Gumball Yo-Yo Design & Manufacturing Final Report

Team K - The Gumbalumballers

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I. Introduction

The Gumbalumballers began with the goal of creating a high-performing yo-yo. We identified the following design elements as critical to this goal: a high moment of inertia, an ergonomic outer body, and a smooth, flat string gap. We decided to make a yo-yo inspired by a gumball machine. Due to a course policy prohibiting the purchase of actual gumballs and the favorable higher density of glass, marbles were selected as an analogue. The marbles function both as decorative and functional elements. Figure 1 depicts the yo-yo.

Figure 1. Left: The Final CAD of the yo-yo. Right: An assembled yo-yo

The yo-yo was designed around the marbles. The body features an internal raised star pattern (depicted in Figure 2) which, coupled with a raised ring, provides three points of contact for each marble, allowing marbles of different sizes to be positioned. A press-fit outer ring retains a thermoformed part which provides a window to see the internal marbles and creates a final fourth point of contact to apply force to contain the marbles. Due to concerns that the press-fit alone would be unable to retain the internal components in a drop, a “cap”—inspired by the knob on a gumball machine—was added[1]. The cap contains an insert-molded nut which screws into a 10-24 x 1-¼” set screw. Each body also contains an insert-molded nut, allowing them to screw into this same set screw. These can be seen in Figure 4. The cap also serves as an adjustable means of pre-loading the thermoformed part. This causes the thermoform to act as a spring, preventing the marbles from rattling. Figure 3 shows an exploded view of the solid model. A full bill of materials is presented in Appendix A.

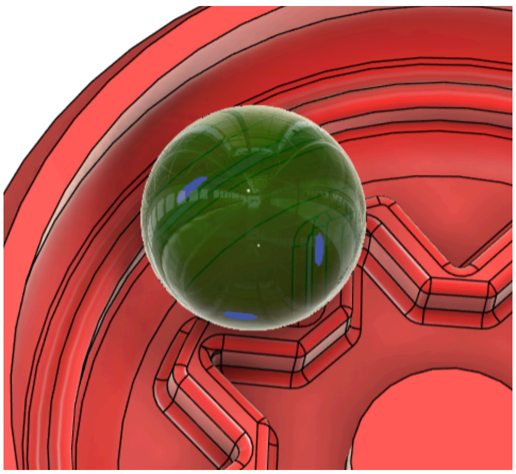

Figure 2. A single marble sitting within the body. Its 3 points of contact can be seen in blue.

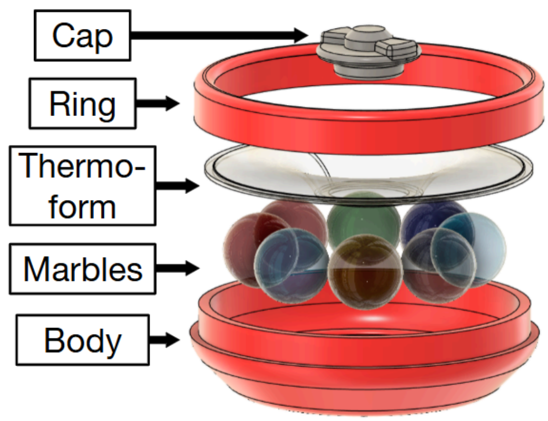

Figure 3. A labeled exploded view of ½ of the solid model. Excludes metal hardware.

