Final Report: Injection Molding Project

Group 10: Rebeka Duckett, Jake Gallardo, Anushri Radhakrishnan, Camila Solis
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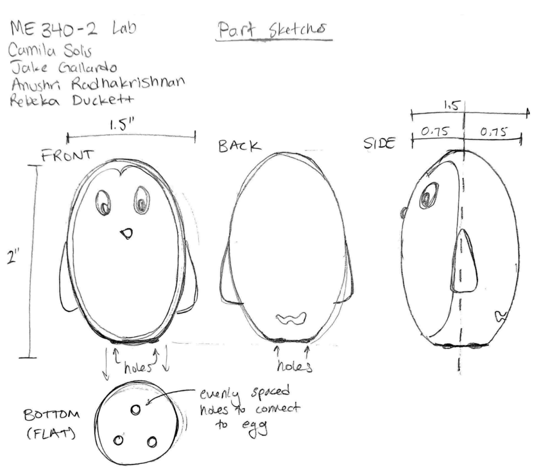
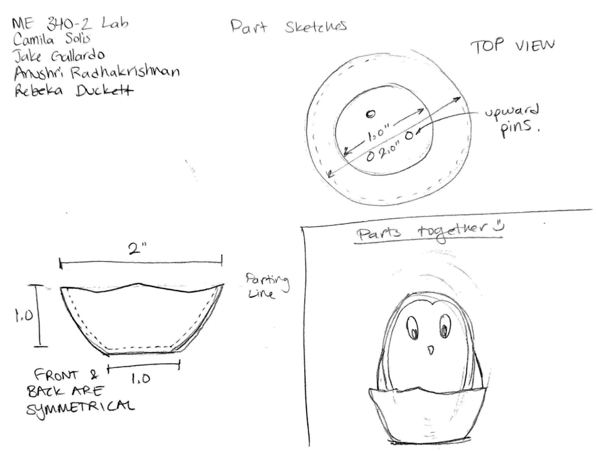
MECH_ENG 340-2

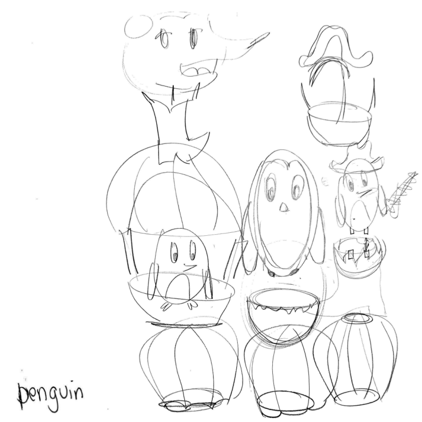
Introduction

We were tasked with creating an assembly of injection-molded parts by designing CAD models, molds, and CNC programming. Through this process, our group was introduced to the applications of injection-molded manufacturing, along with its advantages and limitations. The product we ultimately created was a penguin inside an open eggshell which we named Egguardo (she/her). The penguin consists of two parts: the front and back halves, which are connected by 4 pins with interference fits. The penguin is aligned to sit in the center of the egg through a hole on the bottom and an extruded pin in the center of the egg. As a result, our final product is the combination of 3 separate parts from 2 molds; the front and back of the penguin were produced using one mold, while the eggshell was produced using the other. This report outlines our design, process, and analysis of programs and parts.





Figures 1-2. Original Product Sketches

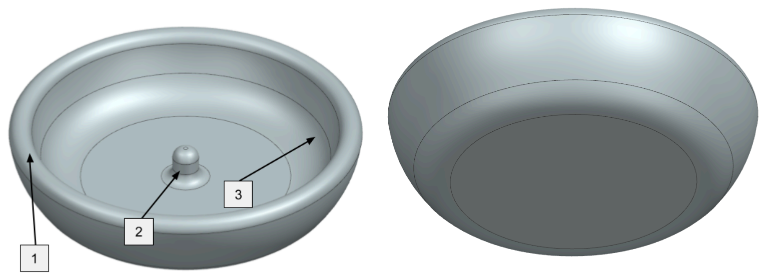


Figures 3-4. Original Concept Drawings

Figure 5. Penguin in Egg Render

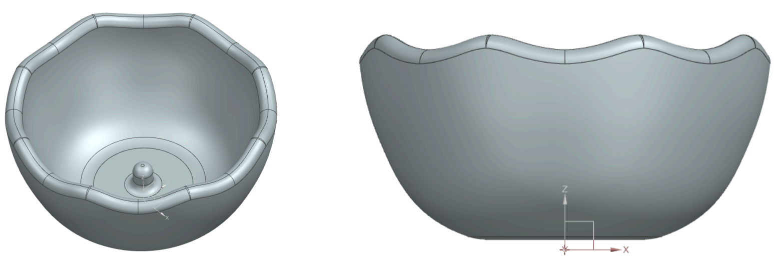
Part Design Overview

We will first discuss our design considerations for the egg, which can be seen in Figures 6-7 below. Dimensioned part drawings are available in Appendix A.



Figures 6-7. CAD of Eggshell with Highlighted Features

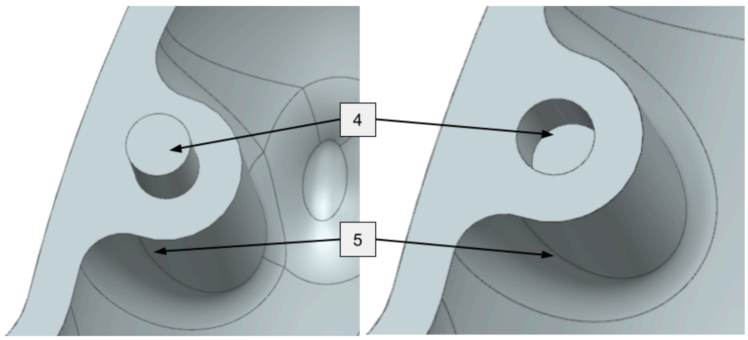
The final design of the egg is 0.5" tall with a maximum external diameter of 1.993" and a uniform wall thickness of 0.13". The height of 0.5" is limited by the length of the 0.0625" ball mill; most of which had flute lengths up to 0.4". The eggshell was originally designed to have a greater height, wavy edges, and an external diameter of 2", as seen in Figures 8-9.



