ME 340-2 Final Report
Winter 2025

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Introduction

In this project, we began by brainstorming different ideas for our injection molded part. Our combined efforts resulted in the ideation of two parts: an axolotl and a boat. The final assembly involves the axolotl freely riding atop the boat. Some of our initial concept sketches are shown in figures 1a and 1b.

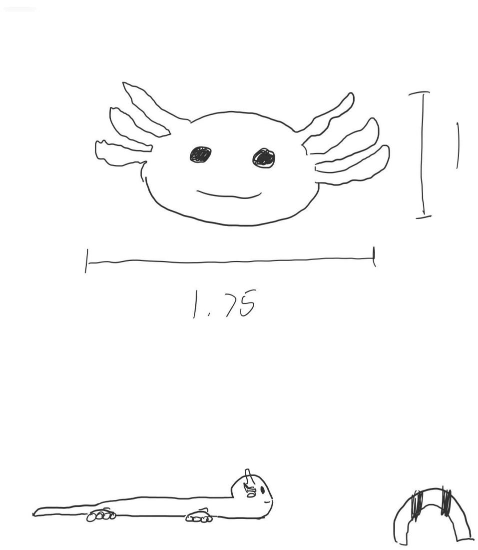


Figure 1a: Sketch of simplified axolotl

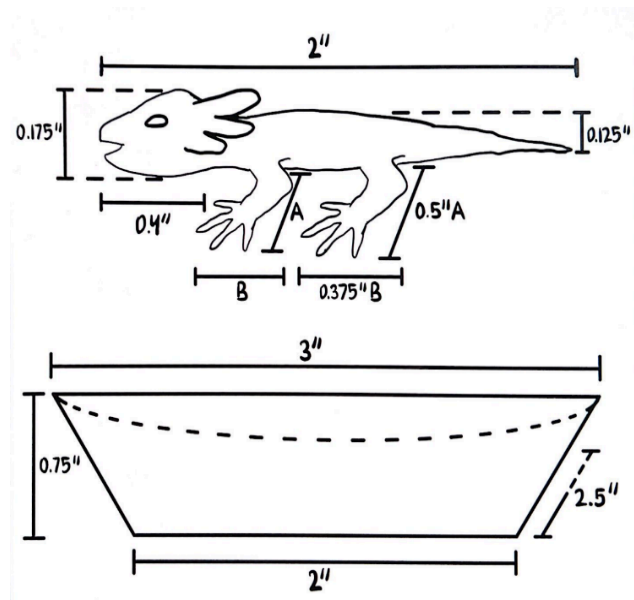


Figure 1b: Sketch of axolotl and boat aligned

Figure 1c: Photo reference of axolotl

We used NX CAD to design the axolotl body and gills (as two separate parts to be assembled); both parts were placed into the same mold for machining. The boat was designed on a separate mold; we split the boat into two symmetrical halves to increase the size of the final assembly (essentially requiring two injection runs to produce one boat). Using the provided part blank models, we designed the core and cavity molds and machining processes, for each part, through NX CAM. Using the Haas CNC machines in the Ford machine shop, we machined our cavities and cores into aluminum blanks. After that, we used the injection molding machines to make our parts out of plastic (polypropylene) and assemble them together. Figures 2, 3, and 4 show our CAD models in NX for the final product. The following report outlines the injection molding process from start to finish.

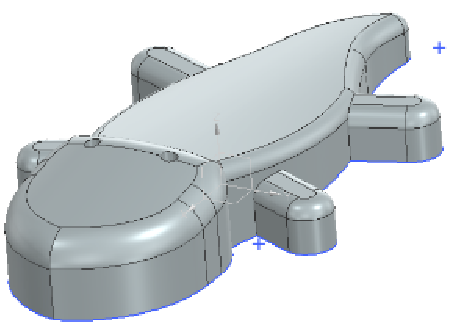


Figure 2a: Axolotl CAD Model
(isometric view)

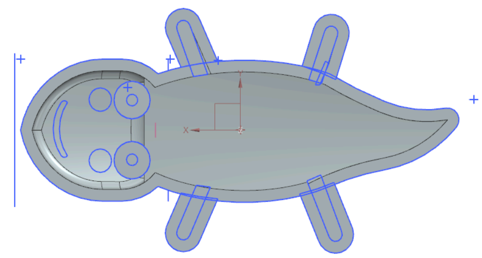


Figure 2b: Axolotl CAD Model
(bottom face)

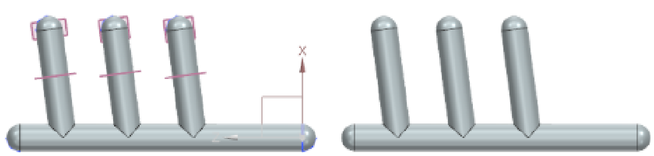


Figure 3: Axolotl Gills CAD Model

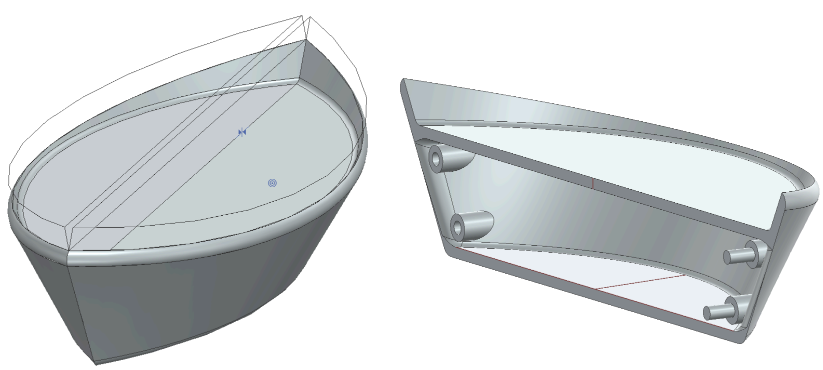


Figure 4: Boat CAD Model

Design Overview

The Axolotl has several features in its design that are catered to injection molding, first of which is its near-uniform wall thickness. Across the entire part, the wall thickness is 0.0625”. This is nearly uniform with few variations, those of which being no greater than +/- .010”.