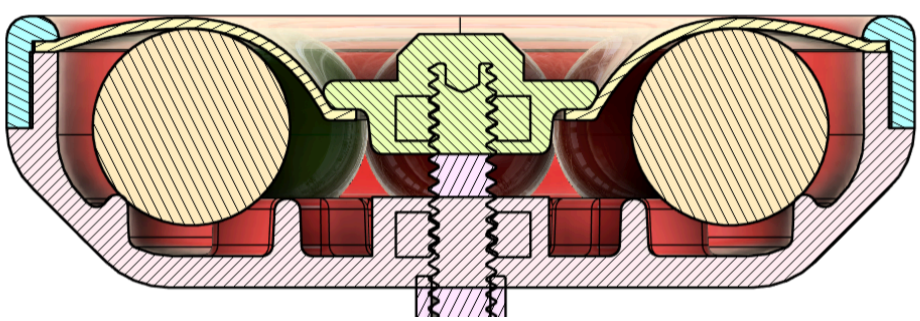

Figure 4. A section view of ½ of the yo-yo. Includes metal hardware.

The initial design and CAD model were done by Yaakov and Luana with Yaakov managing continued edits. Shrinkage analysis was done by Marlow. The body mold’s CAD and CAM were done by Paola. The ring mold’s CAD and CAM were done by Cristopher. The cap mold’s CAD and CAM were done by Amos. Shoulder bolts were

[1] Later testing confirmed the cap was necessary in order to prevent separation during drops.

made by Marlow and Luana. The thermoform mold was designed by Marlow. All group members participated directly in the machining, thermoforming, and injection molding. The poster was done by Cristopher, Paola, Marlow, and Yaakov. The report was written by all members with Amos and Luana taking larger roles.

II. Design & Manufacturing Analysis

A press-fit was used to retain internal components. The press-fit tolerance was derived from both the class recommendation and measurements of past yo-yo designs. Through this benchmarking approach, a target press fit interference of 0.0015 ±0.002 inches was established.

For shrinkage analysis, we integrated theoretical guidelines from lecture with computational simulation. Reference materials identified typical shrinkage ranges for various thermoplastic materials. These are shown in Figure 5. Given the critical press fit diameter experiences shrinkage perpendicular to the injection flow direction (lateral shrinkage) and the selected material is polypropylene (PP), the expected shrinkage range is identified as 1.8-2.1%.

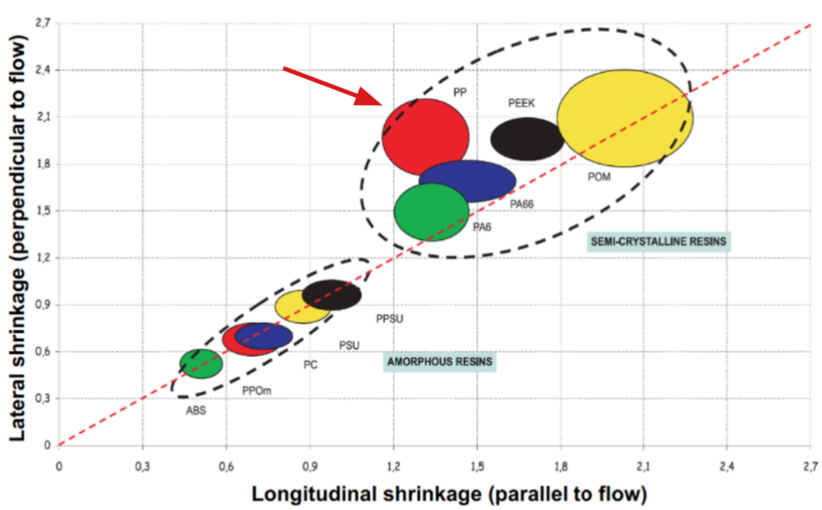

Figure 5. A chart indicating the typical shrinkage percentages for polypropylene and other polymers. Source: Lati.com

To validate these theoretical predictions, injection molding simulations were conducted using Fusion 360. The simulation presented shrinkage predictions of 2.4%

for the body component and 1.3% for the ring component. These shrinkage values fell outside the typical lateral shrinkage range for polypropylene. In order to reconcile the discrepancy between the simulation results and established material behavior, we chose a conservative approach, selecting shrinkage values just at the edge of the typical polypropylene lateral shrinkage range: 2.1% for the body component and 1.7% for the ring component.