Figures 8-9. CAD of Original Eggshell Design

This design was not compatible with machining capabilities due to interference between our smaller tooling parts and the walls of the egg. After applying the edge blend to the rim of the shell, the external diameter decreased to 1.993". This reduction did not interfere with the final assembly and was selected as the final dimension. The rim edge blend [1] removed all sharp corners in our design. The radius was set to 0.065" to maintain a consistent wall thickness of 0.13" throughout the part. Uniform wall thickness promotes even cooling conditions in the plastic after injection molding and prevents defects such as sink marks. The egg was initially 0.125" thick but later increased to 0.13" to account for CAM capabilities. The rim of the egg, in particular, was to be machined by a 0.125" ball mill to create a channel. When both the tool and rim diameter were equal, NX could not compute the CAM operation because the tool was engaged on all faces. On the interior base of the egg, there is an alignment pin [2] protruding from the center. This pin, which forms a rounded stub, has a cylindrical diameter of 0.15" and centers the assembled penguin in the eggshell when placed inside. Lastly, we designed the egg walls to all have convex curvature [3], preventing adherence to the mold walls post-injection molding, thus facilitating smooth part removal and preventing lodging within the molds.

Like the eggshell, the penguin is designed to have a uniform wall thickness of 1/16” throughout the part to prevent defects. The penguin front and back halves assemble via press-fit pins and holes [4] visible in Figures 10-11.



Figures 10-11. CAD of Penguin Pin and Pinhole

We used press-fit pins because they would be easily machinable compared to a snap-fit assembly configuration. The pin shown in Figure 10 has a diameter of 0.09375”, or 3/32”. Our pin diameter selection was limited by the metal pins available to us, which we would press fit into our molds before injection molding. The other viable options, 1/8” and 1/16” diameter pins, were not desirable: 1/8” required much thicker supports that would severely compromise the wall thickness in select areas and 1/16” was too small for us to trust that the interference fit would succeed. With the pin diameter selected, we next set the hole diameter as 0.0977”, or 1/256” greater than the pin diameter. This value was not calculated using the diametral interference equation, but rather selected with the help of our TA. We selected a pin height and hole depth of 0.125” so that a strong fit that maintains assembly while in use could be achieved without going too deep and creating thinner wall sections.

The pin locations were balanced symmetrically on each penguin half, placed equidistant from the top and bottom of the penguin’s “arms”. The wall thickness deviates from 0.0625” at the pin locations [5]. The maximum wall thickness surrounding the pins is 0.0918”. As expected, when injection molding, this contributed to uneven cooling and slight sink marks visible at the pins. However, these defects were hardly noticeable in the produced parts and the rest of the wall thicknesses remained consistent.

In addition to the pins, the penguin includes a hole to fit the alignment pin of the eggshell. To achieve this geometry in our injected part, we designed the CAD model with a shutoff feature [6]. This feature is further explored in the mold design overview. This hole can be seen from the penguin’s bottom view in Figure 12 below. This bottom face is also drafted 2 degrees [7] to ease in part removal from the mold as this was the only face in our design that lay perpendicular to the parting line.

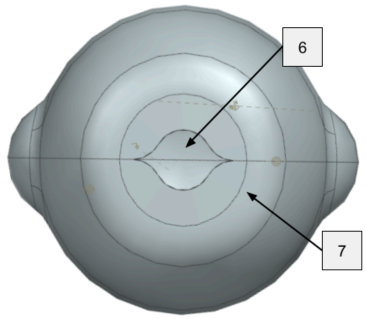


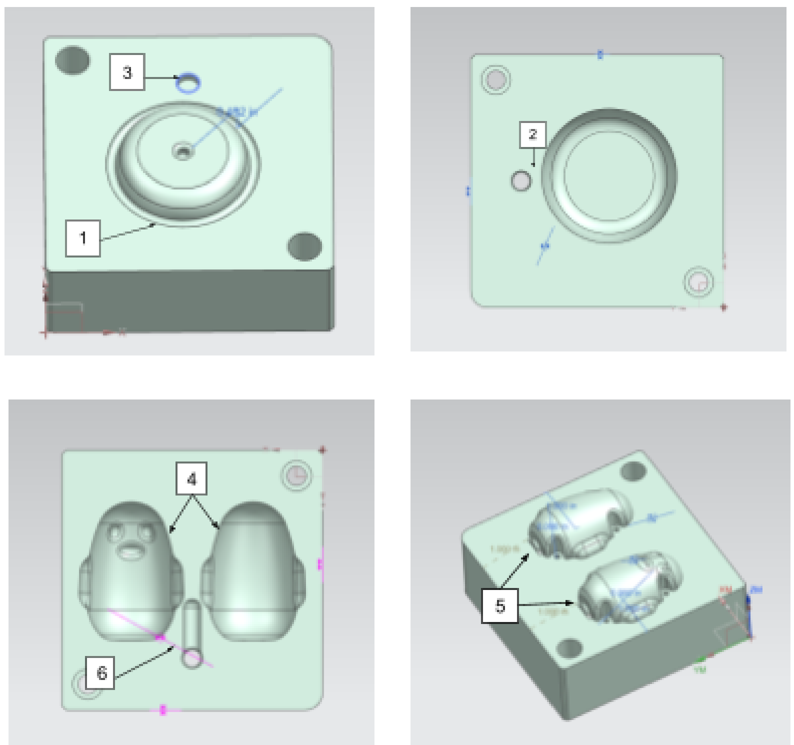
Figure 12. Bottom View CAD of Penguin

Aside from the parting line, all other features were designed with rounded corners and fillets. This minimizes stress concentration, reduces the likelihood of part failure or cracking during molding and use, and aids in part removal from the mold after injection molding. This is especially evident around the penguin's smooth facial features, rounded arms, and pinhole bosses.