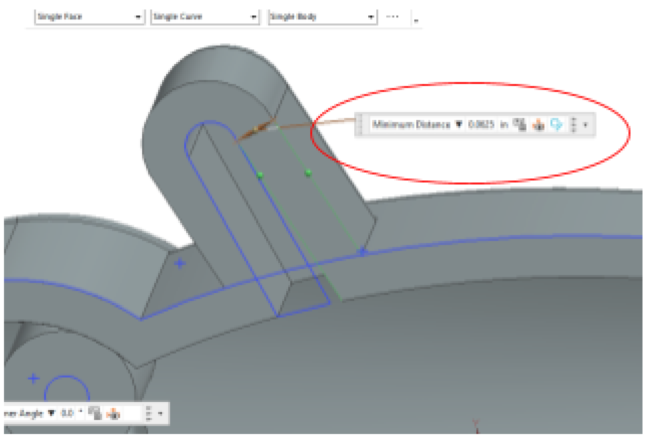


Figure 5a:
Axolotl Uniform Thickness

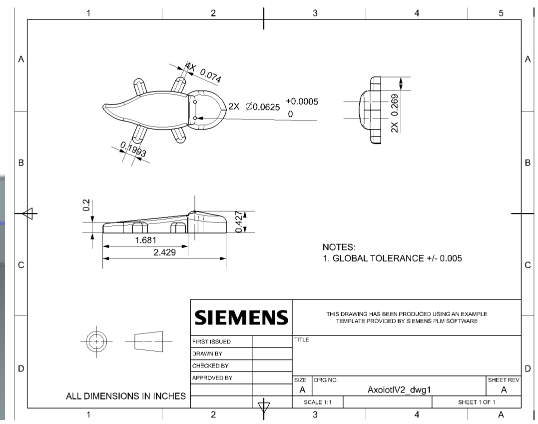


Figure 5b:
Axolotl Part Drawing

The model includes holes for its gills to be inserted. This is visible in the cross section view below.

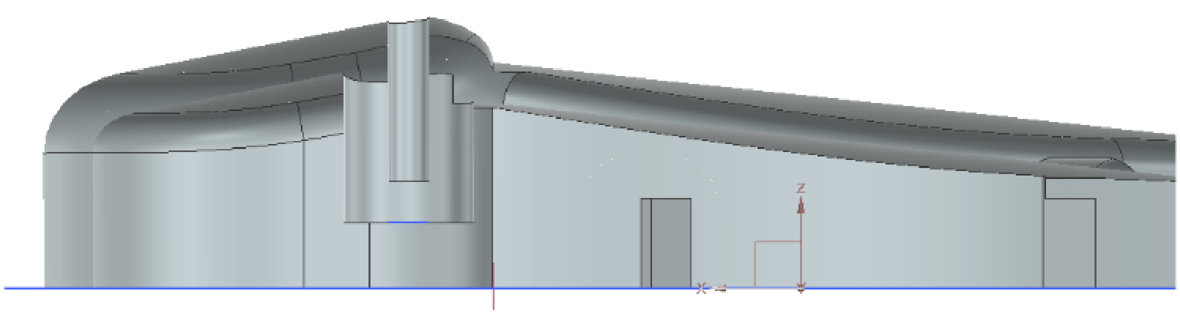


Figure 5c: Axolotl Cross Section

The model also has 1° of draft on the inner face. This consideration allows the part to be more easily removed from the mold and avoids sticking to the core later in the injection molding process.

The gills attach to the axolotl through a press fit in the holes on the axolotl’s head. The holes are made using 1/16” dowel pins. The following are calculations made for the sizing of the gills:

Desired diametral Interference (δ): 0.01 inches

Diameter of desired gill size (D_{gill}): 0.0625 inches
Young's Modulus of Polypropylene (E): 1.3 GPa
Contact Pressure (ρ): $\rho = \frac{\delta}{Dgill \times (\frac{2}{E})} = 0.104\, GPa = 67096.6\, \frac{N}{in^2} = 15080\, psi$
Or simply, interference fit = diameter of gill - diameter of hole

With 0.0625 inch dowel pins and a desired interference fit of 0.01 inches, our axolotl gills would need to have a diameter of 0.0725 inches. However, we decided that machining would be simpler if the gills were the same diameter as the tool (0.0625 inch ball mill), which would create the part geometry in a single pass. Alternatively, the interference would come from gate removal, as it would add residual material (from imperfect trimming) to the surface of the gill's sides.

When designing the gills, the original concepts of the gills included additional assemblies and curved geometries (see figure 6a, 6b). We decided not to go through with the original because the machining process would have been a nightmare. We opted to simplify the real life geometry of an axolotl's gills to three appendages attached to a mounting rod. The appendages represent the three gills of an axolotl while the rod is intended for assembly with the axolotl body (see figure 3). The finalized gill design has rounded corners for easy part removal and simple machining.

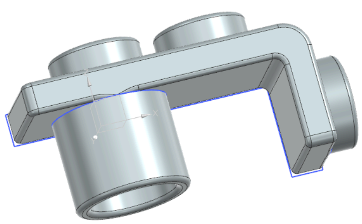


Figure 6a: Axolotl gill attachment piece (OG)

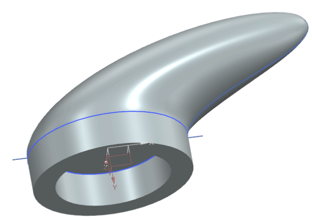


Figure 6b: Axolotl gill original design (OG)

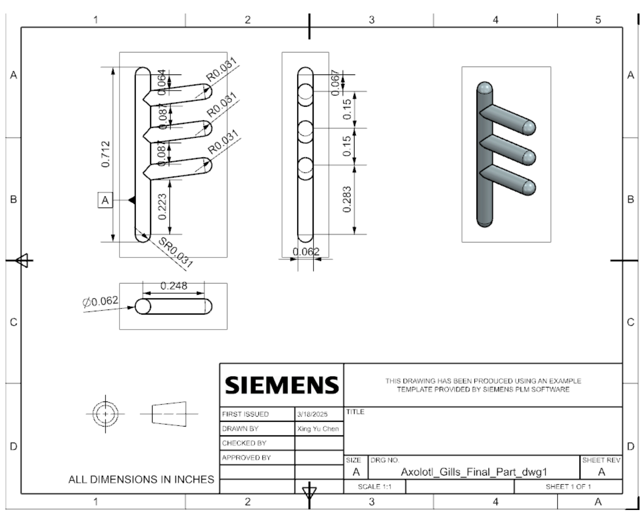


Figure 7: Axolotl Gill Drawing

The boat was designed to be injection molded and has several features that make it well suited for molding. The first of which is a uniform wall thickness. The boat was designed with a uniform wall thickness of 0.05in. However, due to the design of the part, opposing draft angles had to be added which increased the wall thickness to 0.0845 as seen below. These draft angles were also added to all vertical surfaces to allow the part to be removed from the mold easily.