A coordinate measuring machine (CMM) was used to verify dimensional accuracy of the manufactured molds. The body mold outer diameter measured 2.4551 inches, while the ring mold inner diameter measured 2.4324 inches. These measurements fell within tolerances (± 0.002 inches) of our specified dimensions of 2.456 inches and 2.431 inches.

During the injection molding process, we worked to adjust parameters to prevent manufacturing defects. Initial process parameters were established using default injection pressure and shot size as baseline values. Visual inspection of the molded body components revealed sink marks, indicating insufficient material compensation during the packing phase. To mitigate this defect, packing time was extended and the switchover stroke position was increased, allowing additional material to compensate for volumetric shrinkage during solidification. Additionally, cooling time for body components was reduced from 60 seconds to 30 seconds. This modification enhanced cycle efficiency and facilitated ejection by preventing excessive shrinkage of the part onto the core mold features. Similar steps were taken with the ring and cap.

After manufacturing, each body and ring injection-molded component from the first production batch was individually measured using Bluetooth digital calipers to assess manufacturing consistency and press fit compatibility. Statistical analysis of the body components revealed a mean outer diameter of 2.405 inches with a standard deviation of 0.0029 inches. The ring components exhibited a mean inner diameter of 2.397 inches with a standard deviation of 0.0077 inches. Applying standard uncertainty propagation methodology to the measured dimensional distributions yielded an estimated average interference fit of approximately 0.008 inches with a standard deviation of 0.009 inches. This is graphed in Figure 6.

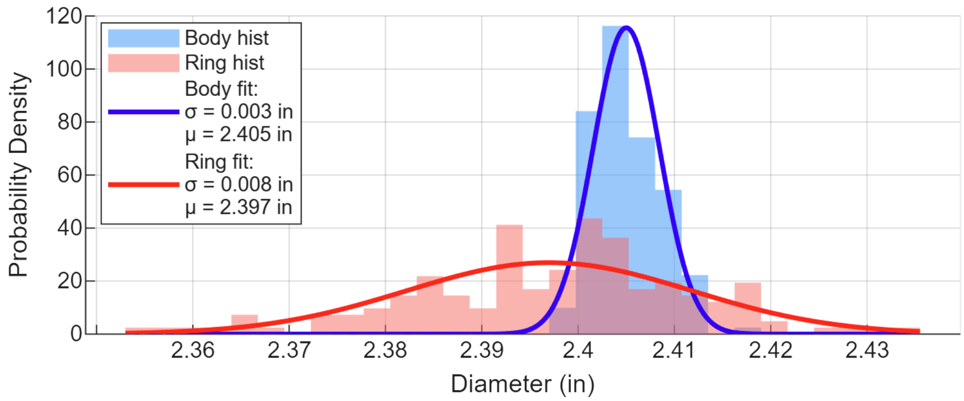

Figure 6. Distribution of the ring ID and body OD measurements. The ring measurements exhibit a large standard deviation due to measurement errors, preventing an accurate estimation of the interference distribution.

Despite our theoretical analysis of shrinkage factors, the measured press fit was much smaller than expected, with 0.008 inches measured average interference and 0.0015 inches desired interference. The relative over- and under-estimates of shrinkage factors reveal that shrinkage predictions from the Fusion Injection Molding simulation were likely more accurate to the actual shrinkage than the values on the material chart. The divergence of our observed shrinkage from theory indicates that geometry may affect shrinkage factors more than generic material properties, making simulation a more helpful metric for shrinkage analysis than static charts.

Due to limitations in the measuring process, the values for the interference fit were more varied than expected. One source of variation was the compliance of the injection-molded parts, as caliper pressure can cause the rings to deform and influence the resulting measured inner diameter. Additionally, small changes in injection molding parameters such as packing pressure, cooling, and ejector pin forces may have caused geometrical variation. Sources of random variation, such as mold wear and room temperature, may have also influenced the resulting parts. One possible modification to the process could be to measure the rings with a custom jig or visual measurement setup, such as a laser, to avoid mechanical deformation. Another future design modification would be to adjust the mold geometry to better match the measured shrinkage.