Mold Design Overview

The design of the mold was determined based on the placement of the parting line, the orientation of the design, and the manufacturing and injection molding processes. Our mold dimensions did not account for shrinkage of the parts. However, we did mitigate the shrinkage through our injection molding process by increasing cooling time and temperature to provide a tighter packed part with less room to shrink. We set the parting line for the eggshell molds [1], at the edge of the rim. This splits the eggshell without impacting the part's aesthetics and aids the rest of the core's curved surface in facilitating mold release. To achieve this, the rim was subtracted from the core along this edge. The original eggshell featured uneven peaks and valleys on the rim. When simplified, the edge was easier to align with the core floor of the mold. In addition, the sloped faces of the eggshell core facilitated the removal of the molded part post-cooling, aided by shrinkage onto the core for simplified extraction. Rather than machining a runner, we directly gated the mold [2] with the eggshell placed 0.15" from the sprue. Eliminating the runner cut down machining time and reduced injected material waste. To better optimize material flow and trap any cold slugs, a cold well [3] was added to the eggshell cavity at the end of the sprue per the recommendation of our professor.

In designing the penguin molds, both penguin parts were placed in the same mold. Both parts had the same parting line [4] split along the front plane perimeter. This served as the easiest choice of parting line and only required the subtraction of the pins from the core through drilling. Each part also included a shutoff feature [5] near the bottom of each penguin half curving towards the core floor. The smooth transition between the mold cavity and core helps to reduce the risk of the part sticking or being damaged during ejection and mitigates flash. This resulted in a rounded diamond-shaped cutout though it ultimately is obscured from view in the final assembly. In injection molding, it was vital that the two molds were properly aligned and pressed closely together for this shutoff feature to work properly. Unlike the eggshell mold, the penguin mold includes a runner [6] extending from the sprue to the channel in between the two bodies. The runner and gate needed to be placed identically in each penguin half to ensure that both halves would be filled at the same rate, and thus cool evenly. To facilitate the assembly of these halves, pins and pin holes were incorporated into our design. We opted to streamline the manufacturing process by drilling all necessary holes for the mold. Prior to injection molding, metal dowel pins were press-fit into the holes surrounding the back half of the penguin. The features outlined above are depicted in Figures 13-16.



Figures 13-16. CAD of Mold Halve with Highlighted Features

Mold Manufacturing Overview

The CAM followed the operations and parameters outlined below.

Table 1. Penguin Core Operations and Parameters

#	Operation	Tool	Method	Depth of Cut	Stepover	Reasoning
1	Cavity Mill	EM_0.75	MILL_ROUGH	0.15”	25% Flat	Cuts the initial first 4 layers then stops so that the spot drill holder does not collide with the part.
2	Spot Drilling	Spot Drill	DRILL_METHOD	N/A	N/A	Creates the initial plunge so the drill can locate the correct pin location centers.
3	Drilling	Standard Drill #42	DRILL_METHOD	N/A	N/A	We used a slightly undersized drill so that the pin would properly fit in the pinhole and to account for any unwanted drill deflection.
4	3D Adaptive Roughing	EM_0.5	MILL_ROUGH	33% Tool	33% Tool	This is the continuation of the first roughing operation using a smaller tool to better fit between the two penguin bodies.
5	Area Mill	BM_0.5	MILL_ROUGH	33% Tool	33% Tool	More closely roughs the penguin faces.
6	Floor Wall	EM_0.25	MILL_ROUGH	0.0000”	33% Flat	Finishes the floor of the core so that the core and cavity correctly fit.
7	Area Mill	BM_0.25	MILL_ROUGH	33% Tool	33% Tool	Roughs the penguin faces with a smaller tool to fit in the gap between the penguin bodies and reach closer to the floor profile of the penguin faces.
8	Area Mill	BM_0.25	MILL_FINISH	33% Tool	0.0005” Scallop	Final finishing pass of penguin faces using 0.0005” scallop for a smooth surface finish with minimal material excess.
9	Solid Profile 3D	EM_0.125	MILL_ROUGH	0.0000”	50% Flat	Since the ball mill could not finish the flat edges along the profile, this operation first roughs the penguin's profiles.
10	Solid Profile 3D	EM_0.125	MILL_FINISH	0.0000”	50% Flat	Finishes the edges of the penguins along the core’s top floor.
11	Area Mill	BM_0.125	MILL_FINISH	10% Tool	33% Tool	Finishes the shutoff feature. The depth of cut was reduced to

						achieve a finer surface finish and mitigate tool deflections due to the tool's smaller diameter.
12	Cavity Mill	BM_0.125	MILL_FINISH	33% Tool	33% Flat	This operation finishes the penguin faces below the specified cut level (0.0765” above the core floor) where material remains near the bottom edges of the penguin faces.

Table 2. Penguin Cavity Operations and Parameters

#	Operation	Tool	Method	Depth of Cut	Stepover	Reasoning
1	Cavity Mill	BM_0.5	MILL_ROUGH	0.15”	33% Flat	Initial roughing pass of the penguin back using a ½” ball mill due to the part’s curved faces.
2	Cavity Mill	BM_0.5	MILL_ROUGH	0.15”	33% Flat	To save time, the initial roughing pass of the penguin front was separated from the first operation because the tool took time every layer to move back and forth between each part.
3	Area Mill	BM_0.5	MILL_FINISH	33% Tool	0.0001” Scallop	Finishing pass with the same tool for the back face. 0.0001” scallop provided the best surface finish without adding much time.
4	Area Mill	BM_0.5	MILL_FINISH	33% Tool	0.0001” Scallop	Finishing pass of the front face.
5	Area Mill	BM_0.25	MILL_FINISH	10% Tool	0.0001” Scallop	Finishes the back face with a smaller tool to reach material neglected in the previous operation.
6	Area Mill	BM_0.25	MILL_FINISH	10% Tool	0.0001” Scallop	Repeats operation 5 for the front face.
7	Planar Mill	BM_0.25	MILL_FINISH	0.0800	33% Flat	Roughs the cavity runner. The depth of cut was reduced to ⅓ of the tool diameter. Planar mill was chosen for efficiency and the runner's simple geometry.
8	Area Mill	BM_0.125	MILL_FINISH	33% Tool	0.001” Scallop	Finishes the front facial features that were unable to be cut by the larger tools. The stepover was slightly increased as it provided a

						similar surface finish as 0.0001" scallop.
9	Cavity Mill	BM_0.125	MILL_FINISH	0.04"	33% Flat	Finishes the runner and removes excess material remaining around the sprue hole and runner.

