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Interdisciplinary Senior Design Project to Develop a Teaching Tool: Extruder Tutor Plastic Injection Molding Machine

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Interdisciplinary Senior Design Project to Develop a Teaching Tool: **Extruder Tutor Plastic Injection Molding Machine**

In recent years there has been a big push to get students into the STEM fields. However, what seems to be lacking in this academic push is the hands on side of it. Engineering simply just isn't about equations, but actually developing and building a physical product. Something you can touch and in most cases see work. The manufacturing field fits into STEM academics and is very important. With learning the importance of manufacturing, the Senior Design team at Drexel University's Engineering Technology Department have decided that one of the best ways to expose new students to exciting Manufacturing Engineering fields from the high school through college level is to give students hands on experiences in this field that would make them interested in it. To do this they have developed a desktop size design of an injection molding machine for educational use. The student design team considered an injection molding machine as one of the best option for exposure since newly interested students immediately can see how a part is made with an easily operated machine that makes the product right away. During the fall quarter the student team proposed this idea, backing it up with research and market studies. The winter quarter had students finalizing the design, acquiring parts, and machining and assembling the frame. For the spring quarter, the machine was tested and put it in working order. Along with that, the students created a user manual and a lab manual to assist those using the injection molding machine. The machine envisioned in September became a working product and closer to educating students in STEM academics and the manufacturing field.

The significance of the methodology to be applied in this capstone course project is to combine theory and practice to prepare the students to become better problem solvers and obtain practical solutions to real life/simulated problems using a project based approach. Students in the Mechanical, Electrical, and Industrial fields along with many others can learn many new skills from multi-disciplinary projects such as the design and development of an Injection molding machine for educators. Such projects show students how to use different types of technology, and demonstrate how advanced technology can be used in an innovative application. Overall, many different fields of engineering can benefit from this application, enabling the development of skill and knowledge in many different engineering aspects and processes. This capstone design project stimulates the students' interest in real-world product realization. As manufacturing laboratories are very expensive to develop, this project can also be adapted at other institutions that have limited funding to improve manufacturing process and prototyping facilities.

Expected student learning outcomes assessment in this capstone course was performed using written reports and oral presentations as well as an evaluation of each student's contribution to the project. Oral presentations were assessed at the end of the first and last quarter and written reports at the end of each quarter. Both written reports and oral presentations were assessed by all faculty members and a number of outside assessors from regional industries. The assessment of individual student contributions was performed by the project advisor and co-advisor. The students' performance was assessed using a set of performance indicators that are also used to assess the program's student a-k outcomes (ABET). Each indicator is assessed according to a Likert-type scale and the results weighted to emphasize technical qualities of the work and scaled to produce a score from 0 to 100 in order to determine the students' final grades.

Background

A job in the manufacturing field, such as a machinist, takes some training, so if students can gain this experience in high school, it sets them up for opportunities after graduation and gives them some direction. College students would stand to benefit just as much from experience with an injection molding machine on helping them with direction and making them more attractive to potential employers. With these benefits in mind, it was decided to design the injection molding machine geared towards the education and safety of the students who would be using it.

To address the student's education, the design team which consist of 4 seniors (one electrical, three mechanical concentration) came up with learning objectives for them that helped guide the design. The learning objectives set forth were included identifying the possible dangers of injection molding, identify various mold safeguards and their functions, use of mold handling tools, safe mold handling practices, and how pressure and temperature affect the final product. Overall, the main educational objective is learning the whole injection molding process, the correct way. As for the safety of the students using the machine, safety features such as enclosing the machine in Plexiglas were incorporated so that students cannot get accidently burned since the heater will be operating around 450°F in most situations.

Market Research

Before making design decisions such as those previously described, the design team conducted research such as product searches to see what products out there on the market were closest to what they had in mind. Products that could ultimately be their competition. They also looked to these products to see what standards and parameters were normal for the industry and this type of machine. Along with searching for different products on the market, patents were searched to ensure they would not be encroaching on an existing product in a legal aspect.

When developing the original design the team looked to the product search along with conducting a literature review and a survey. They found out that the biggest change in the design of industrial production type Injection Molding machine was in the way the machine was powered. They used to be powered by hydraulic systems, but now they are powered by electrical motors. The survey conducted was useful in gauging the viability of an educational product, gauging how much their intended audience would be willing to spend on a machine such as this, and what equipment the educators had access to. The survey was short so that educators would be more apt to respond with their busy schedules, but it was to the point and allowed them to gather the information. A copy of the survey can be seen in Appendix A.