III. Design Journey

We themed our yo-yo around a gumball machine, with marbles to simulate gumballs. This immediately presented a question: What size and how many marbles? The decision depended on the target mass of our yo-yo. By weighing yo-yo's that we liked, we decided on a mass of 90-100 grams. The yo-yo's we measured that were similar to our design without marbles were about 40 grams, so we would need about 50 grams of marbles to reach our target mass. With a diameter of 14 mm and a density of 2.5g/cm^3, each marble weighs about 3.6 grams. We settled on 16 marbles for a predicted added mass of 48 grams. When designing the shape of the yo-yo, we modeled the inner curve based on one yo-yo from a previous year which we heard was designed by national yo-yo champion Alex Hattori.

The added mass of the marbles created the additional challenge that our press fit would need to hold more weight than the typical press fit. To avoid this issue, we decided to contain the thermoformed part with a screw and an injection-molded cap with a nut insert-molded into it. We considered insert molding the head of a hex bolt into the cap. This would have had the advantage of removing a degree of freedom from the assembly, so when disassembling the yo-yo we could unscrew each part from the bolt with the cap head one at a time. Ultimately, we decided that the lack of symmetry would have added too much complexity for a small advantage, and we proceeded with the original idea of using insert-molded nuts.

Mold production went mostly smoothly. We had to remachine the ring molds twice, the cap molds twice, and the body molds three times. Most of the errors were due to user errors in machining and post-processing (such as incorrect reaming and machining ejector pins on the wrong mold). However, we had an issue that wasn't caught in simulation: the tapered endmill created a small chamfer on the press fit face. This occurred while finishing the opposing side of the same groove. We solved this issue by increasing the width of the groove to accommodate the tapered endmill.

The thermoform mold underwent several revisions to address difficulty centering the sheets in the arbor press. We tried adding centering features and using a 3D printed tool to center them, but ultimately decided to return to the original mold while centering the sheets as precisely as we could by eye. We found that during assembly, the thermoform part was very flexible and didn't constrain how much we could tighten the caps. We modified the body mold to add a hard stop so we could tighten the caps to a consistent level.

Our final design was successful at containing the marbles and passing the drop test, but retained some flaws. After dropping the yo-yo, marbles sometimes pop out of their containment, misaligning the yo-yo's principal axes. It is possible this issue could have been avoided by modifying the body to contain the marbles on the inside of a star-shaped rib instead of the outside as shown in Figure 7. Had we used this design, the centripetal acceleration acting on the marbles would press them against a more stable base, and it would be harder to knock the marbles out of alignment.

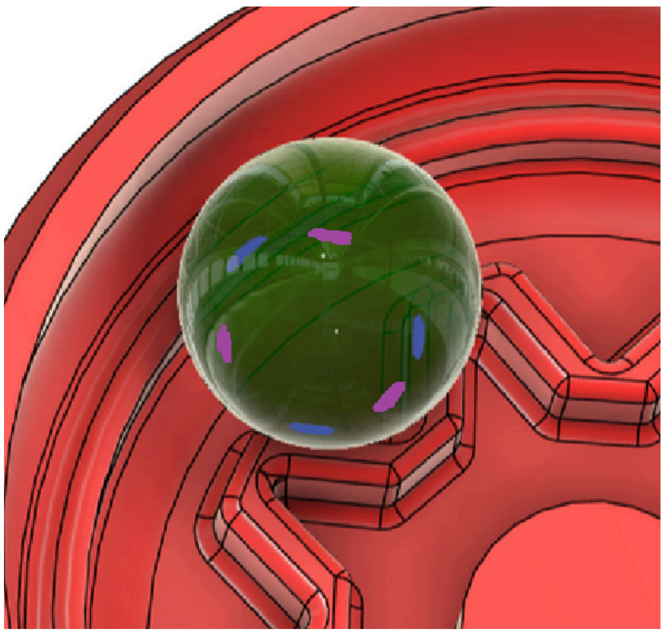

Figure 7. One marble with its current three lower contact points marked in blue. Contact with the thermoform occurs at the top (not shown). The alternative design (hypothetical contact points marked in purple) would have a ring on the inside (closer to the center) and the star shaped rib on the outside.