Table 3. Egg Shell Core Operations and Parameters

#	Operation	Tool	Method	Depth of Cut	Stepover	Reasoning
1	3D Adaptive Roughing	EM_0.75	MILL_ROUGH	0.15"	33% Flat	Initial roughing pass removing the bulk of the core blank using a larger tool and adaptive roughing to increase efficiency.
2	3D Adaptive Roughing	EM_0.75	MILL_FINISH	0.15"	33% Flat	Finishing pass, targeting the core floor surface finish.
3	Area Mill	BM_0.5	MILL_ROUGH	0.15"	33% Flat	Roughs the curved face of the egg using a smaller tool diameter and switching to a ball mill to better machine the curved faces.
4	Area Mill	BM_0.5	MILL_FINISH	0.15"	0.001" Scallop	Finishing pass of the previous operation changing the stepover to 0.001" scallop for a better surface finish.
5	Area Mill	BM_0.125	MILL_FINISH	10% Tool	0.001" Scallop	Finishes the egg with the ¼" ball mill for an even better surface finish. Because the smaller tool is less rigid the depth of cut was reduced to 10% tool.
6	Cavity Mill	EM_0.125	MILL_ROUGH	0.04"	33% Flat	Roughs the cold well for the sprue. The depth of cut was reduced to a little under ⅓ the tool diameter.
7	Cavity Mill	EM_0.125	MILL_FINISH	0.04"	33% Flat	Finishes the cold well with the same tool.
8	3D Adaptive Roughing	EM_0.0625	MILL_FINISH	33% Tool	33% Tool	Roughes the peg using the smallest tool available due to the peg's small diameter. We were unable to specify just the peg geometry for the cut area, resulting in some unwanted random marks around the egg's surface.
9	Area Mill	BM_0.0625	MILL_FINISH	10% Tool	10% Tool	Finishing pass for the previous operation. The depth of cut and

						stepover was reduced to 10% of the tool to mitigate tool deflection. The peg surface finish is not as important as the penguin will obscure it from view.
10	Planar Mill	BM_0.125	MILL_FINISH	0.0000”	33% Flat	Finishes the rim of the egg using a planar mill to simplify the toolpath.

Table 4. Eggshell Cavity Operations and Parameters

#	Operation	Tool	Method	Depth of Cut	Stepover	Reasoning
1	3D Adaptive Roughing	EM 0.75	MILL_ROUGH	0.15”	33% Tool	Initial roughing pass to remove the bulk material of the cavity. Specified a helical engagement for the tool entry with an extended ramp length and lowered angle to guarantee safe engagement.
2	Cavity Mill	BM 0.5	MILL_ROUGH	0.15”	25% Flat	Roughes with a ½” ball mill while reducing stepover to increase surface finish and reduce cutting forces.
3	Cavity Mill	BM 0.5	MILL_FINISH	0.15”	25% Flat	Finishes with the previous tool.
4	Area Mill	BM 0.25	MILL_FINISH	10% Tool	0.001” Scallop	Finishes with a ¼” ball mill to reach excess material not cut by the previous operations. The stepover was reduced to 0.001” scallop for the best surface finish.

Overall, the CAM process went smoothly. The largest obstruction to the CAM process was the limited tool heights for the 1/16” and ⅛” tools. With our original egg design, we encountered difficulties due to inadequate consideration of tool and tool holder dimensions. Drawing from this experience, meticulous measurements of tool lengths and tool holder offsets were undertaken to ensure the seamless execution of subsequent CAM programs. These adjustments constituted the bulk of our modifications.

During the machining of the eggshell core, a critical oversight emerged when the x and y planes offset in opposite directions. This led to the misalignment of the molds by 0.2” in both directions. Nevertheless, the machining operation proceeded without incident, only needing the re-execution of the program with a proper offset.

Another significant challenge encountered in the CAM process pertained to the drilling of pinholes, particularly due to the intricate geometry surrounding these locations. Initial attempts at this program proved difficult, requiring an interruption of the initial roughing operation to allow ample clearance for the spot drill and drill without risk of holder collisions with the core. Minor issues, such as excess material accumulation around the core edges from finishing the core floor, were also observed. These were addressed through light sanding and filing of the final molds to enhance the surface finish and rectify minor imperfections.



Figures 17-19. Mold Manufacturing Process

Metrology Overview

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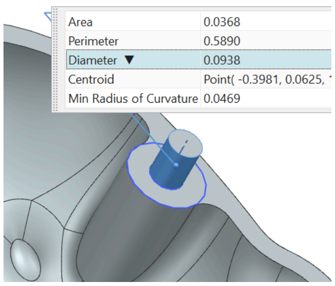
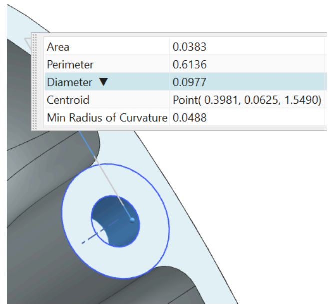
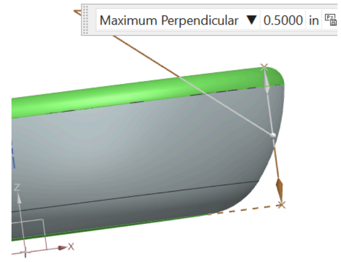
Pin Diameter</th><th>Penguin Back Half:
Hole Diameter</th><th>Egg:
Height</th></tr>
<tr><td>

0.0938” + 0.000”/ -0.002”</td><td>

0.0977” +.002”/- 0.000”</td><td>

0.5” ± .01”</td></tr>
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Figures 20-22. Specified Measured Geometry

In order to create a snug assembly of the two halves of the penguin, tolerances for the pin and hole of the penguin were calculated with a locational clearance fit in mind. The hole diameters were also designed with an increase of 1/256” greater than the pin diameter to have a clearance small enough to maintain assembly between the parts. For the egg, we decided on loose tolerances as it would not have a significant effect on the rest of the dimensions of the egg.