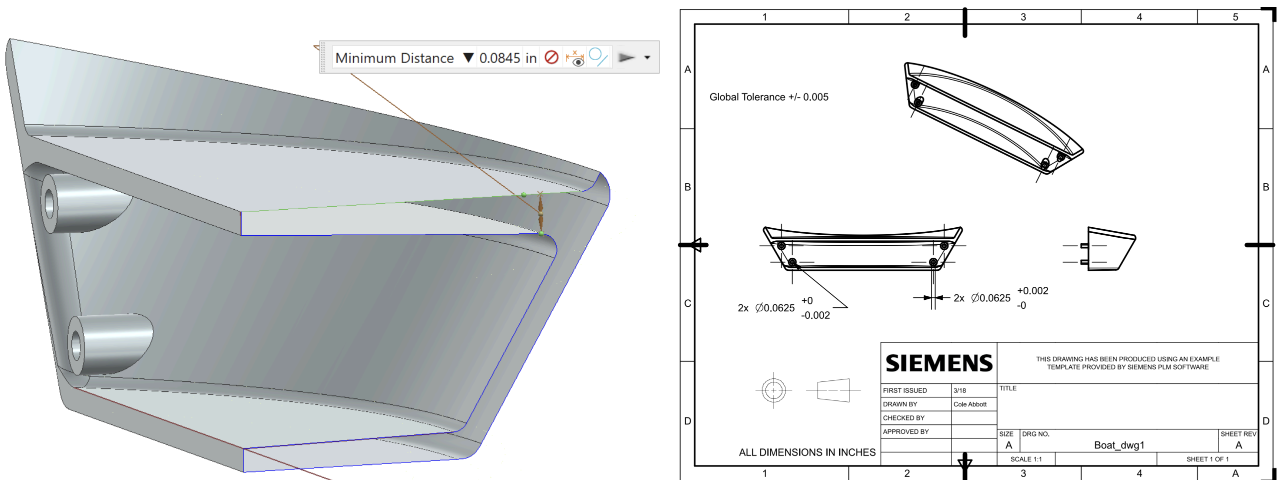


Figure 8: Cross section of boat half and Boat Drawing

An interference fit was used to attach the boat halves together. A hole diameter of 0.0625 was chosen. Interference fit calculations are shown below.

$$I = \frac{S_d \times d}{W} \times \left(\frac{W + v_h}{E_h} + \frac{1 - v_s}{E_s} \right) \qquad W = \frac{1 + \left(\frac{d}{D}\right)^2}{1 - \left(\frac{d}{D}\right)^2}$$

S_d =design stress = 30 Mpa

D = outside diameter = 0.125in

d = 0.0625 in

$E_h = E_s = 1200$ Mpa

$v_h = v_s = 0.45$

W = 1.66

I = 0.0025in

The results of the interference calculations give 0.0025in of interference for a design stress of 30Mpa. This interference will be added to the size of the pin, because the mold feature can be machined with a drill, while the mold feature for the hole is a dowel pin that is only available to us in a 0.0625 size.

Mold Design

The axolotl was designed using a standard core/cavity system. It has a uniform wall thickness of .0625”. One interesting consideration was the need for dowel pins in order to make the holes for the gills. This is seen in the cavity design, where there are two holes drilled into the cavity for the dowel pins to be pressed into. The parting line for the axolotl is shown below in figure 9. The part was designed with this parting line in mind. This seems like the most feasible option for parting considering limitations of machining, and we are able to avoid using a side pull or ejector pins.

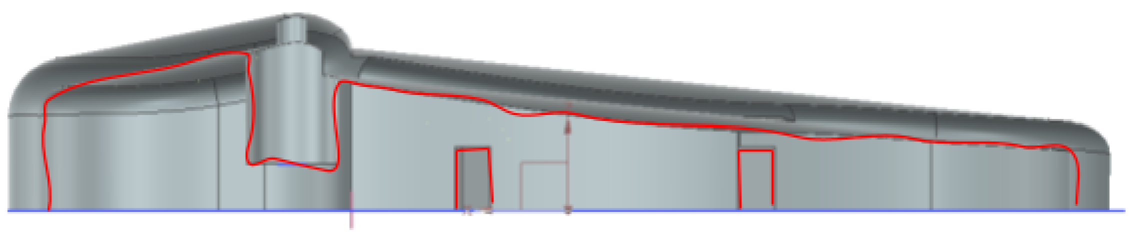


Figure 9: Cross sectional view of the axolotl part showing parting line

The gills were made in the mold using a cavity on both sides (as opposed to a core/cavity combination). Figure 9 below shows a side view of the part with the parting line.

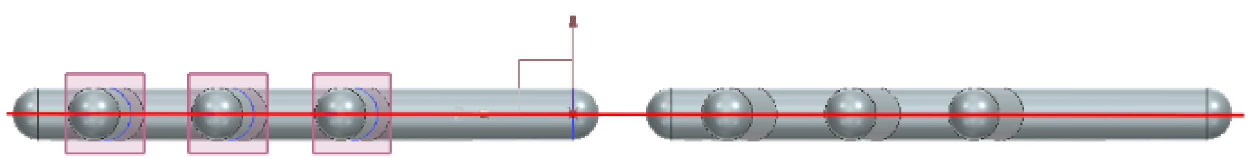
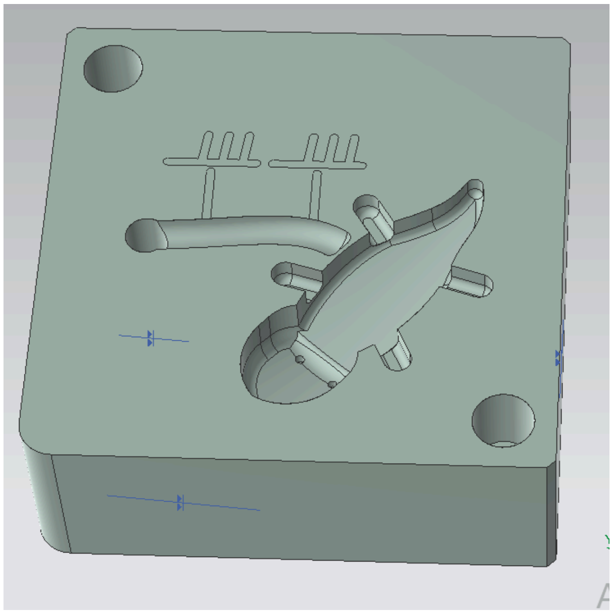


Figure 10: Side view of gills showing parting line

The figure below shows the CAD models of the core and cavity molds for the axolotl and gills. The main runner is large because the axolotl is much larger than the gills. The runners for the gills break off from the main runner; they are much smaller and are placed higher (less steep) than the main runner, allowing the injected plastic to fill the main body a bit sooner than the gills. This design is intended for uniform part filling and cooling, ideally minimizing shrinkage and defects. The runner leads to the center of the axolotl so that it will fill the body uniformly and prevent short shot. It is also placed near the center of the axolotl body to minimize injection filling time, in order to prevent the formation of weld lines. The runners for the gills and body are directed into walls to prevent jetting; this is especially crucial for the gills as the gate is very small (see figures 10a and 10b below for reference).



