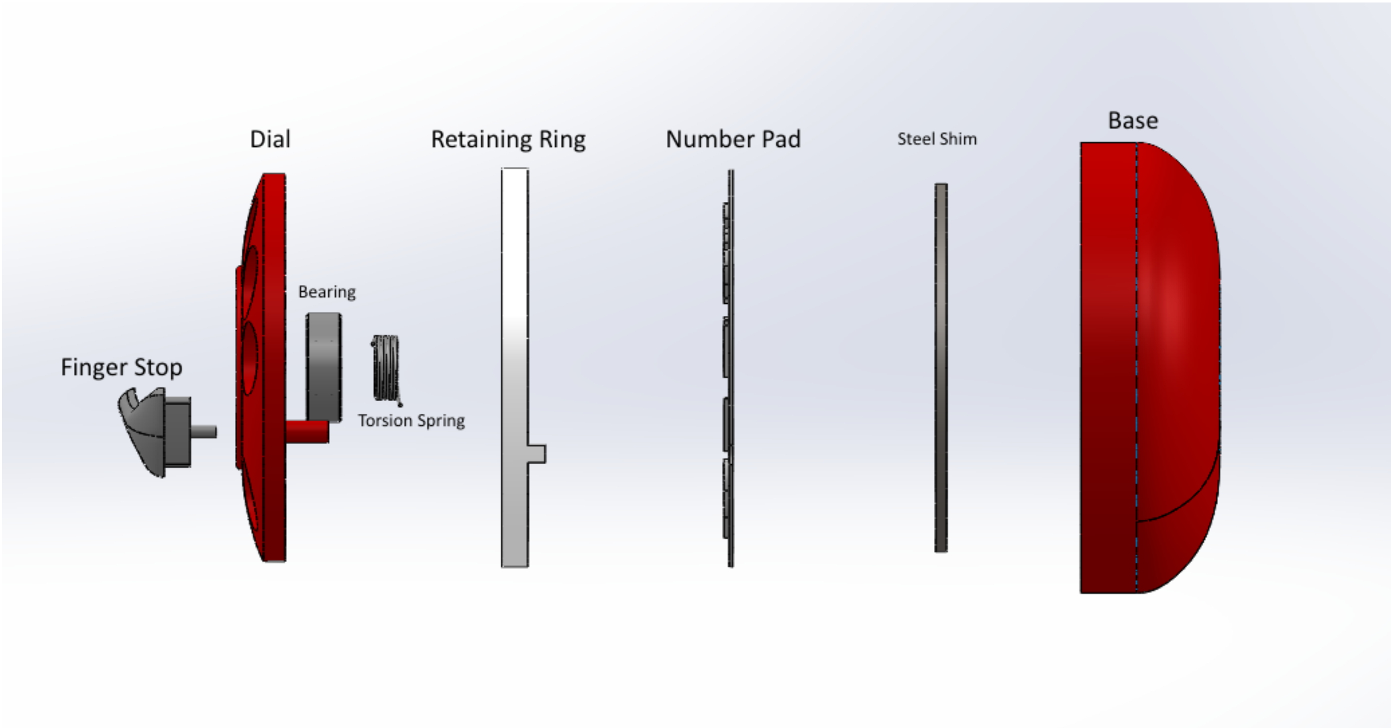
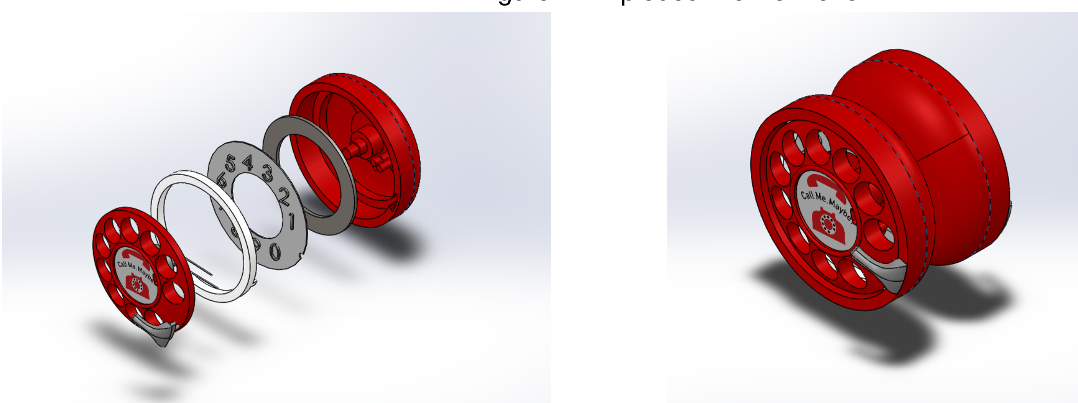


Figure 2: Exploded View of YoYo



(a) Exploded Isometric view

(b) Isometric view

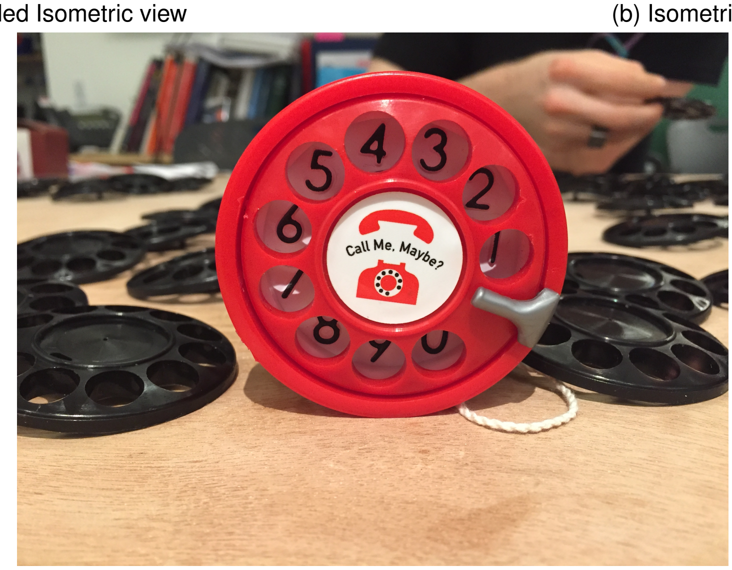


Figure 3: One of the first finished YoYos

2 Critical Dimensions and Variability

Part of the 2.008 manufacturing process and analyzing our parts for variation in dimensionality and quality. What use is a manufacturing process if it lacks consistancy and quality? For each of the parts of our YoYo we looked at the dimensional variability. Our findings are below:

2.1 Base

The critical dimension measured on the base is the width of the finger stop, pictured below:

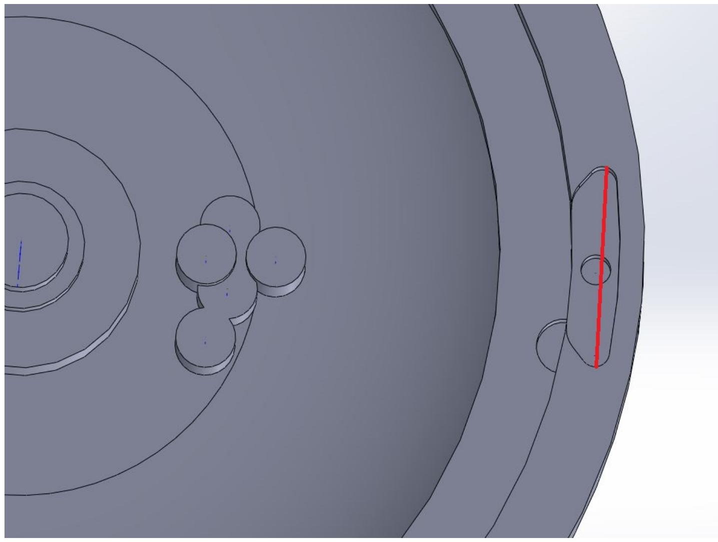
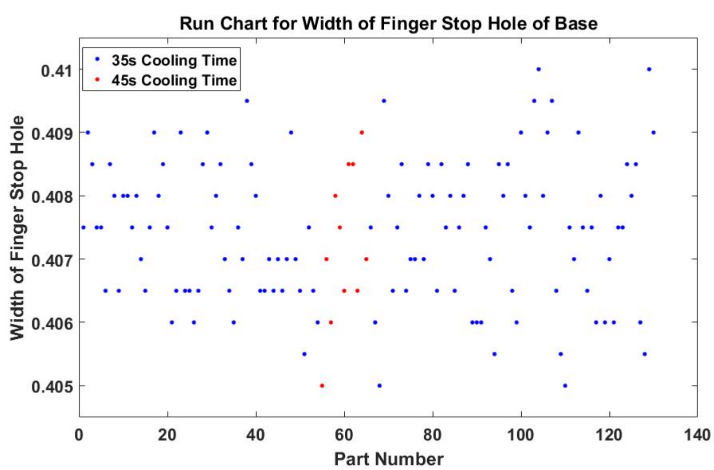
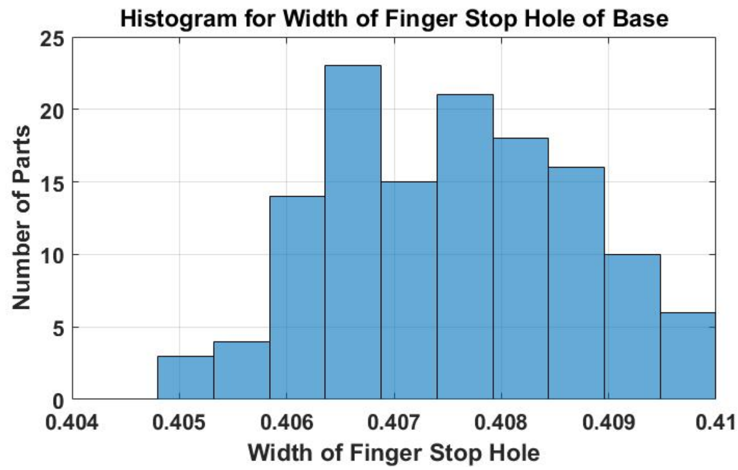