Through injection molding, we produced over twenty pieces for each part of the assembly and collected production data on the process. The injection molded parts closely matched the CAD design, showcasing our smooth surface finish. To assess the accuracy of the manufacturing process, we selected specific dimensions of each part to measure. Taking into account that polypropylene shrinks approximately 1-2.5% (Intertech Machinery), we expected the measurement values to be on average smaller than dimensioned in the CAD drawings.

In the depicted front half of the penguin, illustrated in Figure 20 above, the nominal diameter of the bottom left pin was set at 0.0938”. The average pin diameter measured from the 20 parts was 0.0867”, 0.0071” less than the nominal value, indicating a decrease of approximately 7.5%. This strayed much farther from the specified value than the expected shrinkage of 1.5-2% and is apparent in Figure 23 below. The reason for this significant difference can be attributed to the volume of plastic in the pin. While the pinhole was formed by injecting a thick supporting feature around an inserted metal dowel, the pins themselves were formed only by filling up empty space within the mold without additional support beyond the base. As a result, the pins have far less volume and thus could be unevenly affected by shrink. The standard deviation of production was 0.0006”. While the standard deviation falls under the specified tolerance listed above in Figure 20 and indicates a high precision and repeatability in the process, the values are skewed significantly below the minimum accepted value. Measurements were conducted using calipers and pin gauges. Factors such as variation in caliper angle and plastic softness could have influenced these measurements. Due to the softness of the plastic, the pressure at which the calipers were clamped to the pin could cause the plastic to give in, reducing the measured diameter. In conjunction, the angle at which the calibers were placed beside the pin may have caused varying diameters.

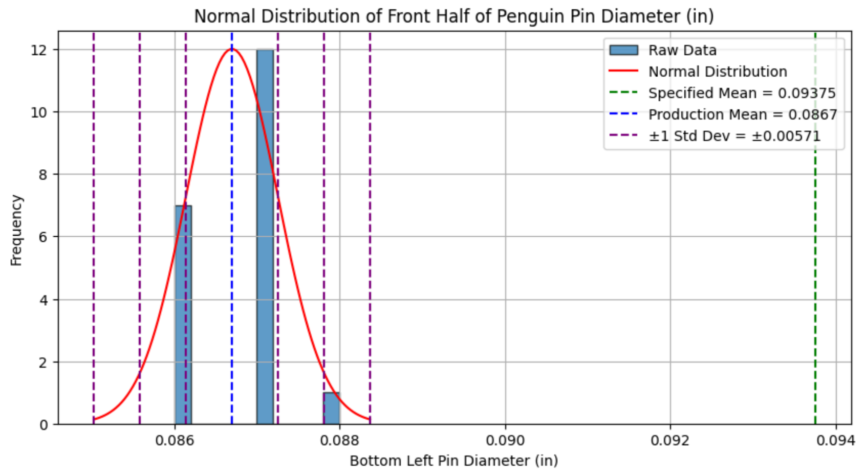


Figure 23. Pin Diameter Production Data

For the back half of the penguin, the diameter of the bottom right pinhole was measured. We chose to measure this feature because this is the pinhole in which the other measured pin fits. The nominal diameter of the pinhole was set at 0.0977” to account for the desired clearance fit of the pin. However, we want to note that the drill used during the CNC process was 0.0935” in diameter. This was to ensure a press fit for the 0.0938” metal dowels placed in the holes of the back half of the penguin for the injection molding process. The average size of the pins measured from the 20 complete parts in production was 0.094” which was smaller than the nominal by 0.0037” (3.7% decrease). The standard deviation calculated was 0.0016”. While the difference in size between the specified and measurement values was a smaller percentage in which the majority of the error could be attributed to shrinkage, the standard deviation was still larger than the specified. The lower precision in the parts may be a factor in the method of measurement. Pin gauges were employed to measure the holes for these parts using a go-no-go method. With pin gauges, slight variations in how the gauge sits within the hole or against the surface can lead to measurement errors. In contrast to calipers, which offer finer measurement increments, pin gauges have a fixed diameter and a narrower range of measurement options. This limitation can lead to less precise measurements, particularly for dimensions that fall between available gauge sizes.

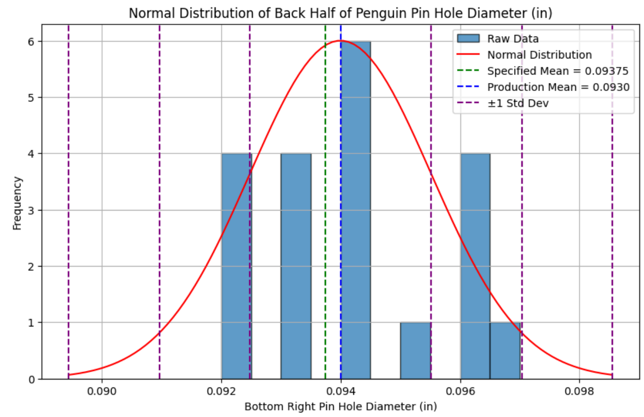


Figure 24. Pin Hole Production Data

For the eggshell, we measured the height from the base to the top of the rim. Calipers were used to measure this, though it was difficult to maintain even and consistent contact with the two surfaces. To mitigate error in measuring against the curved surface of the egg, the height was measured by placing the part between two parallel blocks and measuring the distance between the blocks. While we did make efforts to minimize possible procedural errors, additional factors such as the angle of measurement or the additional pressure of the blocks compressing the piece, could have increased the difference in values. The nominal height was set at 0.5”. The average height measured between the parts was 0.4827”, approximately 0.0173” less than the nominal dimension (3.5% decrease). This difference, similar to the pinhole, is closer to our expectations with shrinkage. The standard deviation was 0.0029” as shown below in Figure 25. Given the looser tolerance provided for the egg, the standard deviation fell within the tolerance.

