Fall 2018

T-Shirt Square Cutter

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Executive Summary

Each year, Americans waste millions of pounds of textiles in the form of clothing that is thrown away. Professor Mary Ruppert-Stroescu from the Sam Fox School of Design seeks to combat this by reusing the old fabric from discarded clothes and creating new, fashionable clothing. To do this, her and her students cut up donated shirts into small squares, by hand, using scissors and fabric cutters and sew them together using a method developed by her.. This process is very time consuming and limits the commercial viability of this process. The T-shirt Cutter design, detailed below, has the potential to significantly outpace hand cutting and make the process quicker, easier and more lucrative to potential investors. The 22-blade design can cut a single T-shirt into many ½" x ½" squares, ready to be sewn into new clothing, using Professor Ruppert-Stroescu's method. The blades required are cheap, easy to replace and the design is built with safety of the user in mind. With a streamlined method of cutting the fabric squares, Professor Ruppert-Stroescu's process can be applied on a much larger scale, potentially even a commercial scale, which would mean significantly less textile waste being deposited in landfills across the country.

MEMS 411: Mechanical Engineering Design Project
Fall 2018

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1 Introduction

Each year, the average American will discard 70 pounds of textiles, which translates to 21 million pounds of clothing wasted[1]. In an effort to combat this unsustainable habit, Professor Mary Susan Ruppert-Stroescu has been creating new designs, using only recycled clothing donated by students. The clothes have to be processed into strips or little squares before they can become the next hot fashion. This process is very time consuming and usually involves many hours hand cutting the clothes. If recycled clothing is to become dominant in the market, a quicker method of cutting must be developed.Designing an automated cutting machine or device that allows for a large quantity of fabric to be cut at once will greatly reduce the time involved with processing the clothes. Our design will reduce the amount of time required to cut the aforementioned small squares, while maintaining a consistently sized output. This design will not only speed up the process, but will increase the volume of raw materials that can be used to create more clothing.

2 Problem Understanding

2.1 Background Information Study

3 Current Designs:

Accuquilt Studio 2 Fabric Cutter

This product is used to cut pieces of fabric in square and rectangular shapes for use in quilts. It is designed to use fabric that you would buy from a store, but could be used on any type of fabric. However, the cost of this product is rather high and it is unable to rounded shapes or strips. This product is about the size we would like our design to be for cutting squares. However, using this product to produce the small squares desired by the customer would be inefficient, as it would require a lot of passes with the blade to make the proper cuts.

Figure 1. Current model of a fabric cutter

Reliable 1500FR Octagonal Knife Cloth Cutting Machine

This product is what the customer is currently using to cut the fabric into squares and rectangles. It is powered, so it is much easier to use than traditional fabric shears. It also has a built-in self-sharpening mechanism, which is a strong point in this design, as dull blades were a major customer complaint. This product is also able to cut through many layers of

[1]*The Fact About Textile Waster*. Council for Textile Recycling, www.weardonaterecycle.org/about/issue.html

thick fabric, making it significantly more versatile than shears or the square cutters. The downside to this product is that it would still take a lot of time to cut out the small squares desired by the customer.

Figure 2. Current model of a cloth cutting machine

[**28" USCutter MH721 Vinyl Cutter w/VinylMaster Cut AND USCutter 15" x 15" Digital Heat Press Machine**]()
USCutter 28" Vinyl Cutter + 15" x 15" Digital Heat Press Machine Signs/T-shirt Making:
This product is an consists of two devices, a cutter clamshell heat press and a vinyl cutter. The clamshell heat press is portable and easy to operate (it weighs 64 pounds). With this device it is possible to cut shirts on a certain pattern and customize them, depending on what the customer is looking for. It has a pressure adjustment knob which helps the user to variate the pressure depending on the thickness of the cloth being cut. The second product is a vinyl cutter which is able to produce vinyl signage. It has guides and a software for the operator so that it is easy and fast to operate. These products are sold in combo for $549.99. Both devices are accurate and avoid wasting material. According to users reviews, both of these products require of previous knowledge of how to operate them, otherwise it might take a while to understand how they work.

Figure 3. Current model of a fabric cutter

2 Patents:

Fabric-cutting machine and method - Patent #: US3304820A

This patent shows a large, industrial-style fabric cutter with a single blade for cutting. It is capable of cutting a long, linear pattern into a long sheet of fabric. This patent's scope is significantly larger than the scope of our design, but it's ability to cut out long patterns could be used to help inform a scaled down variant of this patent for our design.