Figure 4: Critical dimension on base

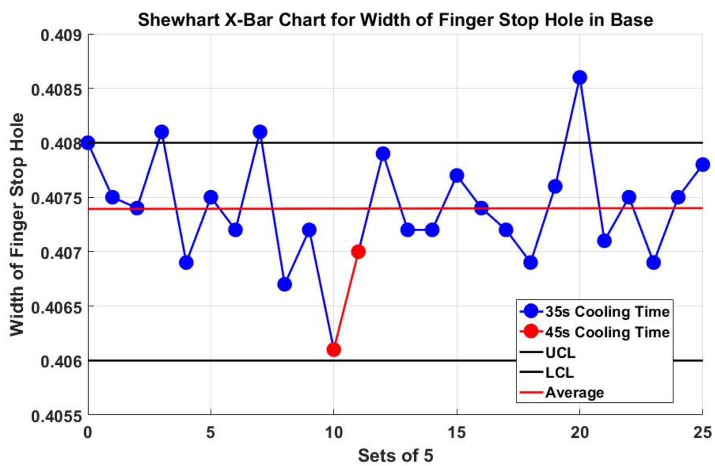
The desired width of the finger stop is 0.4075”, which is based on the mean value of the matching width on the finger stop. The goal was to make the width at least the same size as the finger stop in order to get a good fit between the base and the finger stop. Below is the run chart of production of the bases. 130 were made. All of the bases, with the exception of bases 55-65 were made with a 35 second cooling time, while the other bases had 45 seconds of cooling time.



As can be seen from the figure, there is no real trend between increasing part number and change in width of the finger stop hole. The data is very scattered. However, the histogram of widths of finger stop holes in bases, shown below, has the same general shape as a normal curve.



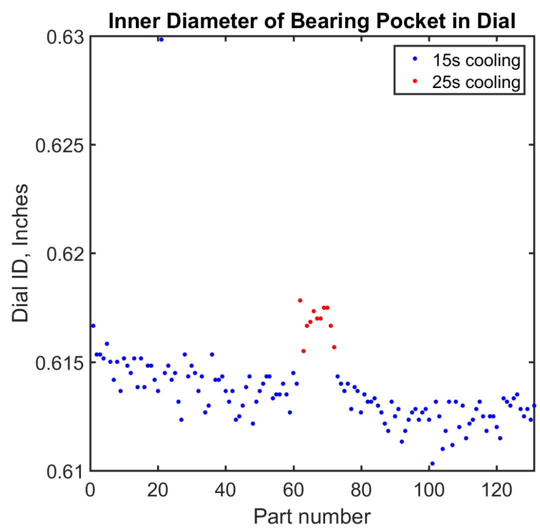
In order to construct a Shewhart X-bar chart of the finger stop dimension, 5 bases was chosen as the size of the ‘rational subgroup’. This size was chosen because it is small enough to be capable of showing trends in changes of dimensions without skipping over small variations in the dimension change.



This graph shows great fluctuations between subgroups, showing no real trend just like the run chart illustrates. The LCL of 0.406” and UCL of 0.408” were chosen by testing fits between finger stops which had already been injection molded and by test bases. Test bases were made with different widths of the finger stop hole to test the fit. The step change induced by the change in cooling time did not have any noticeable effect on the width of the finger stop hole, although this is much better seen in the run chart. This is probably because the finger stop hole is relatively small and makes a lot of contact with the mold, allowing the plastic in that region to cool well. The process capability for the UCL and LCL specified above is 0.2965, which is significantly lower than the recommended value of 1.33. This is because the range between UCL and LCL is very small due to the fact that a good fit must exist between the finger stop and finger stop hole.

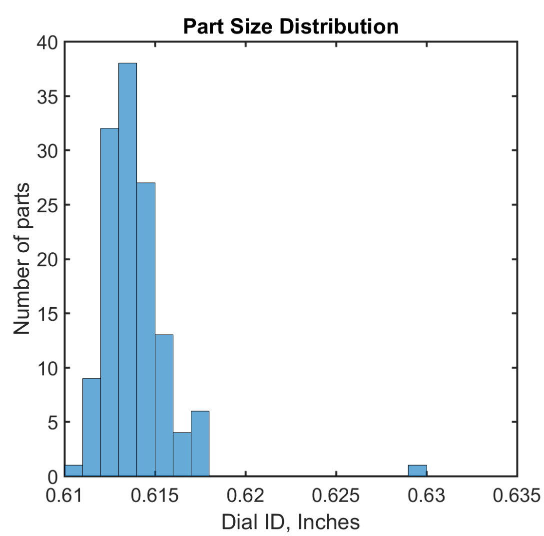
2.2 Dial

After injection molding, the inner diameter of the dial was measured to determine if it would successfully press-fit onto the bearing. The ID of each part was measured 3 times and the results were averaged. The following chart describes the variation of part ID as a function of part number, including when we changed the cooling time.



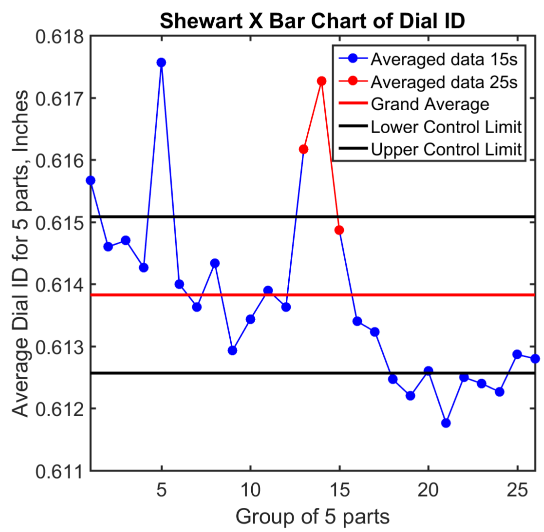
The ID shrunk over time as more pars were made, however it is very clear that the 25 second cooling time had an immediate impact on the dimension. The samples shown in red represent the parts made with a 25 second cooling time instead of a 15 second cooling time.

The variation in part size is easily seen in the histogram below, which expresses how many parts can be found in each range of 0.001".



The one outlier seen in the run chart is much more prominent on this chart. It is also possible to see the affect the longer cooling time represented by the increased amount of parts seen in the 0.616-0.618” range.

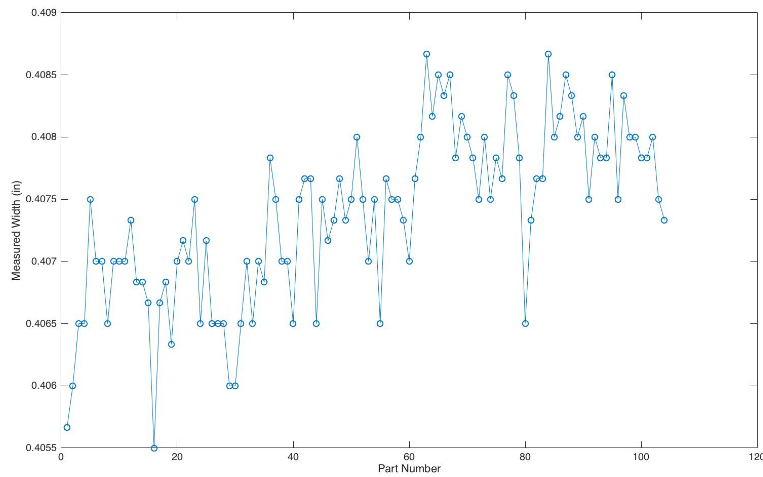
The variation in part size over time can be best shown in a Shewhart X-bar chart. The Shewhart X-bar chart allows you to identify trends in the mean that might be disguised by the large noise between individual samples. Five samples were averaged together for each point in order to smooth out variations over the course of about 2.5 minutes of machine time.