Alternative Designs

Original Design

A screenshot of the original design can be seen below in Figure 1. The original design of the injection molding machine featured an air cylinder to provide pressure to the plastic pellets, a heater chamber to contain the pressure and provide a channel into the mold, a heater band to heat the pellets, and a mold to form the plastic. The layout of the machine oriented the main air cylinder, heater chamber, and mold vertically in-line with one another.

This machine orientation and layout was chosen to minimize the machine footprint. Other features included a pellet hopper to hold the plastic pellets which was mounted adjacent to the main air cylinder and heater chamber. A slide was incorporated to load the pellets from the hopper to the barrel and the slide was actuated by a second air cylinder. The intent of the hopper and pellet loading system was to allow multiple parts to be made successively without the need to manually load additional pellets into the heater chamber.

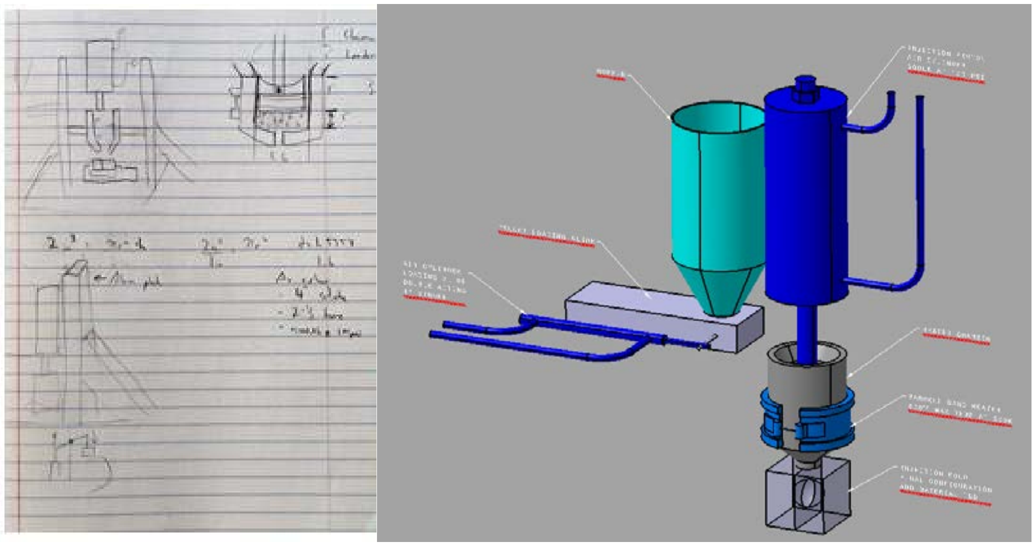

Figure 1: System overview, original design hand sketch (Left) and CAD rendering (right)

Considered Components

When coming up with basic design, the design team had to look at each component closely to see which would be the best option for needs and budget. To do this, they conducted trade studies. In the trade studies they looked at different types of actuators, clamp actuators, injection methods, machine orientation, and machine operation. Within each section they set up a table to compare the options available and set up a scoring system. By using a scoring system, it helped to identify which option would be the best for the application. The scoring was done on a scale of 1- 4 with 1 being the least favorable and 4 being the most favorable, specifically according to their application. A copy of the trade study can be seen in Appendix B. In conjunction with the trade study, they looked to the survey results to see which options the trade studies yielded as the best fit, with what equipment the educators had access to. For example, when looking at different actuators, having the machine pneumatically or electrically actuated were both very appealing. Aside from pneumatic actuation scoring a tad bit higher than electrically, they found out from the survey that every educator but one who responded had access to air compressors. With this bit of information they were able to decide which method would best suit the needs and keep the cost down as well. As for choosing the material the frame is machined out of, they went with aluminum for a few different reasons. The main reason they went with an aluminum frame is due to the weight. To have this machine be portable and easy to be used in a classroom or lab setting, they wanted to make it light enough so it can be transported with ease. The durability and strength of aluminum were other appealing factors that attributed to the decision since they not only want it to be safe for the user, but hold up over time.