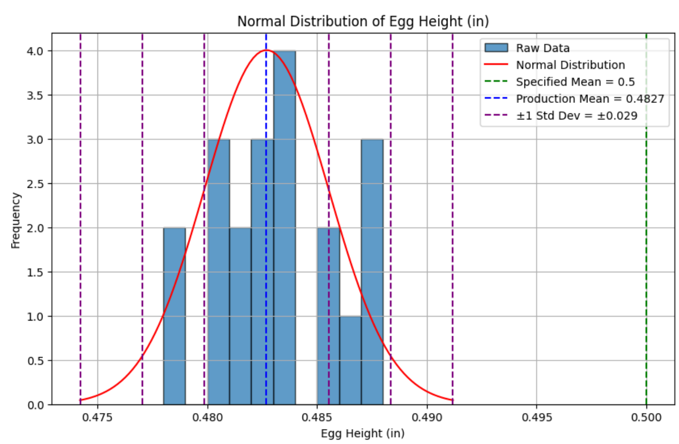


Figure 25. Egg Height Production Data

The observed differences in part sizes were primarily attributed to material shrinkage. Another contributing factor included the measurement process due to the precision of the tools used and the material of the part itself. The use of a slightly smaller CNC drill diameter than the specified dimension played a role in the size difference of the pin diameter, drilling a hole of .0935” as opposed to .0938”. Notably, the pin dimension exhibited the largest deviation from nominal, albeit with a small standard deviation indicating high precision and repeatability within tolerance. Even though the pin and hole were not to the tolerances specified, and the hole diameter, in particular, exceeded the negative tolerance, due to the universal shrinkage of both parts, the relative size difference of the pin and hole was maintained and thus still was able to create the fit we desired.

Conclusion

Throughout the injection molding project, our group encountered various successes and challenges in designing, manufacturing, and analyzing the production of the penguin assembly. Despite facing several obstacles, including CAM program difficulties, machining miscalibrations, and measurement inconsistencies, we produced injection-molded parts that closely aligned with our CAD designs, demonstrated successful assembly, and excellent surface finishes.

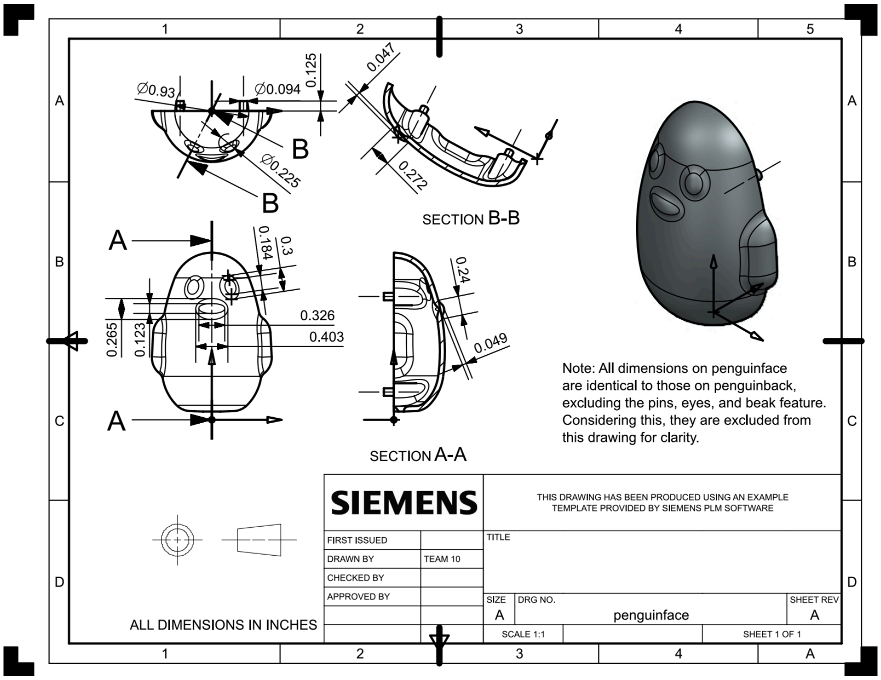
One notable challenge we encountered was the discrepancy between the nominal dimensions specified in our CAD models and the actual measurements of the produced parts. This deviation, particularly evident in the pin diameter measurements, highlighted the influence of factors such as material shrinkage, machining tolerances, and measurement errors. Despite meticulous planning and execution, these discrepancies underscored the importance of continuously refining our processes to achieve more accurate and consistent results. Additionally, the use of calipers for measurement compared to pin gauges revealed limitations, particularly due to the uncertainty of placement and flatness while measuring and the increased influence of human error. This observation emphasizes the importance of selecting appropriate measurement tools and techniques tailored to the specific requirements of the project.

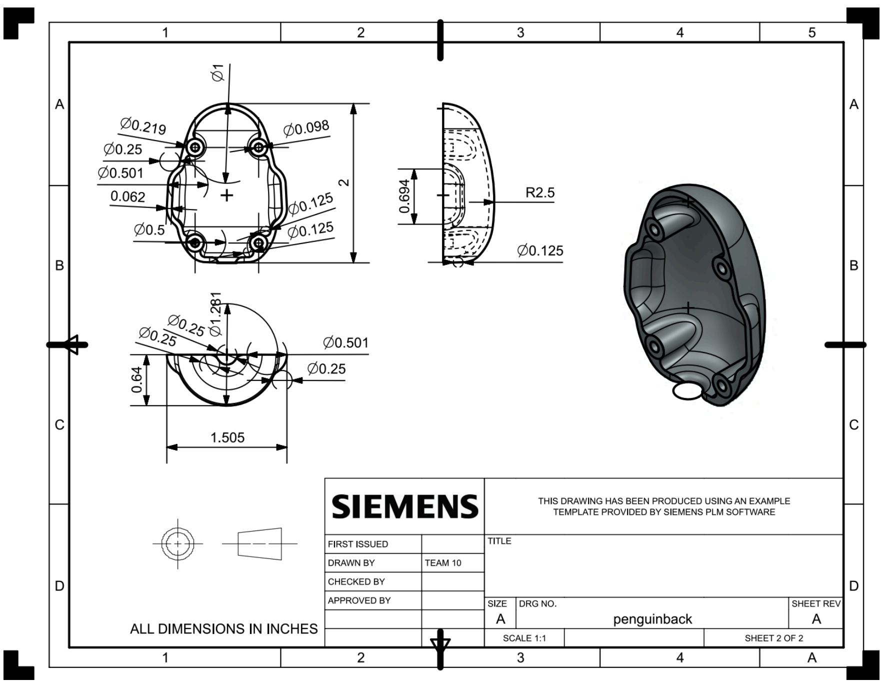
Moving forward, modifications to the molds could address some challenges encountered during the project. For example, optimizing the CAM programs to account for tool dimensions and machining limitations from the onset could minimize collisions and improve overall efficiency in the CAM. This would eliminate the need for so many part revisions due to unknown tool heights. We could also add stronger drafts to the walls of the egg mold near the parting line to aid in part removal after injection molding. Additionally, refining the mold alignment procedure could enhance the accuracy and consistency of the injection molding process.