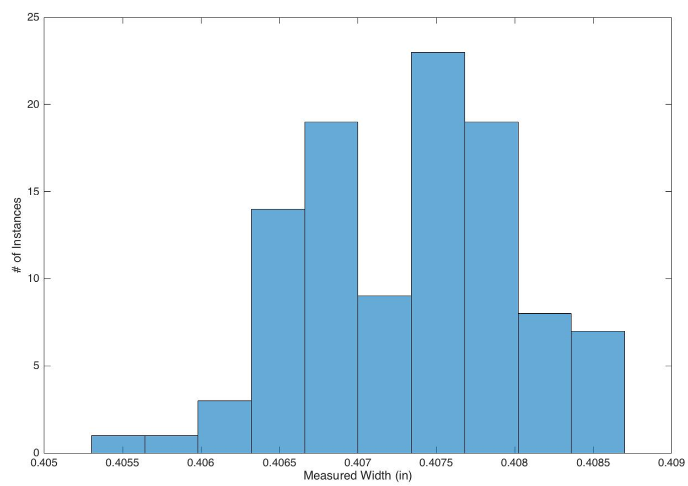


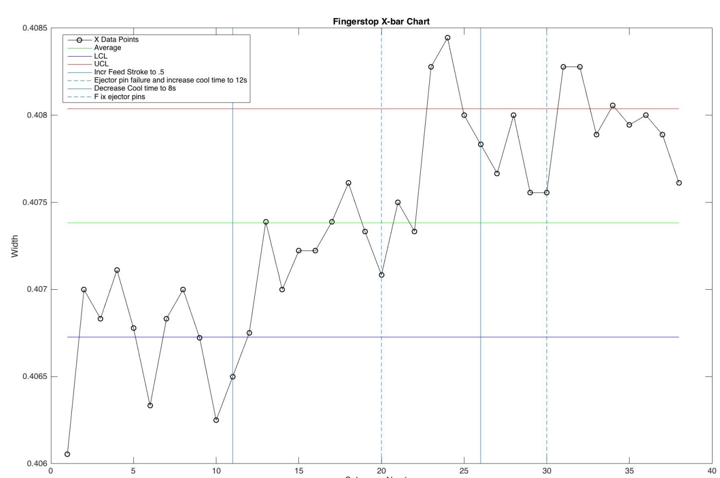
When compared to the grand average, the process data clearly exhibits a decreasing trend in time. The process is not well controlled and frequently leaves the upper and lower control limits. These limits are determined by the number of points averaged together, and the range of each group of five measurements. Since the process exceeds the control limits, we know that the system is changing and parts are varying. Specifically, we can say that the dimensions are changing more than the background noise of variation between individual components can explain. The ten sample parts produced with a longer cooling time can be easily spotted as a large peak, shown in red. The variation between these parts is likely the same, but the mean has shifted because of a different thermodynamic environment. This peak exceeds the control limits and is easily spotted as a non-random source of variation.

The Cp for this process was calculated to be 0.328 indicating a very poor ability to reliably produce parts at high volume. This low Cp is caused by the large drift in the dimension average as the machine settled down. If we ran more parts, it is likely that the average would stabilize and the Cp would increase.

2.3 Finger Stop





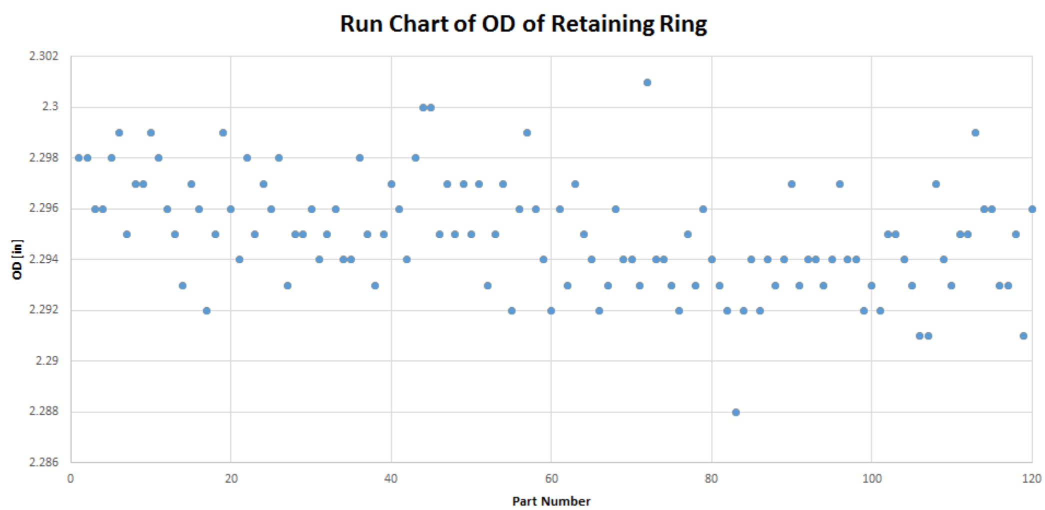


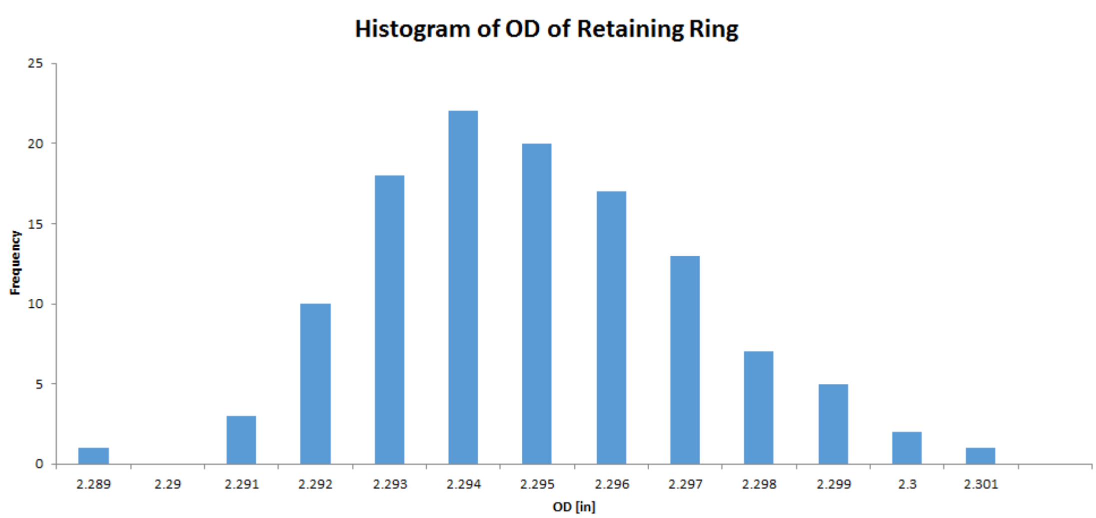
I chose a rational subgroup size of 3. I chose this size because it was a large enough size to allow me to calculate an average between a few values, thereby helping to eliminate outliers, but also small enough that variation within subgroups would be less than variation between subgroups. Having a subgroup size of 3 also provided enough data points within the 100 samples in order to accurately observe trends in the X-bar plot. I placed the upper control limit at $UCL = X + A2 * Rbar$ and lower control limit at $LCL = X \breve{} A2 * Rbar$, where $X = (\epsilon i = 1i = NXi)/N, A2 = 1.023$, and $Rbar = (\epsilon i = 1i = NRi)/N$. I chose these values based on the equations and table for A values by subgroup size given in the variation and quality lecture notes. These equations yielded and $LCL = .4067$ and $UCL = .4080$. When looking at my X-bar Chart, it can be seen that the process is not fully in control, however this can be broken down into a few root causes. The first big jump in my process data can be seen around subgroup number 11, when the mean of the measured critical dimension increases. This jump occurred due to a variation in process parameters that occurred at part 33 – an increase in feed stroke from .47 to .5. This change was implemented due to observed incomplete filling on some of the earlier parts. The other process parameter that was varied halfway through the production run was the cooling time. At part 60 the cooling time was increased from 8 to 12 seconds. However at this point in the cycle the machine also experienced a type of failure – the ejector pins stopped retracting fully. The moment of this failure was determined later by observing which parts had very deep ejector pin holes. At this point in the graph the mean of the measured widths once again experiences a step increases, however it cannot be reliably determined whether the change in cooling time, or the machine failure, caused this step change. Based on my observation that the mean does not drop immediately when the cooling time was decreased, but does begin to drop once the machine ejector pins were fixed, the step increase seen at subgroup 20 is likely due to the machine failure. Therefore an increase in cooling time of 4 seconds does not have an obvious effect on the average width of the parts produced, however an increase in feed stroke and instance of machine failure both do.

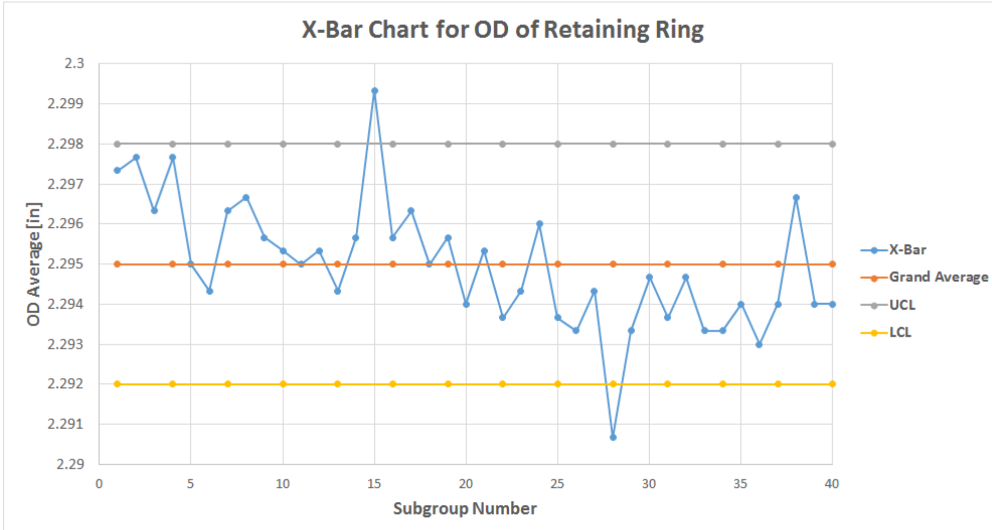
Given the machine failure and out of control nature of my X-Bar chart, I chose to use only a small range of my data to use in calculating the process capability. I chose to calculate the process capability for parts 0-33 (subgroup #1-11, before any process parameters were varied) as well as for parts 33-60 (subgroups #12-20, after feed stroke has been increased, but before machine failure). For subgroups 1-11 the process capability Cp = 0.9720, and for subgroups 12-20 the process capability Cp = 1.3192. Recommended Cp values are 1.33 for existing (stable) process and 1.50 for a new process, so compared to the expectations for mass production these values of Cp are slightly low. This is expected because the machines and molds used in lab may not be as high quality as those used in mass production, so there is more variation between parts. Furthermore in my production run in particular there were other factors that affected part quality including changing process parameters and machine error, leading to more part-to-part variation.