Design Solution & **Final Design**

An overview of the final prototype is shown below in Figure X. The main components of the prototype are machined from standard 6061 aluminum and features a simplified design. This simplified design consists only of the primary air cylinder, barrel, heater, and mold. The heater chamber is a two-piece design that allows the primary heater chamber to float vertically, separating it from the mold to facilitate mold and part removal. The pellet hopper and slide loader have been removed from the prototype design as they only perform auxiliary functions to the main purpose of the injection molding machine. The injection molding prototype is therefore still fully capable of meeting its design objectives without the pellet loader and pellet hopper. When assembling the injection molding machine after having it machined, they were able to take full stock of the machine since it was now a real product. By doing this, they were able to make some adjustments in order for the machine to operate as smooth as possible. One minor change that was made was with the heater band housing. The heater band they picked out for the machine has a bolt holding it together.

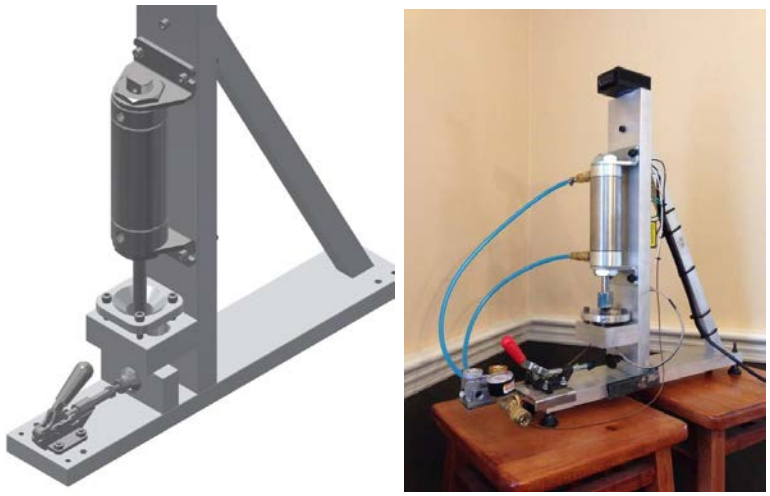

Figure 2: Final Prototype Design using SolidWorks CAD software (left). Finalized prototype assembly (right)

When designing the heating chamber and housing, they did not account for the extra space this bolt would take. It was minimal extra space that they were able to accommodate by using a milling cutter to mill the aluminum in this section down. With the heating section being a floating part from the housing, they found during testing that the chamber would stick to the piston when being drawn back due the vacuum created from the tight tolerances between the piston and heating chamber walls and the stickiness of the plastic. To remedy this problem, the team tapped the existing holes in the heater band housing and increased the heating chamber holes so that they could accommodate a bolt holding them together. The design team made sure that the bolt was long enough so that there was space between the heating chamber and housing for a spring. The springs, which can be seen in Figure 3 below, lifted the heating chamber up so the mold can be placed under and taken out as well as to absorb some of the pressure. The few modifications made helped make the machine operate more smoothly when in use.

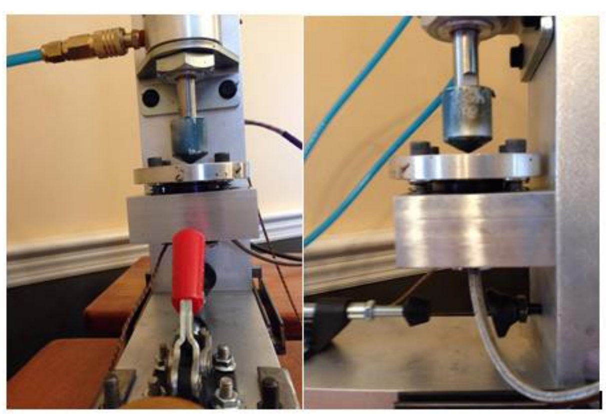

Figure 3: Spring alignment

Stress Analysis

All of the calculations presented were done through Inventor's Finite Element Analysis (FEA), using the models created for the design and manufacturing of the prototype. While modeling of the parts was ongoing, the assembled model was tested for any changes in the strength of the frame. All part materials were defined in the models during the initial design of each part, allowing Inventor to use the correct mathematical models during testing. The initial design located the back support lower than the top piston support. This caused the vertical and back supports to have a high Von Mises Stress, and deform significantly under normal use. After a review of the model, the vertical piece was increased in height and the back support was moved above the piston supports causing all of the bending force to be reduced as the mechanical advantage of the extra length increased. After further FEA testing it was found that the back support would have to be substantially thicker than the other pieces. The back support was decreased in size and the vertical support was increased in thickness. In doing so the tests reported significant improvements in strength and minimum deformation caused by the bending. The increase of the vertical support's thickness allowed the back support to reduce in size with minimal decrease in strength, and decreased the overall weight of the machine as well.