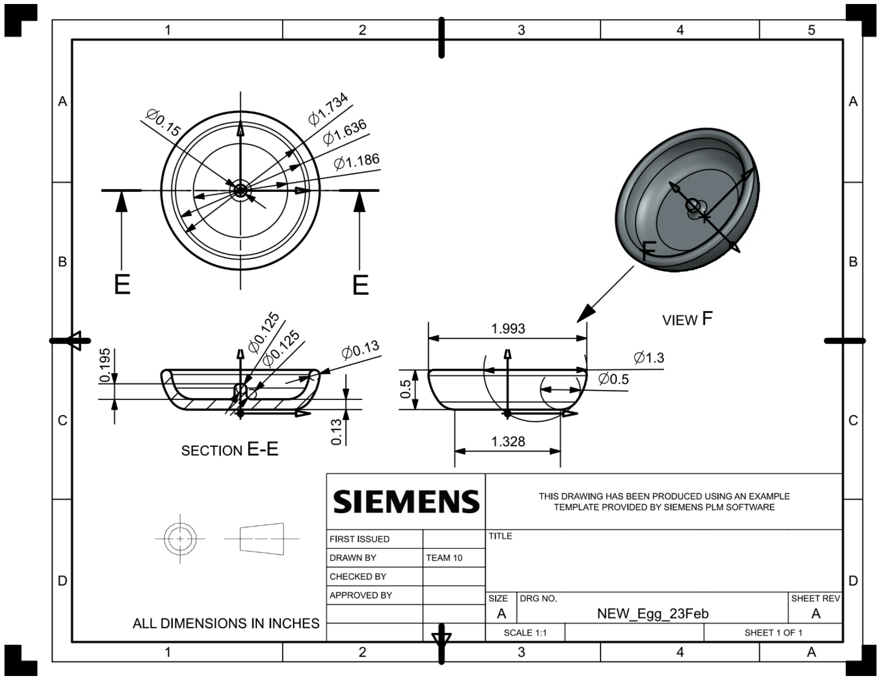
In conclusion, while our injection molding project presented numerous challenges, it also provided valuable insights into the complexities of manufacturing processes and the importance of meticulous planning, execution, and continuous improvement. By addressing the identified issues and implementing suggested modifications, we can further enhance the quality, accuracy, and efficiency of future injection molding projects.