2.4 Retaining Ring

A total of 120 retaining ring parts were injection molded. After allowing sufficient time to pass for proper cooling, the OD of each retaining ring was measured. The following charts describe the variation in the OD of the retaining ring. The cooling time was changed from 15s to 10s on parts 51-60.







A rational subgroup size of 3 was chosen since a total of 120 parts were made, allowing for 40 equally sized subgroups. A subgroup size of 3 also allows for a shift in the mean OD value of the ring to be detected while keeping the variation in each subgroup less than variation between each subgroup. This lessens the effect of outliers and allows for any shift in the mean value of the OD of the ring to be properly detected. From the data there seems to be a clear downward trend of the average OD of the retaining ring.

Using the given UCL and LCL formulas, an UCL and a LCL were able to be calculated. These limits depend on the process, measurement methods, and subgroup size (3 in this case).

The parameter change at parts 51-60 mentioned earlier seems to go unnoticed in the data. One would expect that the reduced cooling time would result in more shrinkage of the part, but parts 51-60 again fit right in with the general trend of the data. This is most likely because the change in cooling time from 15s to 10s was not drastic enough. Had the cooling time been reduced to 5s, one would probably have seen a downward spike of the OD of the ring for parts 51-60 as the parts would have shrunk much more spending less time in the mold.

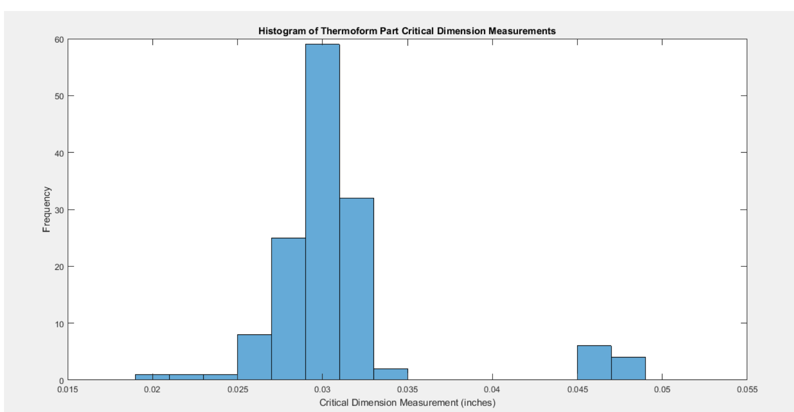
The Cp value for this process was calculated to be 0.75. This value depends the standard deviation of the process and on the specification/tolerance limits of the part which were $+/-0.005$J. These tolerances were chosen because the OD of the ring press fits into the ID of the base. Normally press fits have tolerances of $+/-0.001$J, but the ring also has a small extrusion on it, which originally was just to prevent rotation of the thermoformed number pad. However, this extrusion ended up acting as a second press fit, allowing the OD of the ring to handle more variation.

A Cp value for a new process should be greater than 1.50, so the calculated Cp value is very low. The low Cp value is most likely due to the large amount of variability seen in the data, which would increase the standard deviation of the process. Had more parts had been made, the IM machine probably would have been more settled and produced parts with less variation.

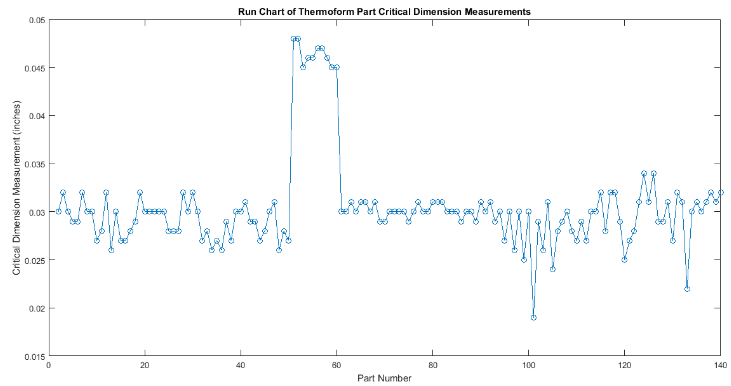
2.5 Number Pad

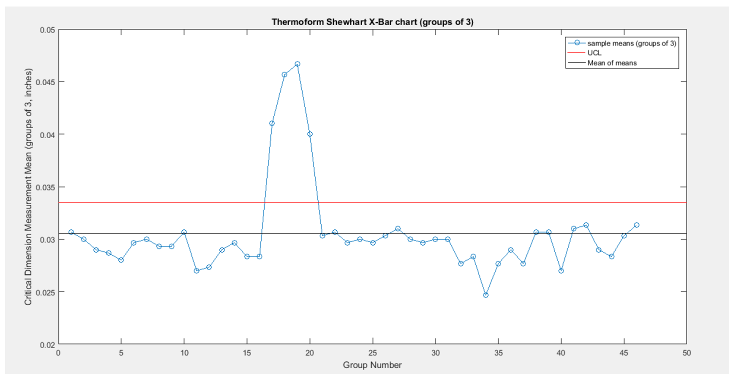
The critical dimension we measured for the thermoform part was the elevation of the depression in the center of the 4 from the backside of the part. We measured this dimension because, even though it is not strictly critical for the assembly to fit together, it measures the quality of the formation of the numbers (where the smaller the distance is, the better the draw is). We made 140 thermoform parts and induced a change in parameters at part 50 by decreasing the heating time from 17s to 7s.

Figure 5: We measured the elevation of the depression of the 4 (marked in black) as our critical dimesion.



The histogram shows an approximately normal distribution, with a few outliers being from the change in parameters.





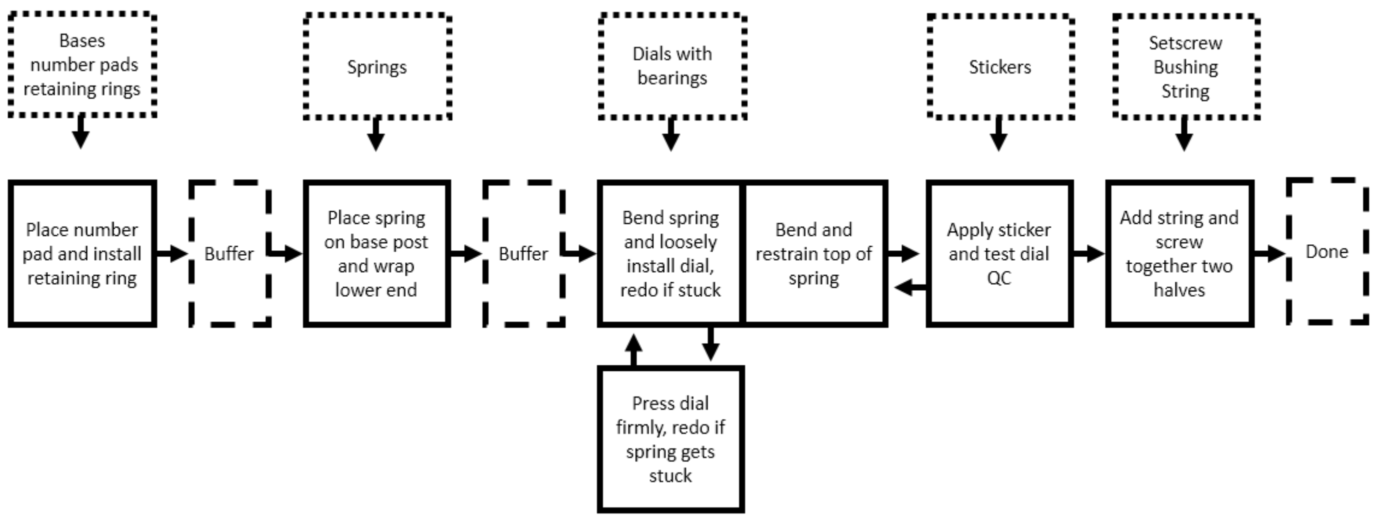
For the Shewhart chart, I chose a group size of 3 because this was enough to filter out some noise from small variations, but large enough to see the effects of the change in parameters starting at part 50. We were able to see the effects of the change in parameters because it resulted in a very significant change in the quality of draw and the measured dimension (the form was so bad that we did not use the parts at all), and the number of parts that was affected by the change in parameters was greater than the group size for the chart.