The final design of the model was tested with 500 psi pressing on the heating chamber's interior, and up on the plunger. This was done because the piston can apply 500 psi from a 100 psi inlet, which is what the design team designed for. The final design was constrained in Inventor and a new FEA was run using smaller nodes to achieve a more accurate model. The nodes are created by inventor are triangular, with size varying based off of the surface that the nodes are covering with approximately 180,000 nodes total. A full Inventor report of the FEA is in Appendix F, as an overview of the main points the entire machine had an average safety factor, or factor of safety (FoS) of 15 and a minimum FoS of 1.833. Inventor gives a report including all calculations done, and includes Von Mises Stress, and a FoS. The Von Mises failure Criteria was used due to part materials being ductile and not wanting the parts yielding in the design. Von Mises correlates well with yield strength, so this is the reason they chose to take this approach. The FoS is given as:

$$FoS = Material\ Strength / Design\ Stress$$

This formula uses the Von Mises Stress as the "Design Stress", and has a library of material properties that the "Material Strength" comes from. From Inventor the yield strength is 39885.4 psi, and the ultimate tensile strength is 44961.7 psi. Inventor uses the yield strength as the "Material Strength" in the FoS calculation. The Von Mises Stress (General plane stress), σ_v is calculated as:

$$\sigma_v = \sqrt{\sigma_{11}^2 - \sigma_{11}\sigma_{22} + \sigma_{22}^2 + 3\sigma_{12}^2}$$

Where σ_{11} and σ_{22} are principal stresses and σ_{11} is shear stress. Using this formula Inventor can find the nodal stress, giving the average stress per element. This shows where the highest stress (16.38 Ksi) is located, based off of a mathematical analysis (Figure 4).

Looking at the Inventor model in Figure 4 the lowest FoS is 1.83 and located on the shaft where the plunger screws onto the shaft. For the design this location was ignored since the piston should be able to withstand the pressure that it can create. Ignoring this area of failure the next lowest FoS is 12, located around the heating chamber as seen in Figure 4. An FEA was run on the heating chamber as a separate component to ensure the full assembly model was accurate. The separate analysis shows a minimum FoS of 12.64, agreeing with the original assembly analysis. This was done as the heating chamber will be a heated pressure chamber while under normal use and will be the most likely place to break with wear. To help prevent harm the heating chamber is surrounded by the heater housing even if an imperfection in the aluminum creates a failure point.