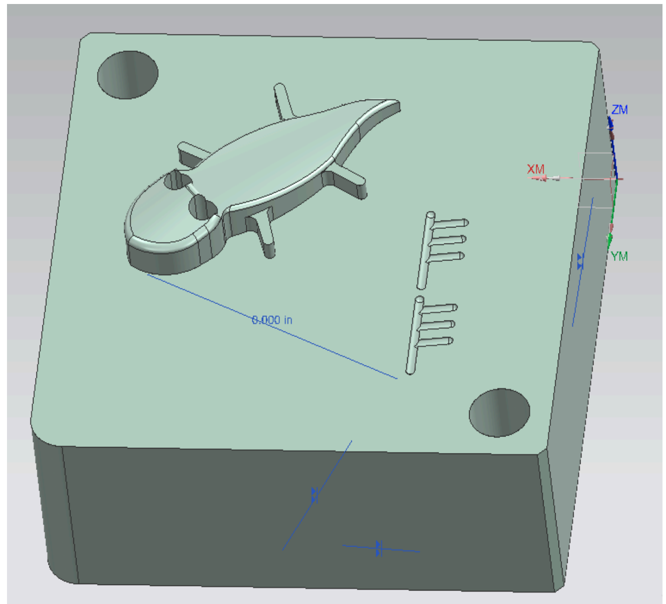


Figure 11a: Axolotl and gills Cavity Model **Figure 11b:** Axolotl and gills Core Model

The boat mold was designed with a standard core/cavity design. However, this would have required a deep slot that would not be machinable with our tooling and machines. Due to this, the mold was split into 2 parts to be machined separately and bolted together. One part would be CNC machined, and the other would be made on a manual mill since its geometry could be machined with tapered end mills and by programming the ProtoTrak mills in the shop.

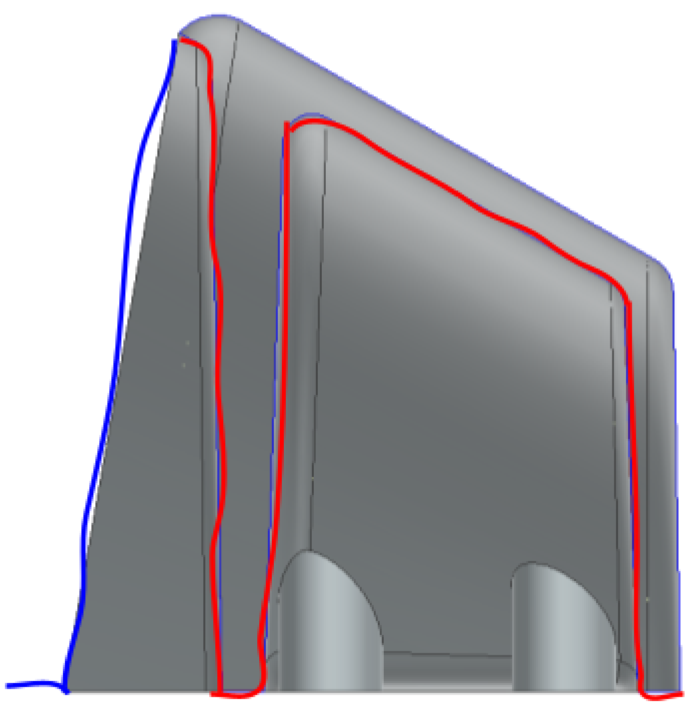


Figure 12: Parting line for boat (Blue = shutoff, Red = parting line)

There is a shutoff between the large flat face of the cavity and the core insert. This was required to create the desired geometry of the boat having a railing around the flat top deck.

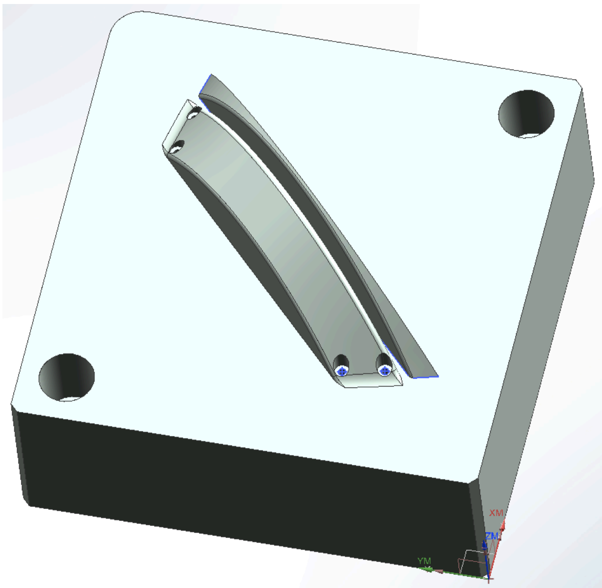


Figure 13a: Boat mold core

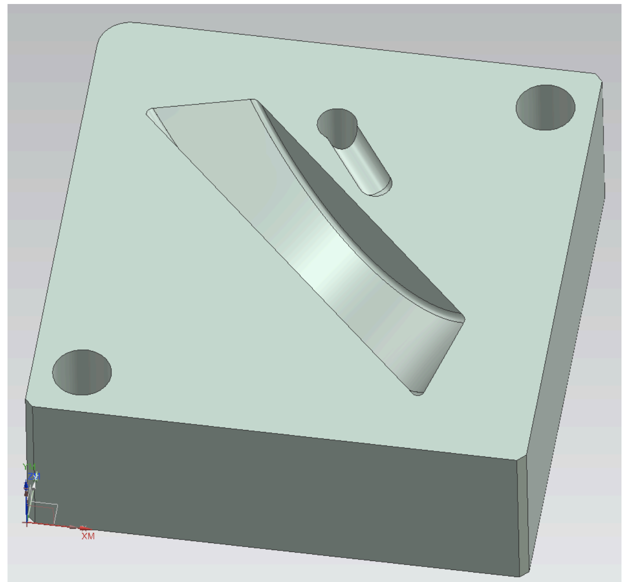


Figure 13b: Boat mold cavity

The runner is placed such that the plastic will flow into a wall immediately upon entering the mold. Dowel pins will be press fit into the 2 holes on one side of the core mold.