One last design flaw is the difficulty of disassembling. One can take apart a normal yo-yo easily by twisting the two halves against each other. However, attempting this with one of our yo-yos will potentially damage the thermoformed part because the caps need to be removed first. Despite these flaws, our yo-yo achieved its design goals to become a fun, functional, and unique product.

IV. Scale Analysis

Improving Current Production Process

Our objective was to produce fifty high-quality yo-yos with the resources in the LMP and a $250 budget. Although our production process emulated practices in mass manufacturing, there are many areas where our design would fall short if we attempted to manufacture one million yo-yos without sacrificing quality.

For example, automating the injection molding (IM) would be a necessary step towards mass production. For the most part, our IM parts required an operator to be present to start the machine after each cycle and remove any improperly ejected parts. This was especially problematic for the ring, which did not eject properly due to the lack of flat surfaces on the part. We attempted to guide the ejection via a runner connected by 3 points to the ring (Figure 8), but the ring still experienced ejection difficulties. Addressing these ejection issues would enable us to run automatic cycles, reducing cycle time and labor costs—critical factors in scaling up production.

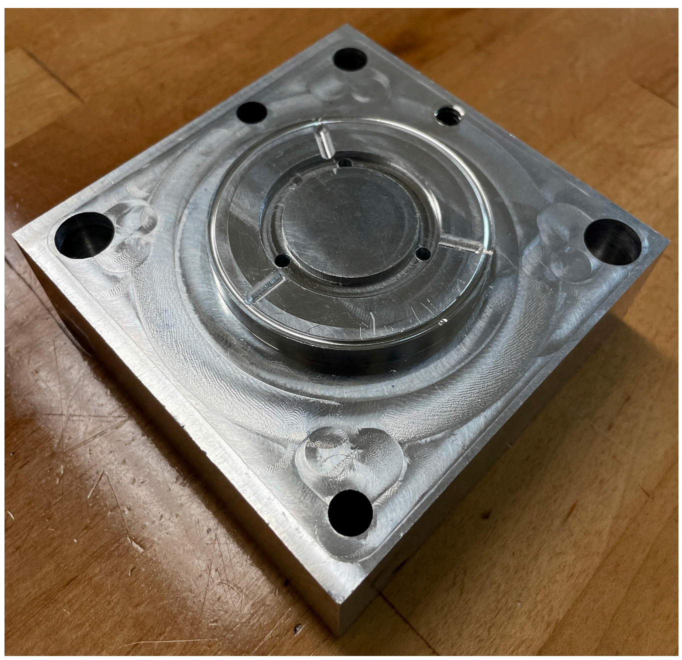

Figure 8. The three runners connecting the ejection surface to the ring

Reducing manufacturing time and improving repeatability for our thermoformed parts could be achieved at the stamping step. The current process requires visual alignment of the parts with both the stamp in the arbor press and with the stamp in the manual punch. This step takes about 40 seconds per part and does not always provide acceptable results. To address this, we could design a jig that self-aligns the part with the manual punch. Our team attempted this, but ran into issues and determined the time and effort to produce this jig would be greater than the effort required to visually align the remaining parts we had left to thermoform. However, it would be a necessary step for mass production.

Scaling Production

In addition to the injection molding and thermoforming process changes described, our team would need to address other assembly logistics and supply chain issues in order to scale production to manufacture 1,000,000 yo-yo's.