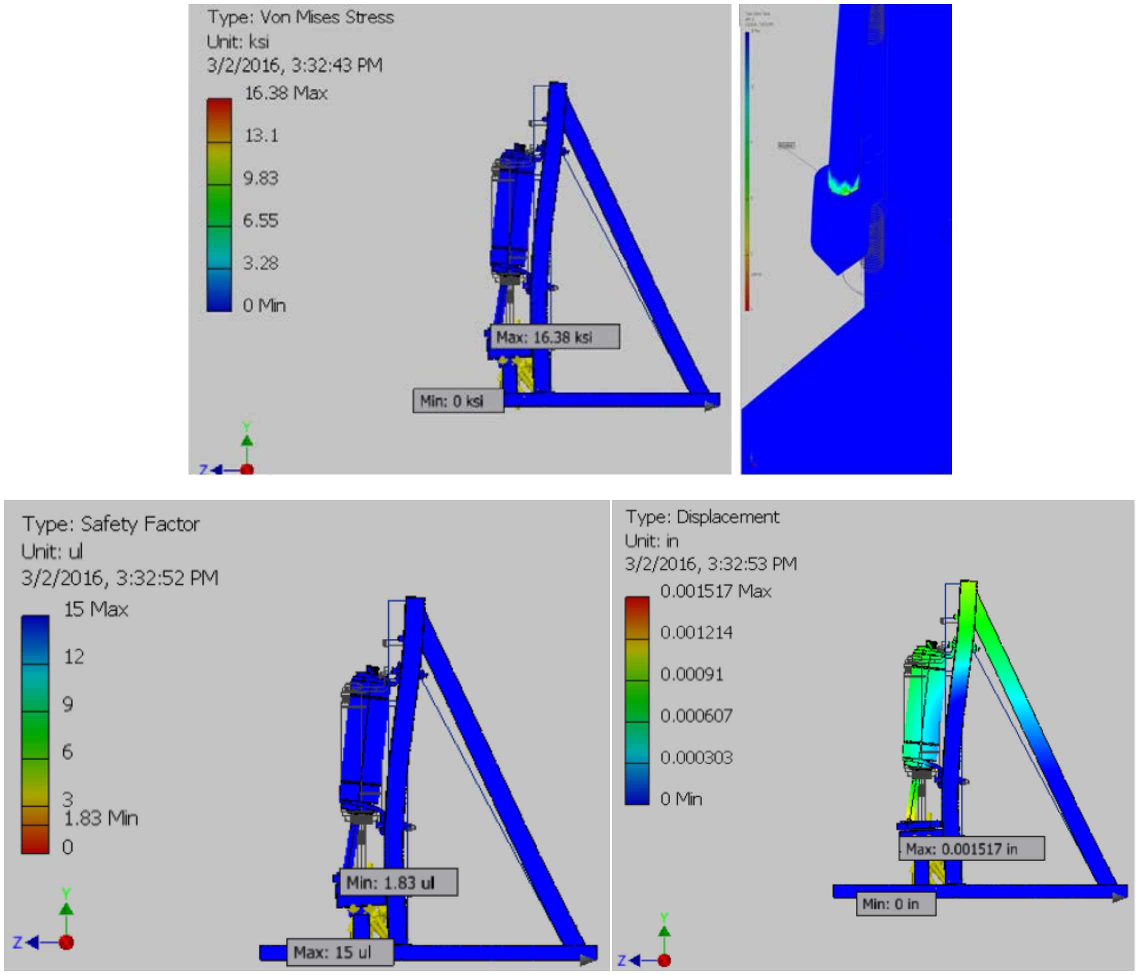

Figure 4: The Von Mises Stress distribution (top left), FoS on the heating chamber (top right), Overall FoS distribution (bottom left), Maximum displacement (bottom)

Using the FoS from Inventor the design should be able to withstand the stresses that occur during normal use of the device and should not be in danger of a critical break that could harm any of the students or teachers handling the machine.

Thermal Analysis

Through the CES EduPack 2014 the design team found the thermal properties, as well as confirming the mechanical properties of Aluminum 6061. The melting point has an average of 1068.5°F, which is at minimum of twice as hot as the plastic that is melting. CES also has a "Maximum service temperature" which they define as "The highest temperature at which the material can reasonably be used without oxidation, chemical change or excessive deflection or creep becoming a problem." They have that aluminum can go up to 692°F before the effects start to happen. Finally for the thermal conductivity of aluminum they have an average of 75 BTU*ft/h*ft^2*F. The full CES information is in Appendix G, for the full ranges and additional information not stated above.

A thermal analysis was done only on the heating chamber and plastic using Autodesk (Computational Fluid Dynamics) CFD Flex. The reasoning was that the important thermal aspects include only those two parts. Both parts are assumed to be 75°F, room temperature, before heating up and the heat source at 450°F for the heater. The plastic has about 1.5 in^3 in the analysis, however the plastic is one solid piece in the model when in reality there will be different pellets melting together before a solid is formed. The simulation was run for 15 minutes, how long the pellets were left to melt before injection, with a save every second. After the 15 minutes the simulation shows a minimum of 441°F for the plastic. This is acceptable as the small amount of plastic will heat up while being extruded due to the pressure, mixing with the warmer plastic, and not all of the plastic is injected into the mold. After 10 minutes the average temperature of the plastic is within the parameters for being injected, but the extra time is to help make the flow smoother which creates a better final product.

To find the heat flux, the amount of heat that can be passed through the material can be computed using Fourier's Law using Q as heat flux, k as the material conductivity, and T as the temperature:

$$Q = -k\frac{dT}{dx}$$

The CFD program uses the nodes to find the (x,y,x) coordinates needed for the formula of:

$$\frac{du}{dt} = \alpha(\frac{d^2u}{dx^2} + \frac{d^2u}{dy^2} + \frac{d^2u}{dz^2})$$

With $\frac{du}{dt}$ being the rate of change of temperature at a point over time, and αbeing the thermal diffusivity.