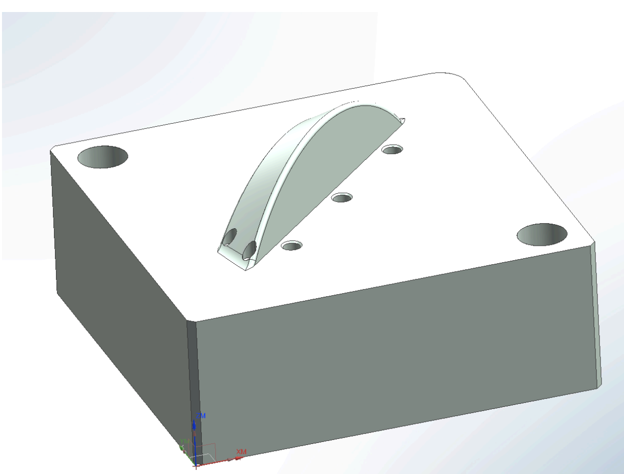


Figure 13c: Main core mold

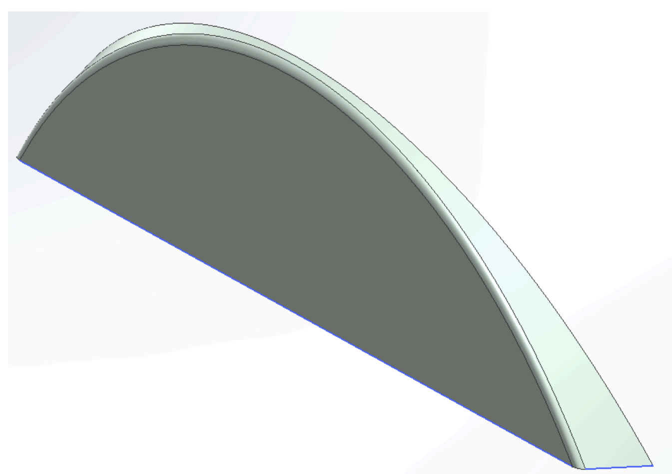


Figure 13d: Core insert

Manufacturing Process

The tables below break down the CAM programs for the axolotl core and cavity molds.

Table 1: Axolotl Cavity Mold

Operation	Tool	Rough or Finish	Description
Cavity Mill	.25 EM	Rough	Remove major material of axolotl
Cavity Mill	.25 EM	Finish	Finishing pass for wall material of axolotl
Area Mill	.25 BM	Finish	Contoured geometry of axolotl's back
Cavity Mill	.125 BM	Rough	Axolotl leg material removal
Area Mill	.125 BM	Finish	Finishing pass for contoured geometry and legs
Planar Mill	.125 BM	Rough	Main runner
Planar Mill	.125 BM	Finish	Main runner finishing pass
Spot Drill	Center Drill	Drill	Spot drill dowel pin holes
Drill	#52 Drill	Drill	Drill dowel pin holes
Planar Mill	.0625 BM	Finish	Mill first gills
Planar Mill	.0625 BM	Finish	Mill second gills
Planar Mill	.0625 BM	Finish	Mill gill runners

Table 2: Axolotl Core Mold

Operation	Tool	Rough or Finish	Description
Cavity Mill	.75 EM	Rough	Remove bulk of material
Cavity Mill	.75 EM	Finish	Finishing pass for last operation
Cavity Mill	.125 EM	Rough	Remove material closer to axolotl
Cavity Mill	.125 EM	Finish	Finishing pass for wall of body
Area Mill	.25 BM	Finish	Contoured geometry of head and back
Wall Floor Profile	.125 EM	Rough	Mill space for gill holes
Planar Mill	.0625 BM	Finish	Mill first gills
Planar Mill	.0625 BM	Finish	Mill second gills

The CAM program for the axolotl/gills worked well. One important modification made to the core mold was making sure that inside corners had enough of a radius to be actually machinable. This was an easy adjustment in the core model with a fillet. Another was ensuring that the location of the runner only went up to about .02-.03” from the part, so that the gate was easy to file into the mold. For the cavity, an important consideration was making the extrusion that results in holes for the gills to fit in. Because the extrude was on a contoured surface, it made sense to drill a hole and insert dowel pins rather than machining it (see figure 14 below).

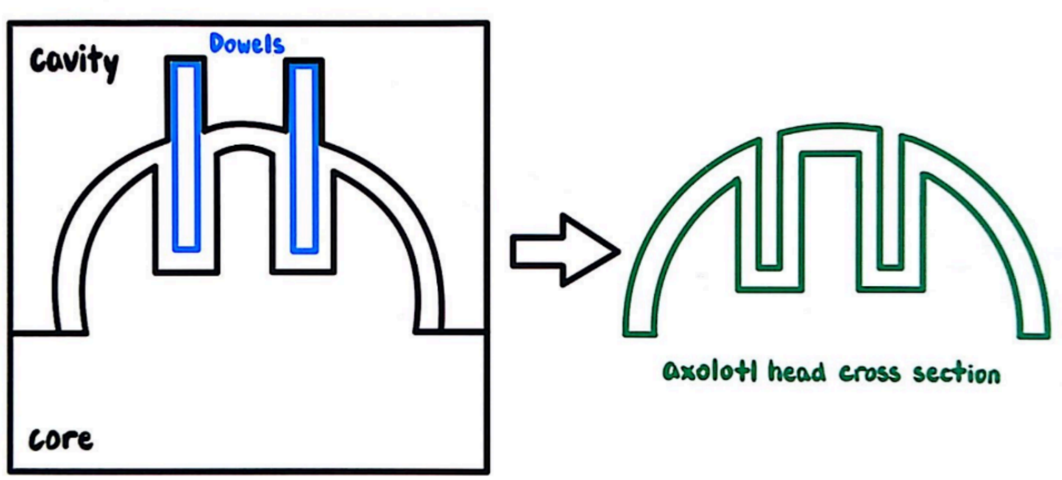


Figure 14: Axolotl cavity design consideration

The tables below break down the CAM programs for the boat core and cavity molds.

Table 3: Boat Core Mold

Operation	Tool	Rough or Finish	Description
Legacy Adaptive Roughing	0.75 EM	Rough	Rough bulk of material
Floor Wall	0.75 EM	Finish	Finish flat floor surface
Spot Facing	0.125 EM	Rough	Machining flat surface for spot drill
Spot Drilling	#2 Center Drill	Rough	Spot drill for drill
Drilling	#53 Drill	Finish	Drill holes
Cavity Mill	0.75 BM	Rough	Rough contour surface
Area Mill	0.75 BM	Finish	Finish contour surface
Wall Profiling	1 deg taper EM	Finish	Machine tapered face
Cavity Mill	0.25 BM	Rough	Rough section that 0.75 BM missed
Cavity Mill	0.25 BM	Finish	Finish section that 0.75 BM missed
Drilling	0.125 EM	Finish	Machine counterbore

Table 4: Manual Machining Operations

Tool	Rough or Finish	Description
Shell Mill	Rough	Rough bulk of material for insert
Center Drill/drill/tap	Finish	Drill and tap all mounting holes for insert
10 deg and 1 deg taper EM	Finish	Machine tapered faces
0.75 EM	Finish	Use ProtoTrak Mill to follow DXF contour of part
Center drill/drill/EM	Finish	Drill and counterbore holes on mold

Table 5: Boat Cavity Mold

Operation	**Tool**	**Rough or Finish**	**Description**
Cavity Mill	0.375 BM	Rough	Rough out majority of material
Cavity Mill	0.375 BM	Finish	Finish what 0.375 BM can reach
Area Mill	0.375 BM	Finish	Finish what 0.375 BM can reach to better surface finish
Planar Mill	0.25 BM	Finish	Machine runner
Cavity Mill	0.125 BM	Rough	Rough what 0.375 BM could not reach
Area Mill	0.125 BM	Finish	Finish with 0.125 BM
Area Mill	0.125 BM	Finish	Continue finishing with 0.125 (wanted to use different settings for different part of mold)

The CAM programs for the Core and Cavity worked well. During the machining of the cavity the tool changer did not properly grab the tool, resulting in a small gouge. No modifications were required. After machining some light sanding was used to remove any machine marks that would have been transferred to the part. 1/16th dowel pins were pressed into the mold. Manual machining was relatively straightforward. A simple fixture plate was made to hold onto the part while machining.