For example, although we developed specialized tools (Figure 9) to provide mechanical leverage when removing caps from the shoulder bolts and screwing the caps onto the set screws, the tool-cap interface would sometimes slip. This happened about once every six yo-yos due to the set screw being pushed through the cap and deforming it, so this step in the assembly process ranged from a few seconds to nearly a minute. The tool-cap interface could be improved by having a thicker cap; this would increase the contact area and decrease slip, decreasing the variability in assembly time. Using power tools to attach the caps could further decrease the assembly time.

Figure 9. Left: The tool used for shoulder bolt removal during injection molding. Right: The tool used to attach the caps during assembly.

Assembly time and variability could be further reduced by refabricating our shoulder bolts. Due to design changes, our previously manufactured shoulder bolts were too short, requiring the center hole to be drilled out. This region is highlighted in Figure 10.

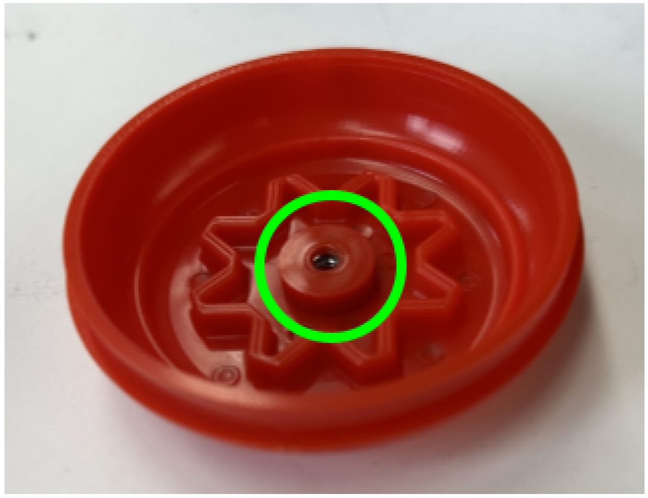

Figure 10. Yo-yo body. The center screw-and-bolt hole is circled in green.

Another issue for mass production is the large diametrical variation in the marbles purchased. We designed with the expectation of 14 mm diameter marbles, but the glass marbles we ordered had large variations in diameter and shape that we did not account for in our design. Having multiple marbles of different diameters and shapes in the same yo-yo prevented them from being tightly constrained. This caused an audible rattle and degraded performance during use. Although our marble sorter (Figure 11) ameliorated this issue for our low-volume production, we would need to source marbles from a more reputable manufacturer or produce our own marbles to a tighter tolerance to scale up. Doing so would eliminate the need for sorting, removing this assembly step.

Figure 11. Marble sorter with marbles.

Total Cost

Costs are an important consideration for high-volume manufacturing, specifically for tooling, equipment, materials, and overhead. In high-volume production, the unit cost to manufacture will approximate the variable costs.

Tooling costs in our process to manufacture 1,000,000 yo-yo's will be dominated by the costs of the molds purchased, the mold's lifetime, and the production volume. This relationship is described in Formula 1 of the table in Appendix B1. A reasonable estimate for the mold cost is around \$30,000 for the body mold and \$20,000 for the ring and cap molds.[2] This assumes we use SPI Class 102[3] molds, made of high strength steel, which lasts 500,000-1,000,000 cycles. Therefore, the tooling cost $C_{tooling}$ = \$0.06 - \$0.12 / part, depending on how long the molds last.

Since we are producing a single product, the only equipment costs will be the injection molding machine and thermoformer. Given the equipment cost formula (Formula 2 in Table B1), at a production rate of 560,000 parts per year, with 80% productivity, and using a second-hand IM machine (~\$50,000) and thermoformer (~\$20,000), $C_{equip.}$ = \$0.03.

[2] Using mold price range estimates by GoodTech MFG Group Limited.
[3] Since we are producing 1 million yo-yos, it is cheaper to use two sets of Class 102 molds than Class 101 molds since Class 101 molds require the utmost precision and hardened steel.