For the aluminum heating chamber, the equation for a cylindrical shell, can be used. The equation is stated as:

$$Q = 2\pi k\frac{(t_i - t_o)}{log(\frac{r_o}{r_i})}$$

With Q as heat flux, k as the material conductivity, t as the temperature, and r as the radius. This is done as most of the heating chamber is basically a pipe. As said earlier, using this equation shows that the energy transfer through the walls is high, and can be ignored in the overall time for the plastic pellets to reach the desired temperature.

The aluminum heating section was also run through a CFD simulation. Since the aluminum is a good conductor of heat the time for the inner wall of the heating chamber to achieve the temperature on the outside, from the heating band, is under 30 seconds. At that time the piece has already heated to 220°F at the furthest points. The full reports for both of these simulations can be found in Appendix H and Appendix I respectively.

Using both types of the thermal models they can see that the biggest factor in time is the plastic with its low thermal conductivity, and its relatively high mass compared to the other components heating up.

Design for Assembly

The design team utilized Autodesk Inventor 3D parametric modelling software to design and layout the parts and assemblies. Purchased parts such as the main air cylinder and quick-release mold clamp were procured from McMaster-Carr, which had available 3D CAD models of these parts along with interface drawings. The design could therefore be analyzed virtually in 3D space to check for part fitment, clearances, and interferences. Tolerance studies were performed and the appropriate Geometric Dimensioning & Tolerancing were applied. Part features were controlled geometrically to ensure that mating parts and holes would align with the appropriate clearances for fasteners while also taking into account the manufacturing methods used to fabricate the parts.

Once the parts were machined, assembly of the frame took no time at all. Everything went together as it should. With designing this machine, ease of assembly was at the top of the list. The design team were divided as a group on whether to have the machine welded or bolted together. This had nothing to do with strength, both options would have left the machine structurally sound, it was more for aesthetic reasons. With how easy the assembly was, clearly having the machine bolt together was the best way to go. Adding all of the controls onto the frame was an easy task as well. Altogether the prototype as a whole was an easy assembly which is greatly beneficial if this were to go into production because that would keep the cost low.

Testing

Finally getting to test the machine was the most fun part of this project for the whole group. To start out with, they tested each component separately to ensure that they worked and to see how they worked before trying it as a whole. The pneumatic actuator was the first piece of equipment to come in and testing that was fairly simple. An air compressor was connected to the up/ down valves and then air hoses were connected from them to the actuator. Testing the actuator allowed to assess the speed and full force.

The other component tested was the heating band. It wasn't just the heating band, but the heater controller as well. They needed to find out first off, if they connected the heater controlled correctly. They then had to get a handle on how to program the heater controller and most importantly how well it worked. In order to make sure they did not damage the thermocouple, they used a laser thermometer to gauge the temperature to make sure it was staying in the range they set it at and how long it took to get to the set temperature. The first time out everything went fine. They found out that it climbs to the set temperature fairly quickly, but they were able to adjust that since they didn't want it climbing too quickly. By doing this they were able to get a hold of how the heater and heater controller worked.

After they tested the individual components mentioned above, they felt confident enough to put everything together. The first time heating up the heating chamber with the pellets in there, they were surprised at the consistency of the plastic. It was expected to be less viscous, but it turned out to be in the consistency of gum. The design team had the heater set to 450 °F which was the recommended temperature for the LDPE pellets by the company they bought them from, so there was no issue there. Before injecting the plastic into the mold, they did a dry run and injected it onto a piece of cardboard to ensure the flow looked good. They clamped the mold into place and injected the plastic. The first time out it did not fill the mold all the way and this defective part can be seen in Figure 5 below, the image on the left. From there the pressure was increased to 140 psi and the temperature to 500 °F. The middle image in Figure 5 below depicts how the part came out with these conditions applied. Clearly, this was not the desired result, so the parameters needed to be adjusted once again. The pressure was kept at 140 psi, but the temperature was lowered to 460 °F. This time around, the testing yielded the desired part and this can be seen below in Figure 5, the image on the right.