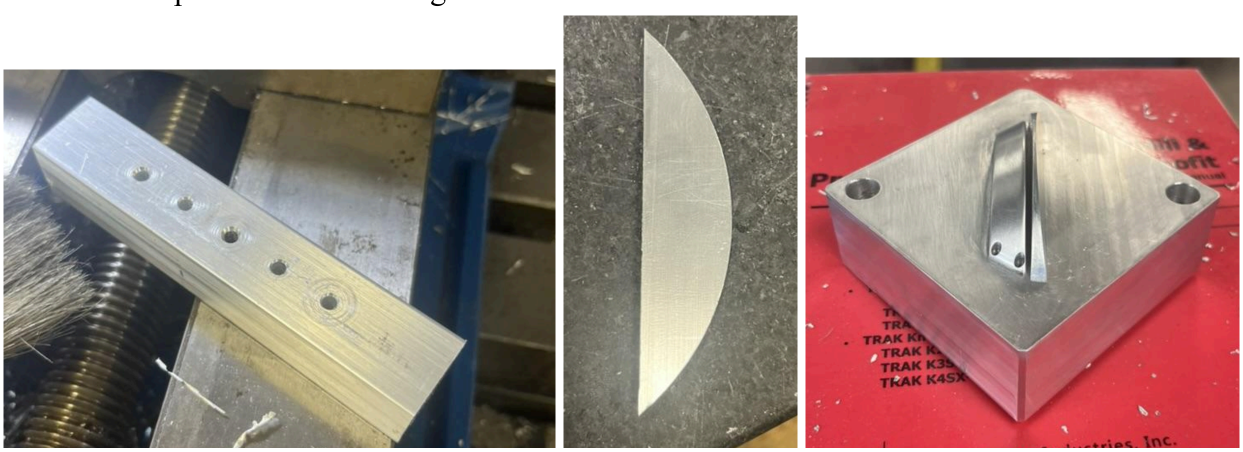


Figure 15: Fixture plate, finished insert, and assembly of mold and insert

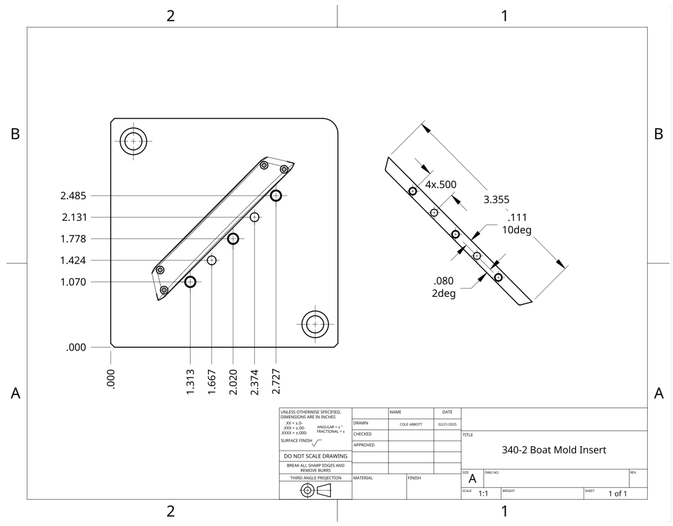


Figure 16: Drawing used for manufacturing mold insert

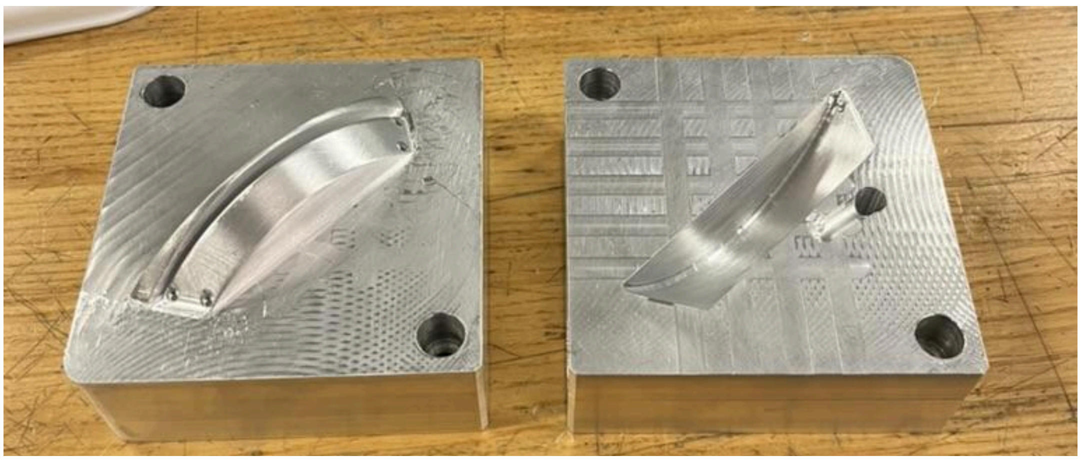


Figure 17: Finished set of boat molds

Figure 18: Finished set of axolotl molds

Molding Process

The following molding parameters were used for injection molding with the axolotl/gills mold:

Table 5: Axolotl and Gills Injection Molding Parameters

Parameter	**Value**
Temperature	430 °C
Injection Time	2.5 seconds
Cooling Time	25 seconds

In order to determine which parameters would work, we started at the recommended values of 450 °C, 8 second injection time, and 30 second cooling time. From there, we made adjustments based on how the parts were coming out. The first part had really bad flash, so we reduced injection time and adjusted the clamp to make sure it was snapping into place well. After still getting some flash, we reduced the temperature and found that 2.5 seconds injection time at 430 °C worked well. The part is pretty small, so after a few samples we reduced the cooling time, and found that 25 seconds was sufficient. Below are pictures of the axolotl part and assembly.

Figure 19: An axolotl with and without gills (left and right respectively)

The axolotl gills are press fitted into two sockets made on the axolotl body. The gills do not fall out and they are not too difficult to put in. We experienced minor difficulties removing the part off the mold, but the overall process was smooth and efficient.