We an upper control limit at 0.0335”, because this bound excluded the parts that were badly formed because of the step change in parameters at part number 50-60, but included the range of parts that were still good, and gave us a tight upper bound on what parts were acceptable to use. We calculated this by using the third standard deviation from the mean when we excluded the bad parts (Since we did not have this as a critical dimension initially, we did not have a specification to match from our design). However, since a lower value dimension is better, we did not include a lower control limit.

For calculating the process capability, we included the measurements of the bad parts in the standard deviation and mean that we used. The formula for a one-sided limit is $C_p = (USL \mu)/(3\sigma) = .231$. This seems to be very low compared to process capabilities for real-life manufacturing (which should be around 1.5). However, we think this the reason why our process capability is relatively low is because our change in parameters induced an extremely large change in the measured dimension, and also because the parameter change was very drastic (decreasing heating time by 10 seconds). So, if we had not picked such a large parameter change, our process capability would be better, since nearly all of the parts made using normal parameters are within the limits. Alternatively, we could loosen our expectations of a “good part” and set our upper control limit to be higher.

3 Assembly Line

Once we had completed all of our individual parts and taken measurements, we formed an assembly line to put all of the yoyos together. We knew that manipulating the spring would be the most difficult task and would require a single person with high skill. The other tasks involved placing or installing simple parts and were comparatively low risk and high speed. We divided the tasks upstream and downstream of spring install and placed buffers on the high speed steps up stream of the spring assembly. The tasks that took place after the spring was installed also performed a quality control role and rejected parts if the dial did not function properly. The assembly line as used is shown in the diagram below:



The line starts by installing the number pad and retaining ring into the base of the yoyo. These parts were quite fast to align and install and a skilled operator could likely perform it in ten seconds. We started this portion of the assembly first and a small buffer accumulated before we started installing the spring. The springs are first placed onto a post in the base and then the lower leg is secured by wrapping it around two pins. This step is also quite fast with a cycle time close to 10 seconds at scale. The speed of these processes compared the dial installation caused a large buffer of parts to form.

The dial installation and spring restraint are two separate steps that were performed by one person as they both required skill manipulating the small spring wires. The upper leg of the spring was bent up and threaded through the dial, the dial was then loosely installed. The dial was then pressed down to firmly set the bearing on the post. Sometimes this process caused the spring to shift and catch on the lower leg posts, preventing the dial from rotating. This defect occurred so frequently that parts went back and forth between dial installation and pressing as many as three times. Once successfully pressed, the top of the spring would be twisted to restrain it within the dial face. This process was very time consuming and variable as the operator learned how to manipulate the wire. Cycle times varied from twenty seconds to two minutes as the task was perfected. With skilled operators, better pliers, and a few helpful jigs, the two tasks could be separated and sped up to about fifteen seconds each. Our struggles were partly caused by a lack of wire handling and an ever-changing approach to how solve the problem.

Once the sub-assembly was approved by the spring installer, a sticker was applied to cover up the spring and center of the dial. However, the sticker often pressed on the spring sometimes causing it to settle and cause the dial to malfunction. Many assemblies were rejected at this stage and had to be rebuilt later. With a skilled operator and an appropriate sticker dispenser, this task could be accomplished in as little as five seconds. After two yoyo halves with stickers were approved, they were screwed together with a setscrew separated by a bushing. The yoyo string was installed and then wound up and tested. At scale, screwing would only take about five seconds, but winding the yoyo and testing it would take about fifteen. These last two steps were often starved for parts because of the spring installation bottleneck and did not form any buffers during our assembly.

It is clear that efforts would need to be made to improve the reliability and speed of spring installation in order to manufacture at scale. The lower leg spring attachment is very simple and easy to install without pliers, but the upper level dial installation is extremely complicated and unreliable. The easiest way to address this would be to use a similar pin constraint system on the dial as we used on the base. This would require a few more features to be machined into the molds, but would be very rewarding. However, even though the sticker covers the spring attachment, you can see the outline of the features below it. Removing more material would crinkle the sticker and threaten the appearance of the part. Even if the mold design couldn't be changed, the way the operator bends the spring has an enormous effect on how well it is constrained. We didn't get a chance to try a lot of possible bends and were experimenting with new techniques during production. If the problem remains intractable, more workers could be placed on spring installation to bring up the total production rate.

On the next page we have some images from our assmebly line.

Figure 6: Half assembled YoYos

(a) Six assembled YoYos

(b) 50 Finished YoYos

Figure 7: 50 Finished YoYos packaged up

3.1 Automated Assembly

3.1.1 Assembly

While assembling our yo-yos, we found that many steps could be automated with SCARA manipulators, because many assembly steps required only precision placement in the horizontal plane. An optical system that recognized holes and features for alignment could be used to ensure accuracy during placement.

Press fitting the bearing into the dial would be very easy to automate using a SCARA robot. Since the press fit required the use of an auger press, we could adjust the press fit to be a lighter fit that a small SCARA robot would be capable of. (Our press fit was almost too tight anyways and resulted in three parts cracking during insertion, so we should adjust the press fit if we were going to do production again). Alternatively, we could also press the bearing in immediately after injection molding the part, when the part is still warm and has not shrunk yet. Since the bearing needs to be well aligned with the hole, a SCARA manipulator would work well for this step for precision.

SCARA manipulators could also be used to place the thermoform part into the base, and align and press the retaining ring into the base. Similar to the bearing press fit step, this would take advantage of SCARA's high precision placement, and would require an optical system to help the robot align the parts.

To insert the springs, we needed to bend the end of the spring into a complex shape to fit the base. However, if we were producing at high scale, the best option would be to source springs that were already the correct shape—then, we would only need to place the spring into the base, which could also be done using a SCARA manipulator, and it would not require additional tooling for bending the spring into a complicated shape. Alternatively, we could change the design of the base so that the spring did not need to be bent in order to be held in place. This could include using a screw to clamp one end of the spring down to a flat surface in the base, which would also not require additional tooling since SCARA manipulators can easily place screws as well.

Pressing the dial into the base could be accomplished with a SCARA manipulator, similar to the bearing press fit.

The last step for assembling parts, which involved bending the spring into a small indentation in the front of the dial, might be difficult to accomplish with automation. It might be best to adjust the design so that this step is simpler and only requires a single bend in the spring, which could be accomplished with something similar to a punch to fold the end of the spring.

The "Call Me Maybe" logo could be placed on a stamp instead of a sticker, so that the final step would just be stamping an image on the center of the dial, reducing the need to handle another component.

Automation could definitely help increase the rate of assembly, though it might require some changes in design. It would be a good choice if we were producing at high enough volume to offset the cost of machinery for assembly.

3.1.2 Manufacturing

Automated sprue and runner removal would be useful for high production volume of our parts. Other aspects of manufacturing that could be automated include punching out the thermoform parts, and painting/spray finishing the thermoform parts. To eliminate the need for spraying the parts, we could have used enamel paint, which would not scrape off the plastic with handling like the acrylic paint that we used did. Also, instead of forming raised numbers, we could simply stamp a number pattern onto a flat sheet of paper or plastic to reduce the complexity of the part.

Additionally, optical measurement systems that could measure the critical dimensions of our parts as they were manufactured would be good to ensure that our parts would fit together.

4 Assembled YoYo Dimensions and Variability

Critical Dimension	Yoyo Design Spec	Measured Spec
Finger Stop Hole Width	0.4075”	0.4074” ± 0.0011”
Retaining Ring Outer Diameter	2.301”	2.295” ± 0.005”
Dial Inner Diameter	0.6245”	0.6135” ± 0.005”
Finger Stop Width	0.4074”	0.4075” ± 0.001”
Elevation of Thermoform Part Depression	0.031”	0.031” ± 0.005”

Figure 8: Critical dimensions for each of our parts

The critical dimension that was the most accurate was the finger stop width. This is because the mold for the finger stop was created first since it had the longest machining run time. The design specification for the finger stop hole width was designed around this. Ideally, there would be an interference fit between the finger stop width and finger stop hole of 0.001” as this allowed for the best fit between the base and finger stop while testing. For this reason, the measured spec of the finger stop hole width would ideally match that of the finger stop width. The most significant deviation between design spec and measured spec was in the dial inner diameter. While this was not originally planned, the dial inner diameter had to be changed in order to create a proper press fit between the dial and bearing. In reality, the dimensions of the measured specification created a good press fit, which helped keep the yoyo together. The elevation of the thermoform part depression was very good, allowing for a high degree of detail in the thermoform part and does not have to change. Finally, the retaining ring outer diameter was designed to make an important press fit with the inner diameter of the base. However, the OD of the ring was not large enough to cause this fit to occur. If mass production of the yoyo were to occur, the designed specification for this dimension would have to be met with a standard deviation which is the same as that of the yoyo ID. From this basic analysis, the following table would be a good choice for mass production:

Critical Dimension	Desired Spec for Mass Production
Finger Stop Hole Width	0.4074” ± 0.001”
Retaining Ring Outer Diameter	2.301” ± 0.005”
Dial Inner Diameter	0.6135” ± 0.005”
Finger Stop Width	0.4075” ± 0.001”
Elevation of Thermoform Part Depression	0.031” ± 0.005”

Figure 9: Critical dimensions necessary for mass production

5 Comparsion: Injection Molding and Additive Manufacturing

5.1 Base

Shapeways was chosen as the additive manufacturing service bureau. To begin, the part was uploaded to their website. The Shapeways ‘black strong and flexible plastic’ was chosen because this was the closest material to wht was used in our yoyos. From this, Shapeways generated a quote based on a combination of labor, material cost, and production cost for a variety of materials. The price for printing each base was a flat cost of $22.57 for each base, yielding a price of $45.14 for two bases and $2257 for 100 bases.