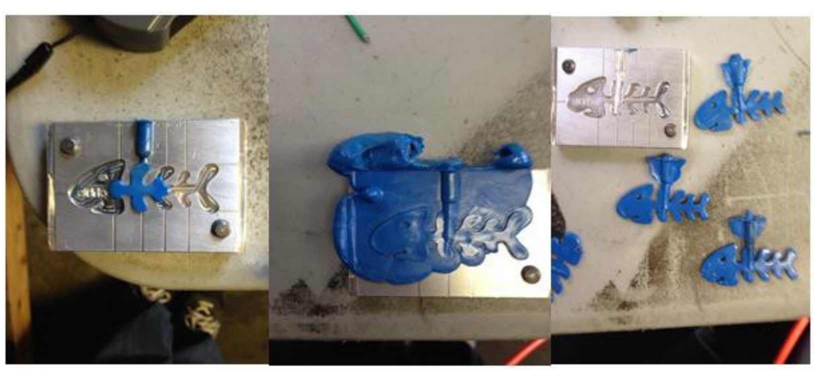

Figure 5: Injection molding test samples.

Economic Analysis

The main goal of the senior project was to focus on educating students at different levels. A main factor in achieving this goal is the cost and selling price of the machine. Senior design student wanted to make the machine affordable that way it can reach a larger number of educators and students. The survey previously mentioned helped them to gauge what an affordable price would be and from there they came up with the price tag of $1,050 for the base machine. Due to the purpose of the machine, the goal was not to make a huge profit. Therefore the budget was set at $850. This would leave a $200 per machine profit and the opportunity to maybe reinvest the money or have capital to work with. With the components they used, it actually ended up coming under budget by almost $200 and the actual cost of the machine incurred by the group was even lower because of labor and raw material donation.

Table 1 provide a complete economic analysis of the prototype machine. It is important to note that there was a lot of labor hours spent up front by the design group, which is to be expected.

	Machine Cost		
	Base	Starter Package	Parts Package
Cable Winder Aluminum Mold		$65.00	$65.00
Royal Blue Color LDPE Pellets		$10.00	$10.00
Heater Band	$91.88	$91.88	$91.88
Air Cylinder	$119.44	$119.44	$119.44
Foot Bracket	$14.36	$14.36	$14.36
Thermocouple	$19.40	$19.40	$19.40
Heater Controller	$8.00	$8.00	$8.00
Aluminum	$329.40	$329.40	$329.40
Labor:			
Engineering Technology	$12,480.00		
Machinist	$39.66	$39.66	$39.66
3 Year Part Replacement			$100.00
Total	$622.14	$697.14	$797.14
Actual Total	$13,102.14		
Sales Price	$1,050.00	$1,125.00	$1,225.00
Profit	$427.86	$427.86	$427.86

Table 1: Economic Analysis

Assessment and Student Outcomes:

Oral presentations and written reports during the senior capstone course series are evaluated by department faculty and qualified external engineering professionals according to the Likert-type scale. Each assessor assigns a value for Performance Indicators according to a Likert-type scale. The scale (rubric) indicates the following three levels: Exceeds, Meets, and Minimally Meets (these values may be interpolated resulting in a 5-level scale). These results are used to produce an average assessment of a student team's oral and written presentation. Overall assessment scores are provided in Figure 6 for fall, winter and spring quarters indicates that Injection Molding senior design team attained ABET student learning outcomes in each assessed category.