To estimate the material cost, Formula 3 in Appendix B1 is used. Our yo-yos are primarily made of polypropylene, which weighs \$1.50 / kg. At a dry mass of 50 g per yo-yo, and assuming 10% waste, $C_{mat.}$ = \$0.08 / part.

The main overhead costs will be associated with paying employees, facility rent, maintenance, and utilities. For a production facility with ~2-3 employees, a relatively small production floor, and regular maintenance, we estimate an overhead cost of \$500,000. Using the overhead equation in Table B1, Formula 4, $C_{o.h.}$ = \$0.90 / part.

Adding these four costs (Formula 5, Table B1) gives an approximate unit cost of C_{unit} = \$1.09. To appropriately price our product, we can apply a 40-50% gross margin (common for low-complexity plastic/mechanical toys), selling our yo-yos for \$1.80 - \$2.20. This assumes we are the manufacturer selling to wholesalers. However, if we were selling directly to consumers, we would bypass the retailer markups and could apply an 80% gross margin, selling each yo-yo for \$5.40.

V. Acknowledgements

We'd like to thank the folks in the Laboratory for Manufacturing and Productivity for their incredible support in making this project possible. We are especially grateful to our lab instructor, Tom Garcia, for his guidance, mentorship, and tutelage, and of course the many anecdotes about brass instruments. He kept us on track and made our time in the lab enjoyable. We'd also like to thank our laboratory assistant, Servando Avalos, for his guidance throughout the process. We were also supported by other LMP instructors, including Hannah Mishin both in the shop and the classroom as well as Dr. Josh Ramos and Wade Warman.

We'd also like to thank the 2.008 teaching team: Lecturers Dr. Kait Becker and Dr. John Liu as well as the teaching assistants Daniel Massimino, Minna Wyttenbach, and Seiji Engelkemier, for an incredible semester.

VI. Appendix

Table A: Bill of Materials (BOM) for Section I: Introduction

Part	Description	Acquisition	Qty. Per	Qty. Total
Body	injection-molded polypropylene with insert-molded nut, press fit with ring	Manufactured	2	100
Ring	injection-molded polypropylene, press fit with body	Manufactured	2	100
Cap	injection-molded polypropylene, insert-molded nut	Manufactured	2	100
Thermoform	0.030" thick, clear PETG	Manufactured	2	100
Marbles	14 mm, translucent colored glass	Purchased	16	800
Overmolded Nut	10-24 Zinc Plated	Provided	4	200
Spacer	¼” OD x ¼” Long, Unthreaded	Provided	1	50
Set Screw	10-24 x 1-¼" Long, Stainless Steel	Purchased	1	50
String	Colored twisted strand	Provided	1	50
Total	Unique Parts: 9		31	1550

Table B1: Relevant Formulas for Section IV: Scale Analysis

Number	Formula	Description
1	$C_{tooling} = c_t / N * Roundup(N/n_t)$	Tooling Cost
2	$C_{eq.} = 1 / n_{rate} * (c_m / (L * t_{wo}))$	Equipment Cost
3	$C_{mat.} = (m * c_{mat})/(1 - f)$	Material Cost
4	$C_{o.h.} = C_{oh} / n_{rate}$	Overhead Cost
5	$C_{unit} = C_{tool} + C_{eq.} + C_{mat.} + C_{o.h.}$	Total unit cost

Table B2: Relevant Variables for Section IV: Scale Analysis

Number	Variable	Description
1	c_t	Cost of Tool ($)
2	N	Production Quantity (# parts)
3	n_t	Tool Lifetime (# parts)
4	n_{rate}	Production Rate (# parts / yr)
5	c_m	Machine Cost ($)
6	L	Load Factor (%)
7	t_{wo}	Write Off Time (years)
8	m	Part Mass (kg)
9	c_{mat}	Material Cost ($/kg)
10	f	Scrap Fraction (%)
11	$c_{o.h.}$	Overhead Cost ($)