5.2 Dial

I uploaded the dial to Shapeways and selected their black “strong and flexible” material for the dial. Shapeways charges for labor, material cost and footprint, all of which are fixed per part. I chose this material because it matched the color and properties of the injection molded dials. I did not need a metallized or ceramic dial face. They quoted me $9.13 for each part at a volume of 2 parts and at a volume of 100.

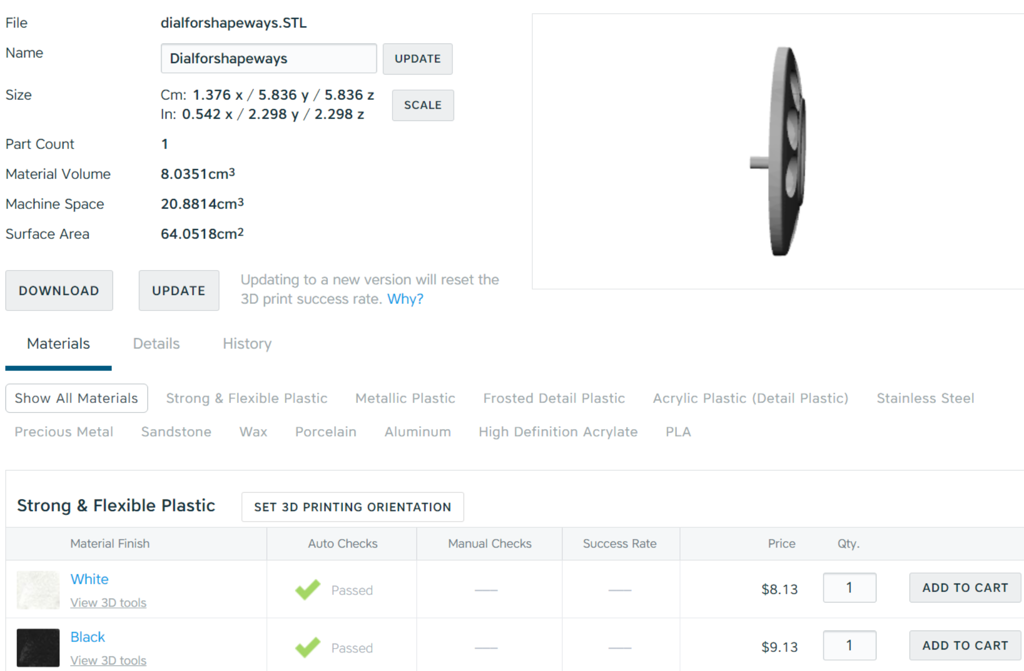


Figure 10: Additive manufactring quote for the dial

5.3 Finger Stop

For the Fingerstop we chose to use Shapeway's additive manufacturing process with "Strong & Flexible Plastic" as our material. We chose this because the material had the desired elastic properties, as well as the correct color offerings. Cost for 2 = $3.70 ($1.85 each) Cost for 100 = $185 ($1.85 each)

5.4 Retaining Ring

sing Shapeways as the AM service bureau, I was able to upload a solid model of the retaining ring and generate an automatic quote. The quote was generated using Shapeways' "strong and flexible white plastic" to keep the same color and general physical properties as the injection molded retaining ring. This hard plastic is also best for the press fit of the small nub on the retaining ring into the base. Taking into account labor, footprint, material costs, and etc. the quoted price was $3.36 per part. This price per part was the same for 2 parts and 100 parts totaling $6.72 and $336.00 respectively.

5.5 Number Pad

I used Shapeways to get a quote for AM manufacturing. I picked the "Strong and Flexible White Plastic" material because the color matched the part, and I did not need the part to be especially high detail or made of metal. It makes sense that the unit price is the same between 2 and 100 parts, because the build rate and material cost are the same per part. Since Shapeways takes orders of many different quantities for many different clients and projects, they probably pool labor and equipment between all of the orders they get, so the labor and equipment costs are also the same cost per part regardless of the change in quantity.

2: $6.12 + 4.99 shipping 100: $306.00 + 4.99 shipping (Cost for both = $3.06 per part)

6 Cost of Manufacturing

Correctly modeling the cost manufacturing is critical in the all projects that involved manufacturing. In the case of 2.008 students the prospect of failure due to budget constraints is much less of a problem then in the real world. Without the correct cost projections the project you're working on could tank. In 2.008 we use Ashby's Model of cost analysis. This includes a number of different items, but categorizes them into tow areas: Fixed cost (F) and Variable cost (V). Within each of these categories we looked at the cost of the machines we were using, teh overhead cost of the space we were using (energy, heat, labor, etc.), the cost of tooling, and the material cost.

When looking at the cost of our YoYos we are going to consider two different graphs. One will show the total unit cost as it changes with production volume. The other shows each of the components of cost and how they change with production volume. When looking at our cost predictions keep in mind that our YoYo has extremely high overhead costs – the cost of the hardware needed in each YoYo (the bearing, spring, and sticker) keeps the price of our YoYo higher than other YoYos that exist without this hardware.

In 2.008 we'll look at three different manufacturing techniques and compare the cost of each. We will analyze the cost of the three following manufacturing methods:

1. Production of YoYos in 2.008 (2.008 materials and resources)
2. Production of YoYos using modern additive manufacturing technique
3. Production of YoYos at scale using professional IM services and tooling

To find the Excel chart we used for our calculations and the MATLAB script we used to graph our data, pease go to:

Excel Sheet: <https://web.mit.edu/libsackt/Public/Call_Me_Maybe/cost_analysis.xlsx>

MATLAB Script: <https://web.mit.edu/libsackt/Public/Call_Me_Maybe/cost_graphs.m>

$$C = F + V \cdot N$$

Figure 11: General Equation used for cost analysis

Total cost

Tooling cost
+

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

Equipment cost
+

$$C_2 = \frac{1}{\dot{n}}\left(\frac{C_c}{Lt_{wo}}\right)$$

Material cost
+

$$C_3 = \frac{mC_m}{(1-f)}$$

Overhead cost

$$C_4 = \frac{C_{oh}}{\dot{n}}$$

$$C_T = C_1 + C_2 + C_3 + C_4 \quad \text{[\$/part]}$$

Figure 12: This are the equations we used to model the cost

6.1 2.008 Process (medium production)

The 2.008 method of production is the productuon method we are most familar with, although analyzing the cost of this system turned out to be more difficult due to the huge variability throughout the semester. In order to correctly and accurately perform this analysis we first made these assumptions:

- The molds we made were low qualiy aluminum molds (Class 104)
- The thermoforming mold was made using inexpensive resin and a Formlabs printer
- IM Machines cost $100,000 to purchase
- Thermoforming mahcine cost $10,0000 to purchase
- Machining time (overhead) based on the costs given

From these assumptions and the equations above we were able to come up with the following cost predictions for our YoYo:

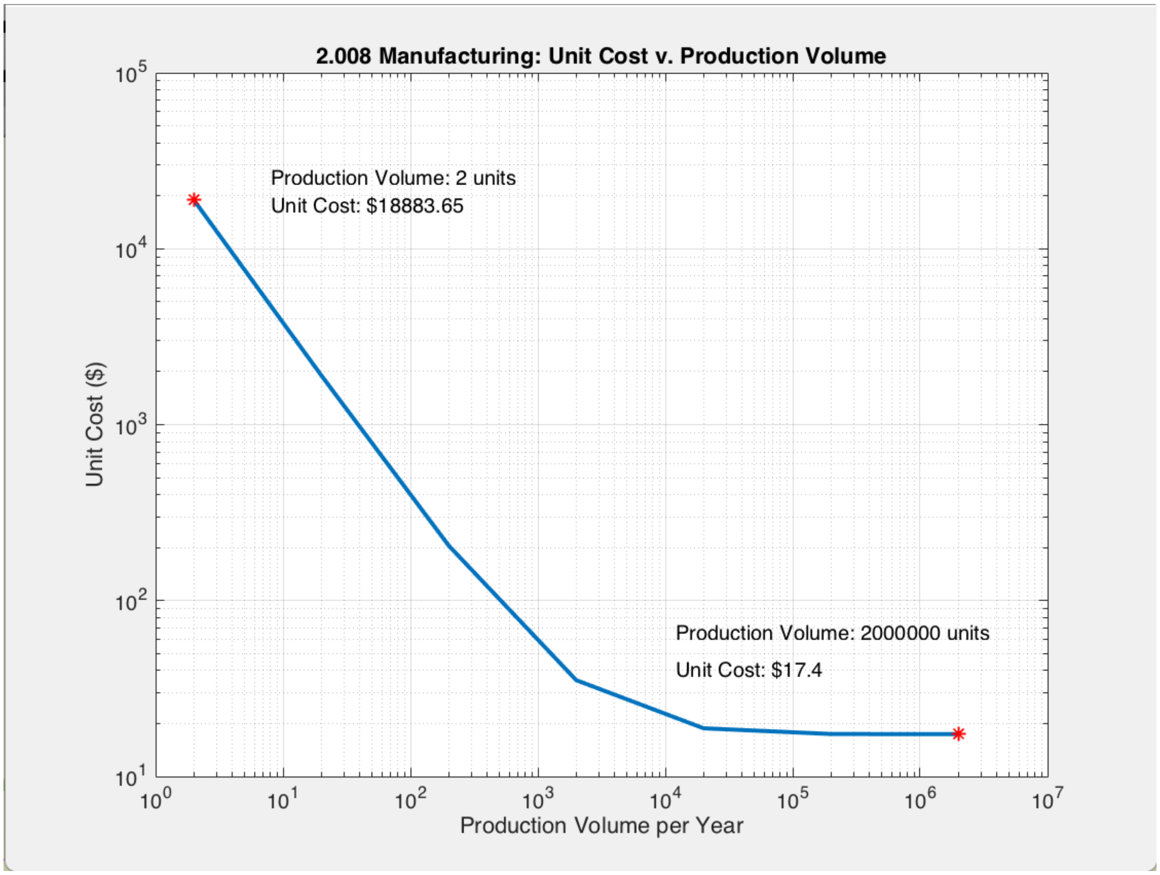


Figure 13: Total cost of manufacturing

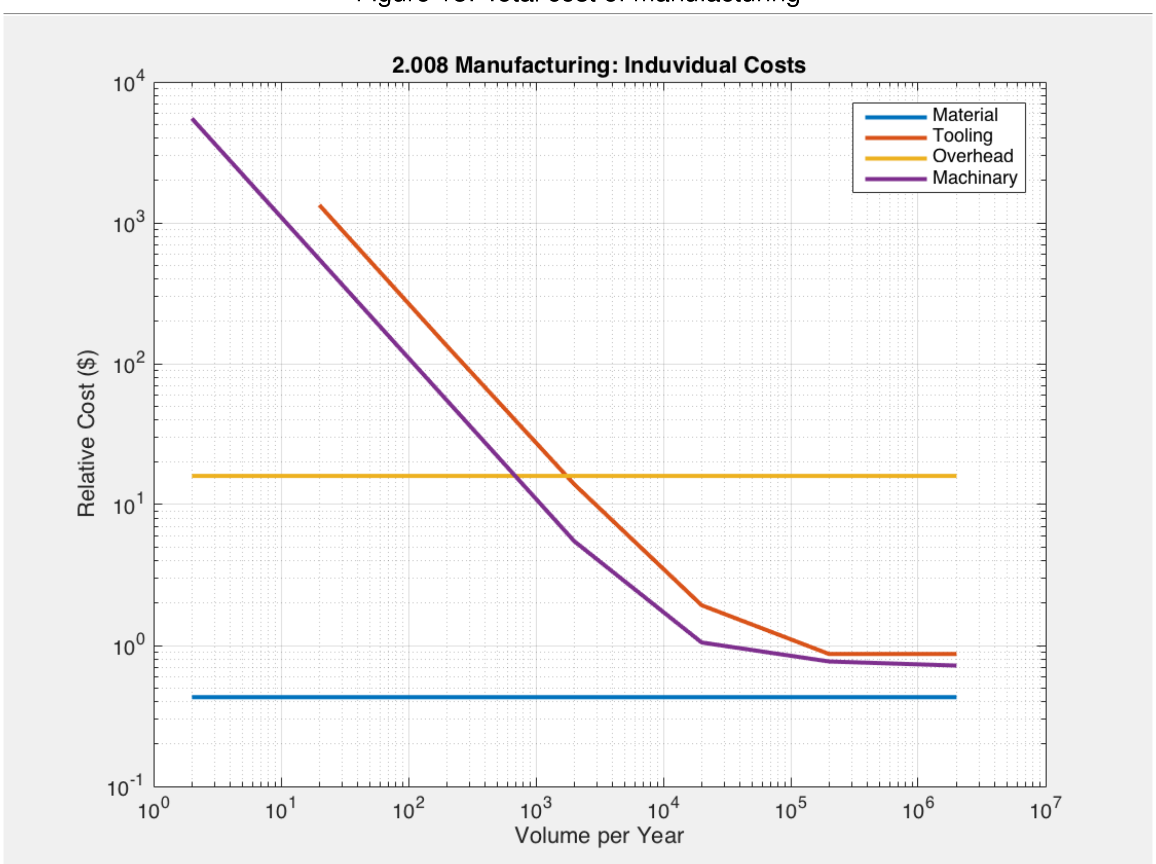


Figure 14: Cost breakdown

6.2 Mass Manufacturing (huge volumes)

The mass manufacturing sytle of producing our YoYos is noticeablt more expensive in small production volumes, but eventualy evens out becoming less expensive than the 2.008 style manfufacturing at higher quantities. This is becsuase things such as tooling quality and machine runtime becomre important. Again, we had to make assumptions to make this analysis possible. The assumptions we used here were:

- Using high quality aluminum molds lasting >1million uses (Class 102)
- Assume 1% scrap on all components
- IM Machines cost $200,000 to purchase
- Thermoforming mahcine cost $35,0000 to purchase
- Same cycle time as our 2.008 cycle time

The following are our cost predicitons based on this analysis:

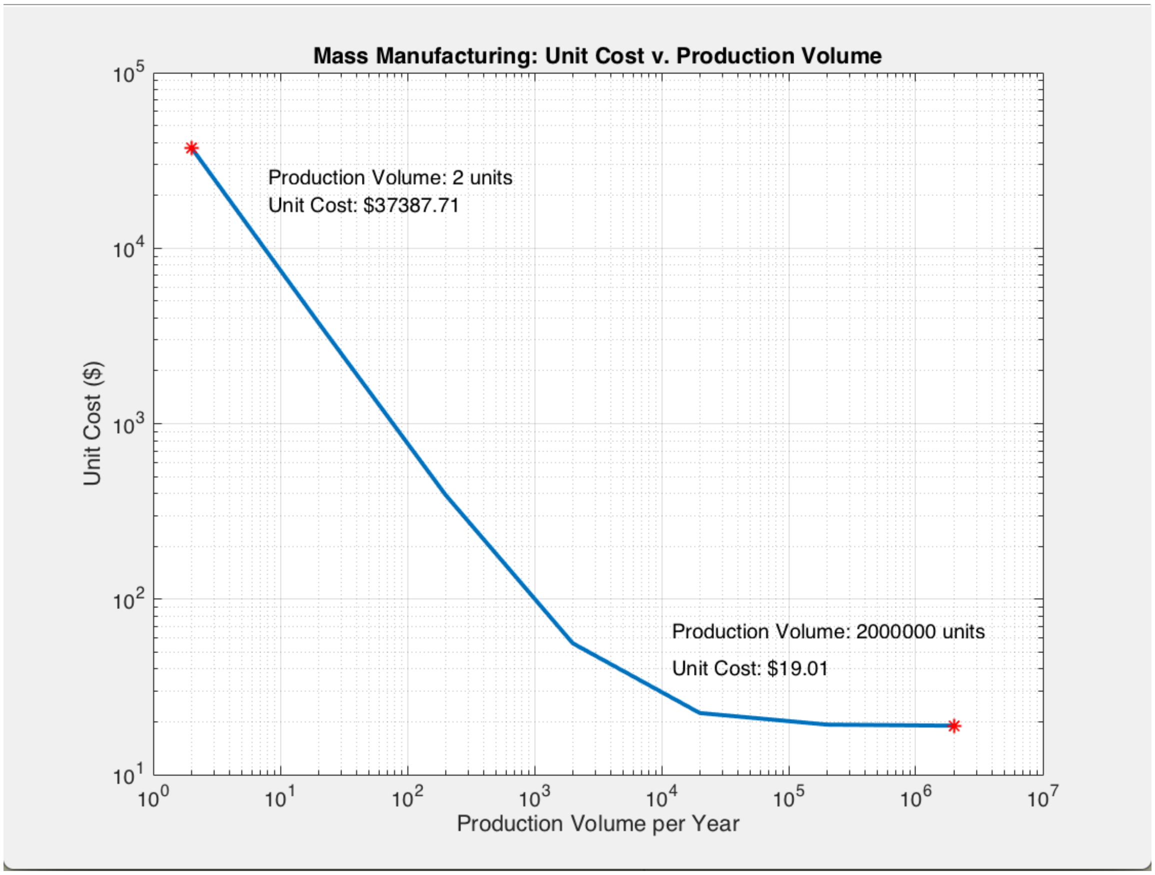


Figure 15: Total cost of manufacturing

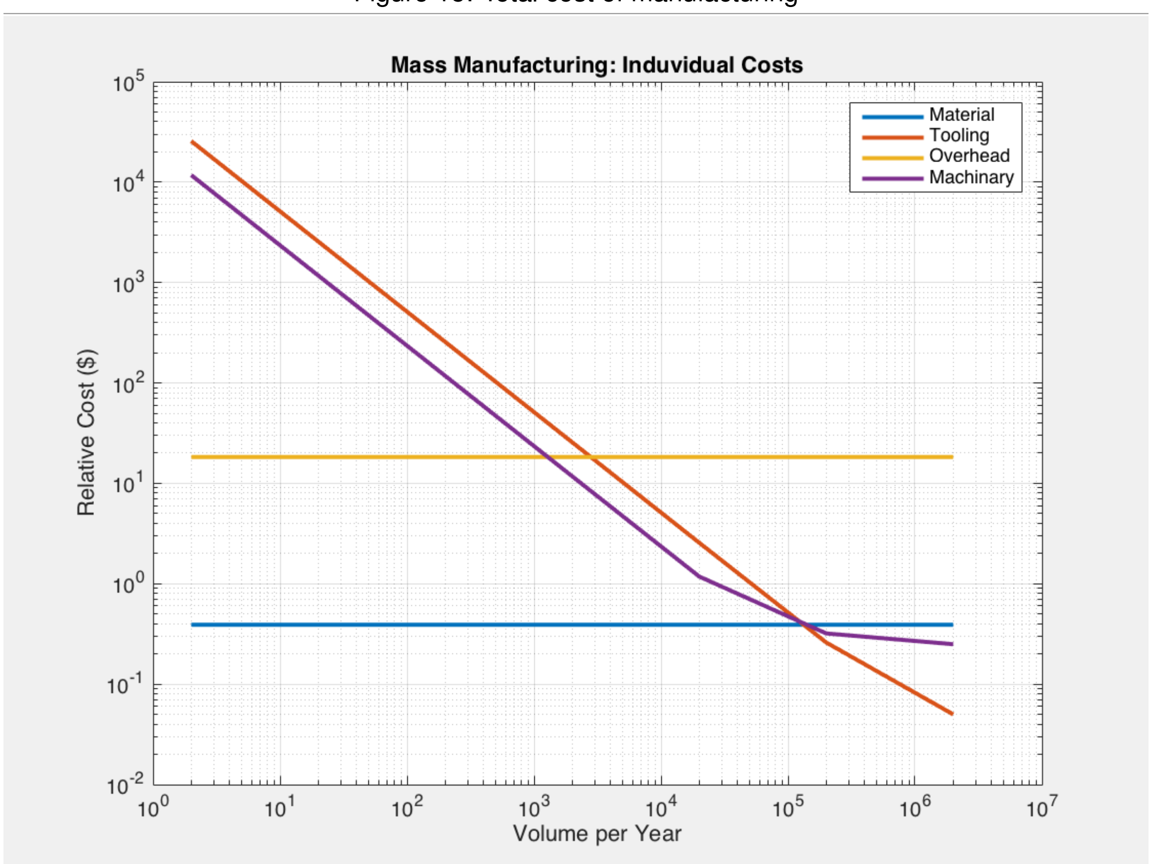


Figure 16: Cost breakdown

6.3 Additive Manufacturing (low volume)

We found additive manufacturing to be invaluable during our design process. However, when looking to use additive manufacturing to mass manufacture our YoYo it is impossible to compare. While the cost of additive manufacturing stays constant, the time required to print each components stays linear, thus making the production of millions of parts impossible. As you can see in the graph below the unit cost for AM *never goes down*. This is a huge issue when talking about mass manufacturing – the reason you decide to mass manufacture something is to reduce the cost per unit.

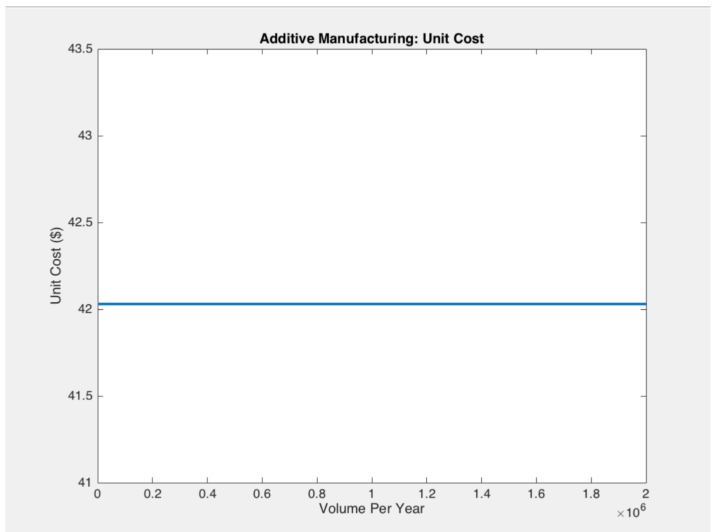


Figure 17: AM unit cost using ABS like plastic

The cost of manufacturing in the injection molding manufacturing methods above decrease with the increase in production volume. However, based on the production volumes seen in 2.008 it is not obvious that the method we used to produce our YoYos was the most cost effective way to produce those prototypes. Given the amount of time we've spent in lab we might have as well sent off our parts to get printed and shipped to us.

A chart of the different YoYo costs are below:

	Machine Cost	Tooling Cost	Material Cost	Overhead Co	Unit Cost
50x AM:	$ -	$ -	$ -	$95.57	$95.57
50x 2.008:	$ 220.00	$ 534.69	$ 0.43	$ 15.98	$ 771.10
100000x Professional:	$ 0.44	$ 0.51	$ 0.39	$ 18.31	$ 19.65

Figure 18: Comparision of different methods

The dominant costs in each of the YoYos is the material cost for our YoYos. The hardware we have in our YoYo makes it an all-around expensive YoYo. Other than that a majority of the cost for both the 2.008 and professional manufacturing methods comes from the machining of the required tooling. This is very expensive and, at low production volumes, eats up a done of the per-unit cost.

What's also interesting is that this method of analyzing cost does not invlude total capital. When looking at this chart it seems obvious that the best, most cost effective, manufacturing method to choose is the professional IM service. However, if you look a little close you'll see that this requires $100,000 * 19.65 = 1.9$ million dollars! This is a huge amount of capital to invest in a YoYo startup. If you compare this to the AM method you'll end up with a much more reasonable number $50 * 95.57 = 4778$. This is a much more reasonable number to pay for protoypes while it is still more expensive per unit than the other methods.

The "crossover" between the cost of producing YoYos using the "2.008 Method" and additive manufacturing is higher than you might think. Based on the quotes we recieved it costs us $84 for get the plastic of the YoYo made using AM. In order to beat this price our cost analysis using the 2.008 method above must ne less than the $84 (after correctly account for the $11.75 in mechanical compoents used per Yo-Yo).

This cross over happens at roughly 550 units, meaning 225 YoYos. This number is massive and, although it looks cost effective, it would not be reasonable to mimick using AM. At 550 units we would have days of printing required. At only 1 hr a piece (which is a huge underestimate) this would require:

$$(5part * 1hr * 550times)/(24hours) = 114days$$

This is a crazy amount of time required and is in now way superior to spending the time and money making the necessary IM euipment.

7 Yo-Yo Comparison: Amazon v. Call Me Maybe

While our yoyo meets many of the goals and specifications that we aimed to achieve, it is still noticeably different from the yoyo purchased on Amazon. The most obvious differences between the two are the existence of defects and reduced yoyo sturdiness. The surfaces of the Amazon yoyo are very smooth and shiny, indicative of post processing, whereas our yoyo's surfaces are matte with some noticeable blemishes, including a small amount of flash on some pieces or visible marks where the runners were detached from the parts. Some of our pieces, such as the dial, also contain minor sink marks. Another noticeable difference in the appearance is how the respective logo is added to both yoyos – our yoyo contains a sticker, which must be manually placed after assembly, while the Amazon yoyo has a logo printed directly on the plastic. Aside from looks, our yoyo is also slightly more fragile than the Amazon yoyo. The Amazon yoyo has one very high quality, tight press fit, which makes it almost impossible to pull apart by hand. This fit is then further reinforced with screws and a small amount of glue, making it even more resistant to any sort of rough use or abuse. On the other hand, ours risks breaking when dropped due to looser press fits caused by variation in part shrinkage, spring pre-tensioning, and lack of other hardware reinforcements. However, despite these defects, our yoyo continues to function on a comparable or even higher level than the amazon yoyo, primarily due to its stable distribution of mass and significantly heavier weight. It also has a more complicated and exciting design than the Amazon purchased yoyo – including both a rotating and spring actuated dial.

Even with a functioning yoyo, there are a number of changes to the design and process that we would have to make in order to successfully sell our yoyos to customers. First we would need to eliminate the previously mentioned defects, including reducing blemishes, polishing the plastic after production, and changing the injection parameters, modifying our design, or using a different IM machine in order to reduce flash and sink marks. Second we would need to reinforce our yoyo using glue or another fastening method. This would ensure that the yoyo was safe and difficult to break, while an added fastening method would allow us to loosen the tolerances on our press fit parts, thereby reducing our part rejection rate when we move to a larger scale. We would also have to change our process and materials in order to mass manufacture the yoyo. This would include improving the spring addition step of the assembly process by reducing the need for highly manual, skilled labor, adding the bearing to the dial before the part has fully cooled in order to avoid cracking, and finding cheaper springs and bearings to use in our yoyo.

Overall, while our yoyo is both functional and unique, it could not currently be produced at a compelling price and sold on Amazon. Based on our cost analysis our yoyo would be very expensive to produce, costing around $17.40 per yoyo when produced at a quantity of 1 million, and $205.08 per yoyo when produced at a quantity of 100. The high fixed cost of our tooling, as well as the cost of the materials and hardware incorporated into each yoyo, would make it very difficult to turn a profit. Even if were to manufacture 1 million yoyos, we would need to sell each upwards of $20. This price is not competitive when most Amazon yoyos are of higher or comparable quality and cost under $10. However if we were able to decrease the skilled manual labor required for assembly, reduce defects, and find less expensive springs and bearings, it could be possible to produce and sell our yoyo on Amazon.