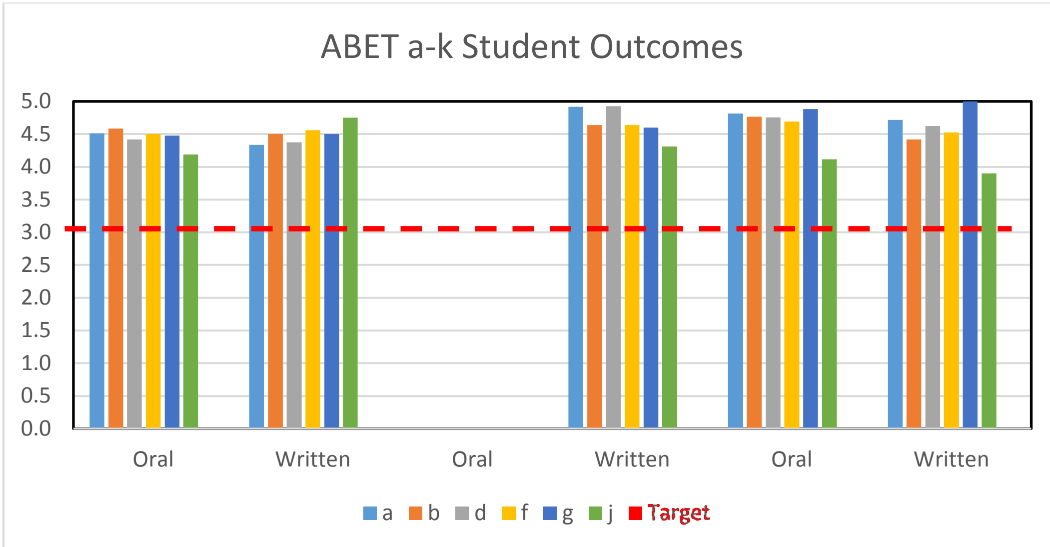

Figure 6. ABET assessment for Injection Molding senior design team during Fall, Winter and Spring 2015-16 AY.

Conclusion

The duration of this project has been from August 2015 to May 2016. During this time period the project went from a hand drawn sketch, which can be seen below in Figure 1, to a completed machine that produces parts as seen in Figure 2. This paper has documented the complete process it entailed to reach the end goal of creating an injection molding machine for educational use.

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Appendix A: Survey Form

Injection Molding Machine Research

Introduction

This survey is being conducted by a senior design group from Drexel University's Engineering Technology Department, a part of the College of Engineering. The survey is in no way being done on behalf Drexel University, the College of Engineering or the Engineering Technology Department. We are conducting this research independently as a part of our final senior project. Please answer each question to the best of your ability. We thank you in advance!

1. Address

Name

School

City/Town

State/Province

ZIP/Postal Code

Email Address

2. Are you familiar with what an injection molding machine is?

- Yes
- No

3. Are you familiar with how an injection molding machine works?

- Yes
- No

4. Do you think your students would benefit by having one in class/ lab?

- Yes
- No

5. Do you have access to an air compressor?

- Yes
- No

6. Interest level of having one as a teaching aide:

- Low
- Moderate
- High

7. How much would you be willing to spend on one?

- $250
- $500
- $1,000
- $2,000

8. Do you have any comments, questions, or concerns?

Done

Appendix B: Trade Studies

Trade Studies- Actuators					
	Hydraulic	Air	Electric	Air/ Hydraulic	Comments
Cost	1	4	1	1	Electric actuators are preferred but are cost prohibitive. Hydraulic and air/ hydraulic offer too much technical risk.
Complexity	2	3	3	1	
Strength	4	3	3	4	
Integration	1	3	4	1	
Technical Risk	2	4	4	1	
SCORE	10	17	15	8	

Trade Studies-Clamp Actuators				
	Hydraulic	Air	Manual	Comments
Cost	1	3	4	Workholding clamps are available in both powered and manual designs. Hydraulic would require a custom design. Manual clamps are easy to engage, offer high strength, low cost, and easy actuation.
Complexity	2	3	4	
Strength	4	3	3	
Integration	1	3	4	
Technical Risk	2	4	4	
SCORE	10	16	19	

Trade Studies- Machine Orientation				
	Vertical	Horizontal	Optional	Comments
Cost	3	3	2	Vertical and horizontal orientations are similar, but vertical orientation results in a smaller footprint. Optional orientation would add design complexity and risk.
Complexity	3	3	1	
Machine Size	4	2	4	
Technical Risk	3	3	1	
SCORE	13	11	8	

Trade Studies- Machine Operation				
	Automatic	Semi- Auto	Manual	Comments
Cost	1	3	4	A fully automatic machine has high cost and high technical risk/ complexity. Semi-automatic machines blends low cost with ease of use and features. Manual machines have the lowest cost, but are the hardest to use, and have safety issues, along with possible patent infringement.
Complexity	1	2	4	
Ease of Use	4	3	1	
Marketability	3	4	2	
Safety	3	4	2	
Technical Risk	2	3	3	
SCORE	14	19	16	

Trade Studies- Injection Type			
	Screw	Plunger	Comments
Cost	1	3	Screw type has better injection quality, but has higher costs due to being custom made and would be harder to implement due to linear and rotary movement. Plunger type is able to produce acceptable results with reduced costs and complexity.
Manufacturability	1	4	
Machine Size	3	3	
Injection Quality	4	2	
Complexity	1	3	
Technical Risk	1	4	
SCORE	11	19	