The following molding parameters were used for injection molding with the boat mold:

Table 6: Boat Injection Molding Parameters

Parameter	**Value**
Temperature	450 °C
Injection Time	6 Seconds
Cooling Time	20 Seconds

We started with an injection time of 20 seconds and a cooling time of 30 seconds. These were decreased until defects such as short shots started to occur. The part was reasonably easy to remove from the mold due to the draft angles and smooth surface finish.

Figure 20: Finished Parts

2 Identical boat halfs can assemble together to form the finished boat. The halves press fit together easily and are secure once assembled.

Metrology

For the metrology study, we chose to look at the width of the axolotl's bottom right leg.

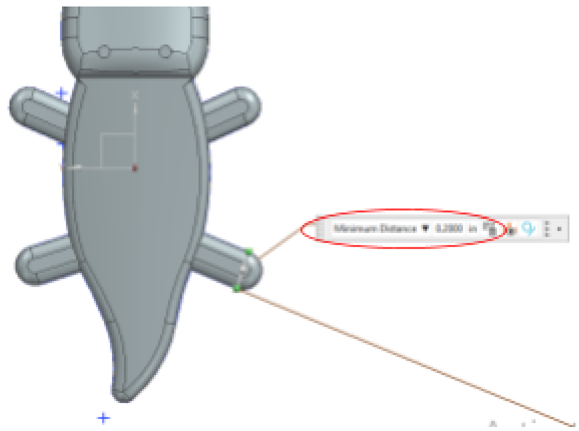


Figure 21: Axolotl specific measured geometry

The dimension for the width of the leg in the model was 0.200". We believe, considering shrinkage, a real dimension of 0.190-0.198 is a reasonable tolerance for the part. Based on the data, our production average was 0.194 with an upper control limit of 0.1965 and a lower control limit of 0.1915. Actual measurements ranged from 0.1904 to 0.1968, with various points outside of our UCL and LCL. This variation could be due to small flashing around the leg that was trimmed off causing inconsistency in the part size. It also may be due to measuring errors caused by deflection in the part during measuring due to the plastic being kind of squishy.

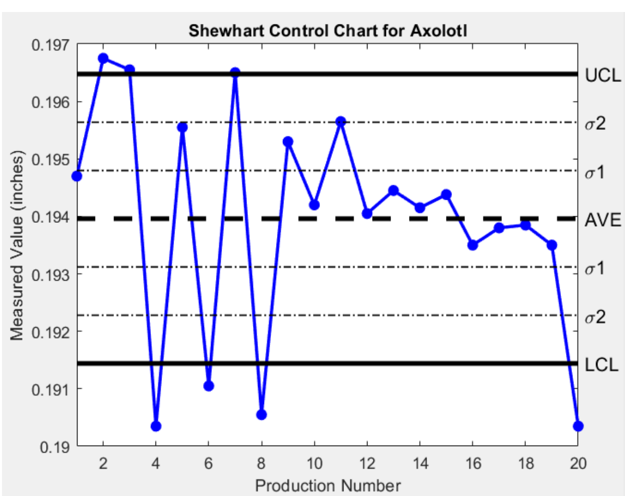


Figure 22a: Axolotl Shewhart Control Chart

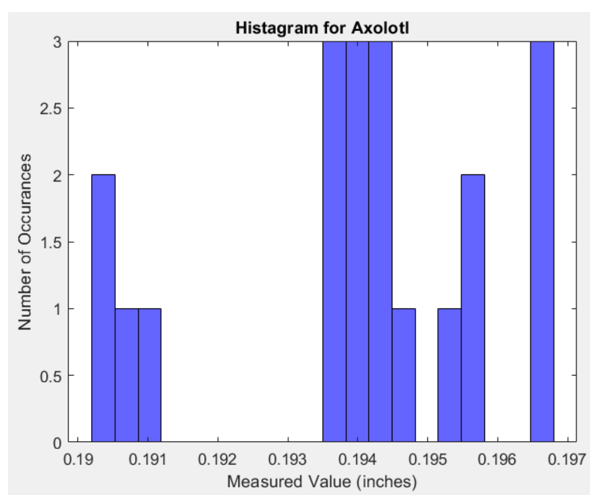


Figure 22b: Axolotl Histogram

For the gills, we looked at the diameter of the bottom tip (see figure 23).

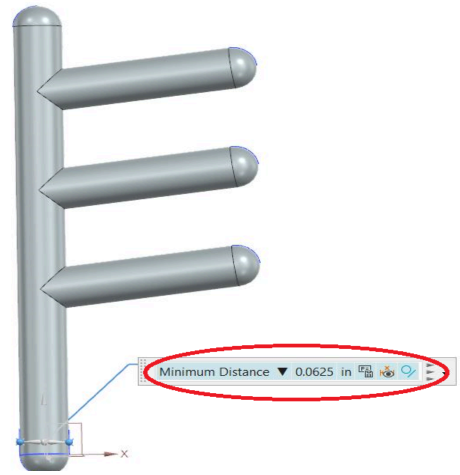


Figure 23: Axolotl Gill Measured Geometry

The thickness of the entire part was designed to be 0.0625 inches, with a tolerance of -0.005 for potential shrinkage.