Appendices

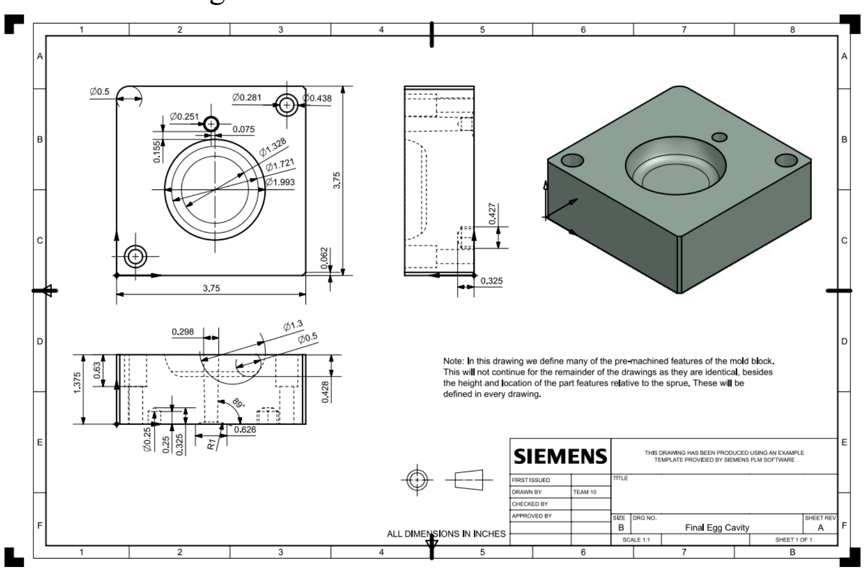
A. CAD Drawings of Parts

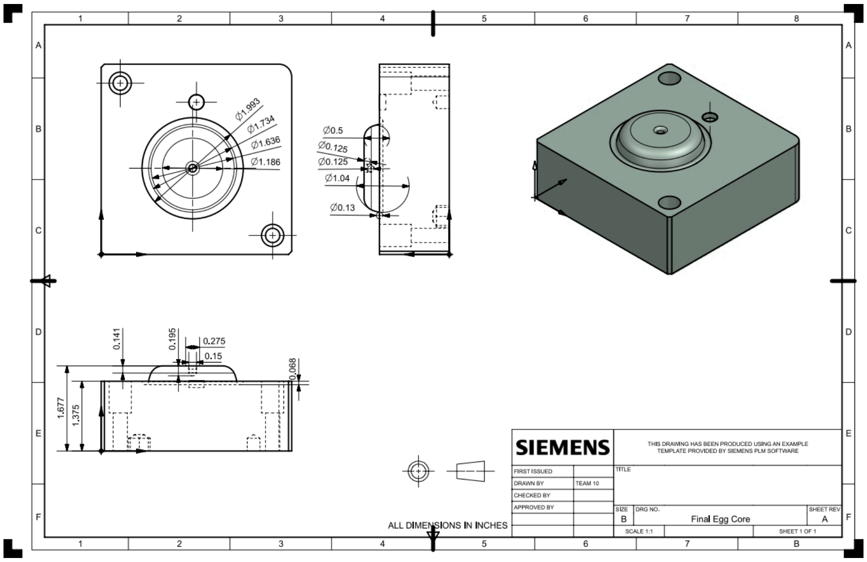


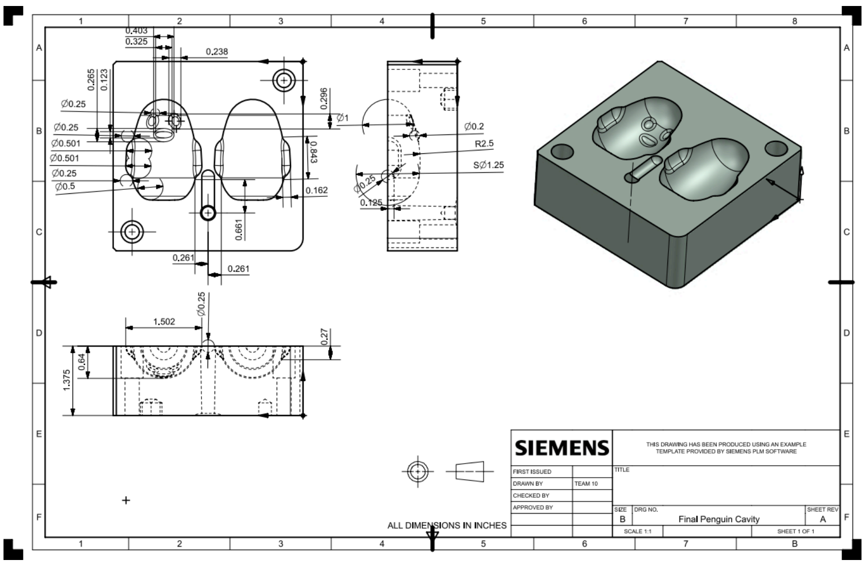




B. CAD Drawings of Molds




SIEMENS
THIS DRAWING HAS BEEN PRODUCED USING AN EXAMPLE TEMPLATE PROVIDED BY SIEMENS PLM SOFTWARE
FIRST ISSUED
DRAWN BY
TEAM 10
CHECKED BY
APPROVED BY
TITLE
SIZE
B
DRG NO.
Final Egg Core
SHEET REV
A
SCALE 1:1
SHEET 1 OF 1
ALL DIMENSIONS IN INCHES


SIEMENS
THIS DRAWING HAS BEEN PRODUCED USING AN EXAMPLE TEMPLATE PROVIDED BY SIEMENS PLM SOFTWARE
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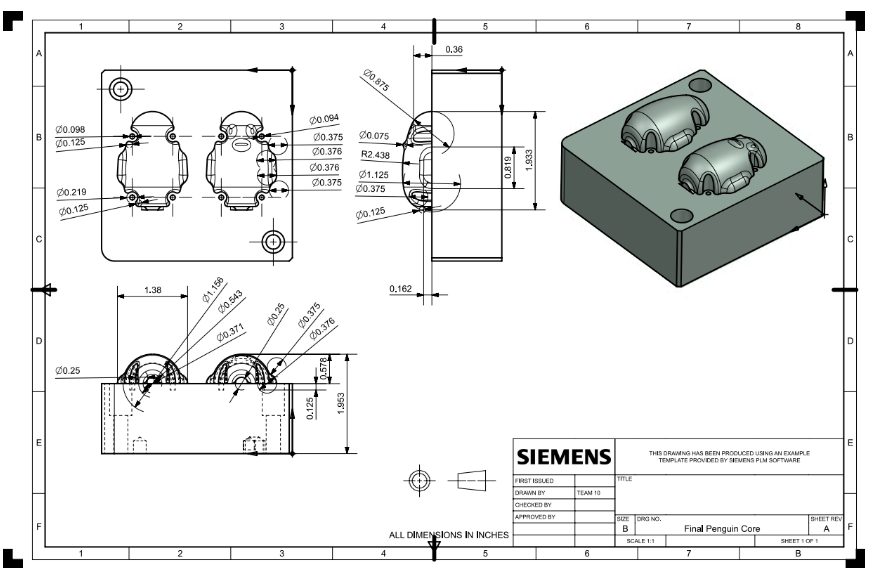
TITLE
SIZE
B
DRG NO.
Final Penguin Cavity
SHEET REV
A
SCALE 1:1
SHEET 1 OF 1
ALL DIMENSIONS IN INCHES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TITLE
SIZE
B
DRG NO.
Final Penguin Core
SHEET REV
A
SCALE 1:1
SHEET 1 OF 1
ALL DIMENSIONS IN INCHES

C. Production Data

Part No.	Pin Diameter (IN)	Pin Hole Diameter (IN)
2	0.087	0.095
3	0.086	0.096
6	0.087	0.094
7	0.087	0.093
9	0.088	0.094
10	0.087	0.092
11	0.086	0.092
14	0.086	0.093
15	0.087	0.096
16	0.087	0.096
17	0.086	0.094
18	0.087	0.094
19	0.086	0.096
20	0.087	0.097
21	0.086	0.094
22	0.087	0.094
28	0.087	0.092
30	0.087	0.093
31	0.087	0.092
32	0.086	0.093
Average	**0.0867**	**0.094**
Standard Deviation	**0.0005712405706**	**0.00155597321**

Part No.	Egg Height at Gate (IN)
3	0.482
4	0.48

5	0.487
6	0.48
7	0.481
8	0.478
9	0.478
10	0.485
11	0.481
12	0.483
13	0.48
14	0.488
15	0.485
16	0.482
17	0.483
18	0.487
19	0.483
20	0.483
21	0.482
22	0.486
Average	**0.4827**
Standard Deviation	**0.002903718125**