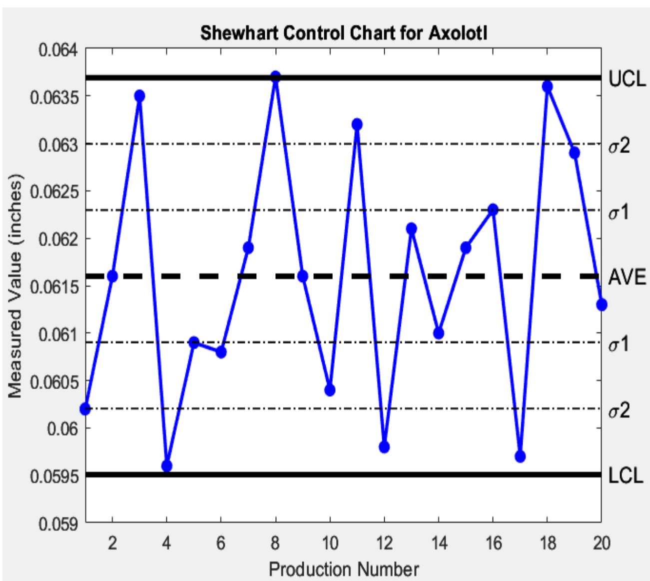


Figure 24a: Axolotl Gill Shewhart Control Chart

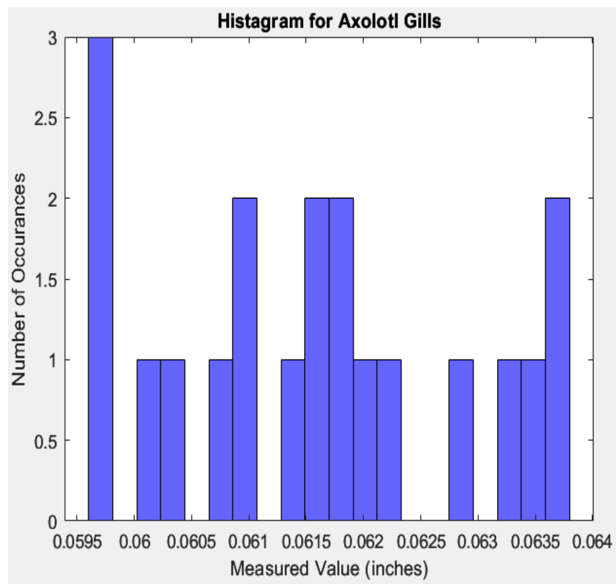


Figure 24b: Axolotl Gill Histogram

The production average of the gills was 0.0616 inches, ± 0.0021 within 3 standard deviations. Compared to the CAD measurement of 0.0625 inches, these results are within our expectations of -0.005 inches due to shrinkage. The unanticipated maximum of 0.0637 inches (and any measurement above 0.0625 inches) might have come from rough surface finishes, as we press fitted a few of the gills into the axolotl before taking these measurements. Another possibility is that some of the gills had small bits of flash (which we tried to trim) and that extra material could have affected the final measurements.

For the boat, we looked at the bottom thickness.

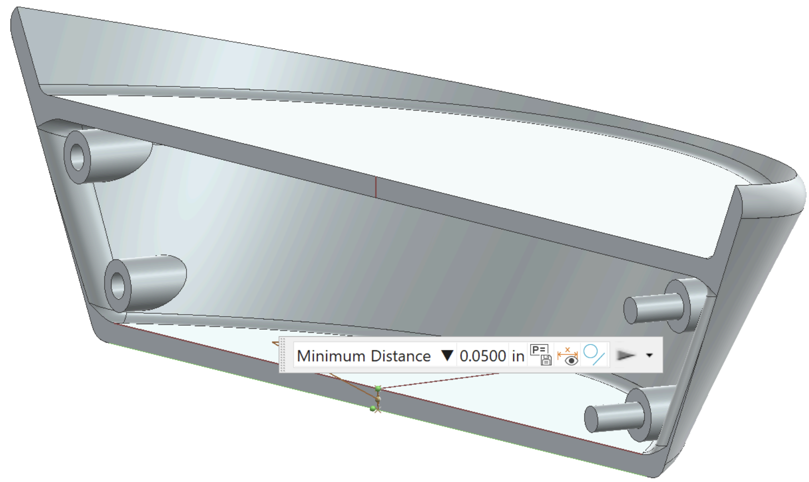


Figure 25: Boat Measured Geometry

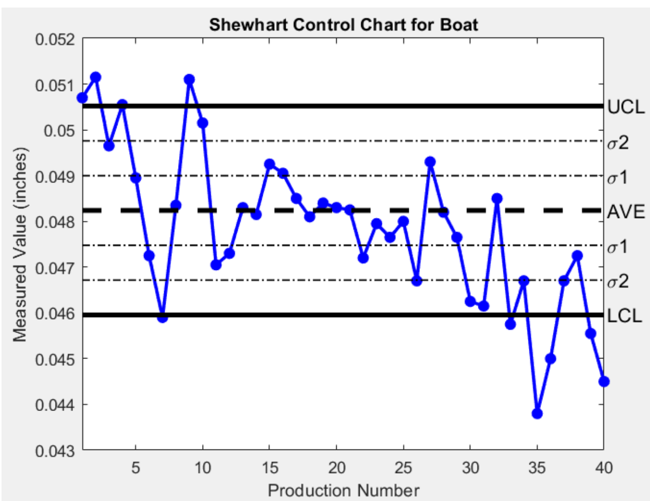


Figure 26a: Boat Shewhart Control Chart

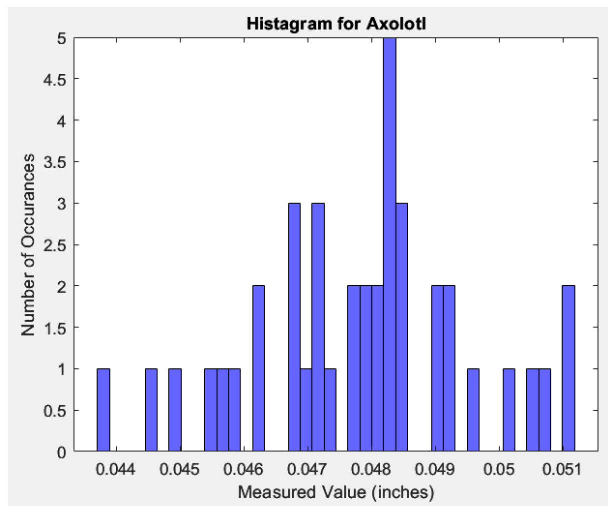


Figure 26b: Boat Histogram

The molded parts are very accurate to the CAD design, with only a few parts falling more than 0.005in off the intended size. Parts tend to be smaller than designed due to shrinkage.

Conclusion

This project provided valuable hands-on experience in designing, machining, and injection molding custom parts. The axolotl and boat designs were successfully manufactured, with careful consideration of mold design, machining constraints, and molding parameters. The uniform wall thickness, proper draft angles, and interference fits contributed to the overall success of the final assembly.

However, several challenges were encountered throughout the process. One of the most significant issues was the misalignment of the cavities for the axolotl's gills, which required filling the cavities with epoxy and manually machining them post-CNC. This additional step introduced inefficiencies and increased the risk of dimensional inconsistencies, but overall went over smoothly. Another complexity arose with the boat mold, where deep slots were nonmachinable with our available tooling, requiring a split mold design and additional manual machining.

Other minor inconveniences included a tool loosening during a finishing pass on the axolotl, which resulted in a chipped leg and tail on the core mold; while machining the boat cavity, a collet wasn't held tight enough by the machine, which drilled a small divot into the side of the boat. Fortunately, we identified these issues early, and the chipped molds did not impact the injection molding process or the final assembly of our parts.

To improve future iterations, precise cavity alignment should be ensured through enhanced quality control during CAM programming and machining setup. It would have been worth it to double check the alignment by making an assembly of the two mold halves and checking the cross section, which would have saved us a lot of time machining. Additionally, refining gate placement and optimizing runner design could further enhance material flow and minimize defects like flash.

Despite our minor setbacks, the project went smoothly as we were mostly careful in our design considerations in injection molding and used critical insights into the challenges we may have encountered. The experience gained will be invaluable in future mold design and production endeavors.