Rotary cutting blade assembly for a hand-held cutter - Patent #: US5355588A

This patent shows a hand-held, pizza-cutter style fabric cutter. This patent shows the quickest possible, manual way to cut fabric. This patent could be used to inform a wheeled-style design we may use going forward, serving as a sort of base to build upon. This design falls short, due to the amount of time required to cut many small squares that are desired by the customer.

2 Standards:

ISO 10821:2005 - Industrial sewing machines - Safety requirements for sewing machines, units and systems

This ISO standard for industrial sewing machines establishes safety requirements for industrial sewing equipment. With our project being textile related, it will serve as a good guideline for the hazards and safety requirements present in working with fabric and cutting fabric. While the scope of the ISO standard is a larger than the scope of our design, it will serve as a good starting point for safety considerations.

ISO 01.100.20 - Mechanical engineering drawings

This ISO standard informs how all aspects of technical drawings are to be implemented. This will be helpful as a guide on how we are to generate our own drawings for our product. Following this standard will allow our drawings to be professional and accessible to other designers, engineers and fabricators in the US and abroad.

2.2 User Needs

The following table summarizes the information collected during the interview with Professor Mary Rupert. This interview helped us understand what the machine should do and the goals it should achieve.

Table 1. Customer Interview Table

Customer Interview Table

Product: T-shirt Strip Cutter			
Customer: Dr. Mary Susan Ruppert-Stroescu			
Address: Bixby 11, Washington University Danforth Campus			
Notes: Previous techniques for cutting the shirts were discussed. Most efficient seemed to be by hand but very time consuming. While more automated techniques involved less time but had quality issues or needed more development.			
Date: September 7, 2018			
Question	**Customer Statement**	**Interpreted Need**	**Imp.**

Size of strips/squares?	3/8 – ½ inches	Adjustable sizes	4
Size of device?	Fit on table top, but size isn't a limiting factor.	Needs to be portable but still function. Cosmetics not very important.	5
Cut a single shirt vs. a stack	Stacking but if single is more efficient/faster than either is fine.	Needs to be able to produce large quantities.	1
What is the end product supposed to look like?	Square or rectangular pieces.	Need to consistently produce raw stock.	3
How often do you have to change or sharpen blades?	The blades have to be sharpened frequently.	Has to be serviceable.	2

Based on the needs Professor Mary Rupert needed to achieve we organized them and ranked them according to their importance. The results can be seen in the table 2:

Table 2. Interpreted Customer Needs

Interpreted Customer Needs

Need Number	Need	Importance
1	Cutting lengths need to be adjustable.	4
2	Machine should be moveable/portable.	5
3	Produce large quantities of raw stock.	1
4	Machine should make consistent cuts.	3
5	The blades should be serviceable or easy to sharpen.	2

2.3 Design Metrics

Before starting to build the machine cutter we needed to know certain parameters and targets the machine needed to fulfill. the target specifications can be observed in Table 3:

Table 3. Target Specification

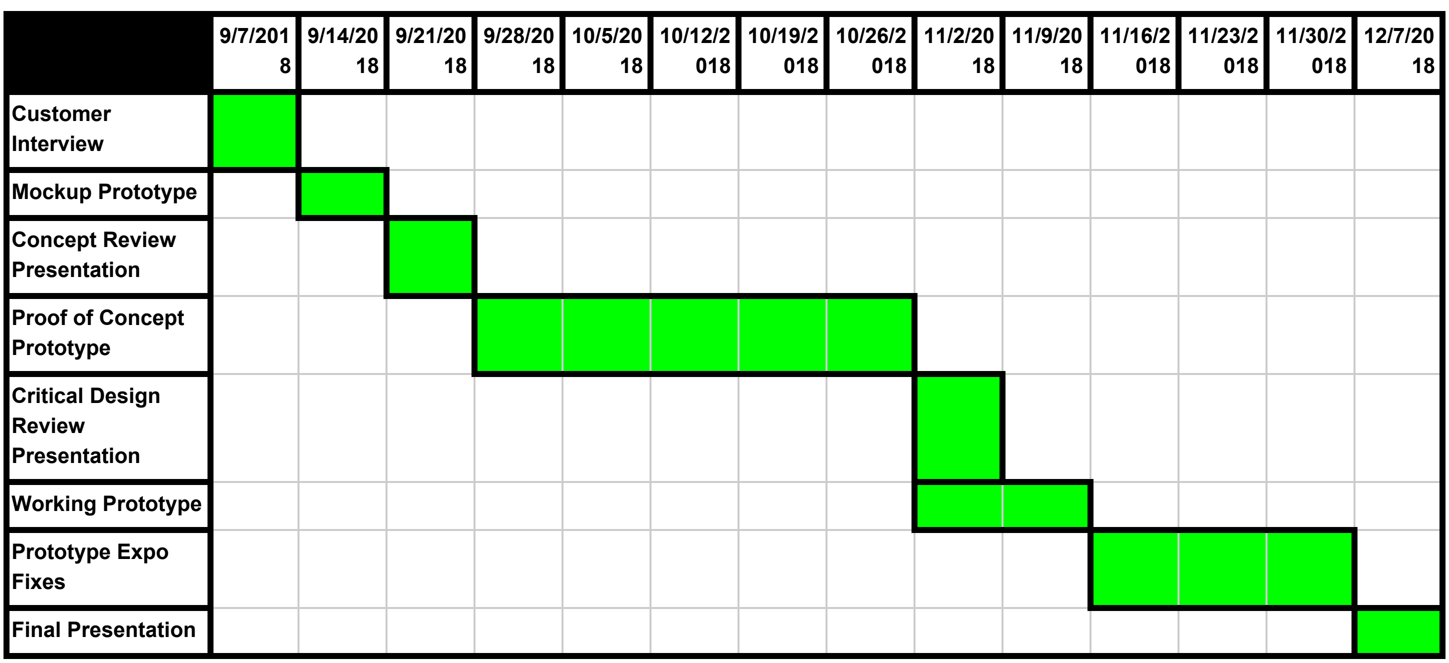
Target Specifications

Metric Number	Associated Needs	Metric	Units	Acceptable	Ideal
1	1,2	Total weight	kg	10-30	15
2	1,2	Total volume	in^3	20 x 25 x 2	15 x 20 x 1.5
3	3	Full Cut Speed	min	1	0.5
4	4	Consistent cuts	in^2	2 x 2	1 x 1
5	3,4	Amount of squares cut per shirt	Integer	<70	<100

2.4 Project Management

As seen from our Gantt chart below, we were able to stay on schedule and complete all of our tasks.

Table 4. Gantt Chart



3 Concept Generation

3.1 Mockup Prototype

Before starting to build the mockup we had some rough sketches and ideas of how the t-shirt cutter would look like and how it was going to work. Nevertheless once we started cutting the pieces and putting everything together, new ideas came up and the initial design we had in mind was changed. The mock up helped us realize how big the machine has to be, what materials should we use to build the actual cutter, and the mechanisms we have to use so that it works perfectly. The mock up also brought to our attention that we have to include some safety instructions and include some other pieces that will avoid the contact of the user with the blades. Overall it was a good exercise that brought as a step closer to what is going to be our final design. Figures 4-7 show the final mockup prototype.

Figure 4,5. Initial mock up designs showing the general function of the cutting "press" and rotational bottom section.

Figure 6, 7. Final Mockup Prototype

3.2 Functional Decomposition

Figure 8 shows a simple function tree for our design. Figure 10 shows some of the ideas we came up with for the individual systems that make up the T-shirt cutter. The main concern was safety and how to minimize the users exposure to the blades.

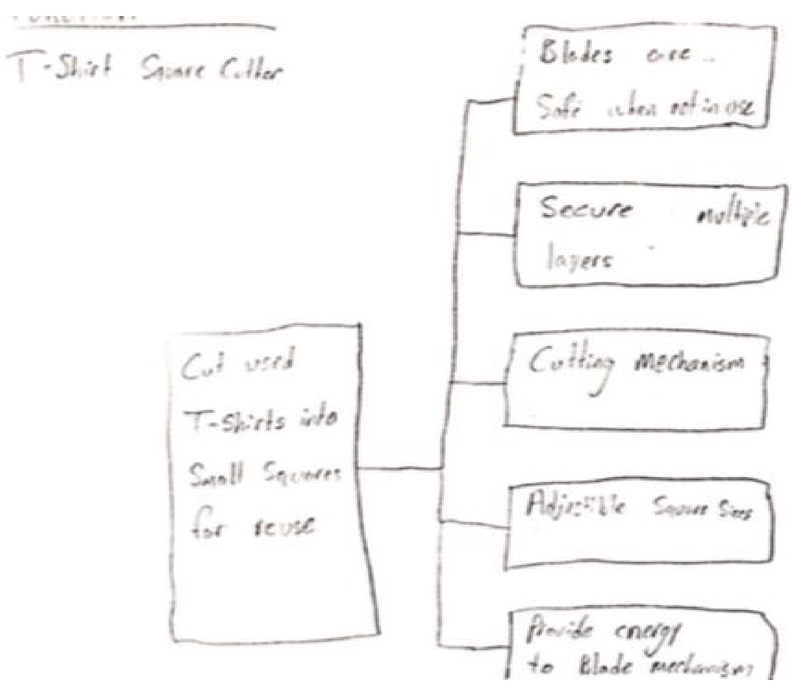


Figure 8. Function Tree

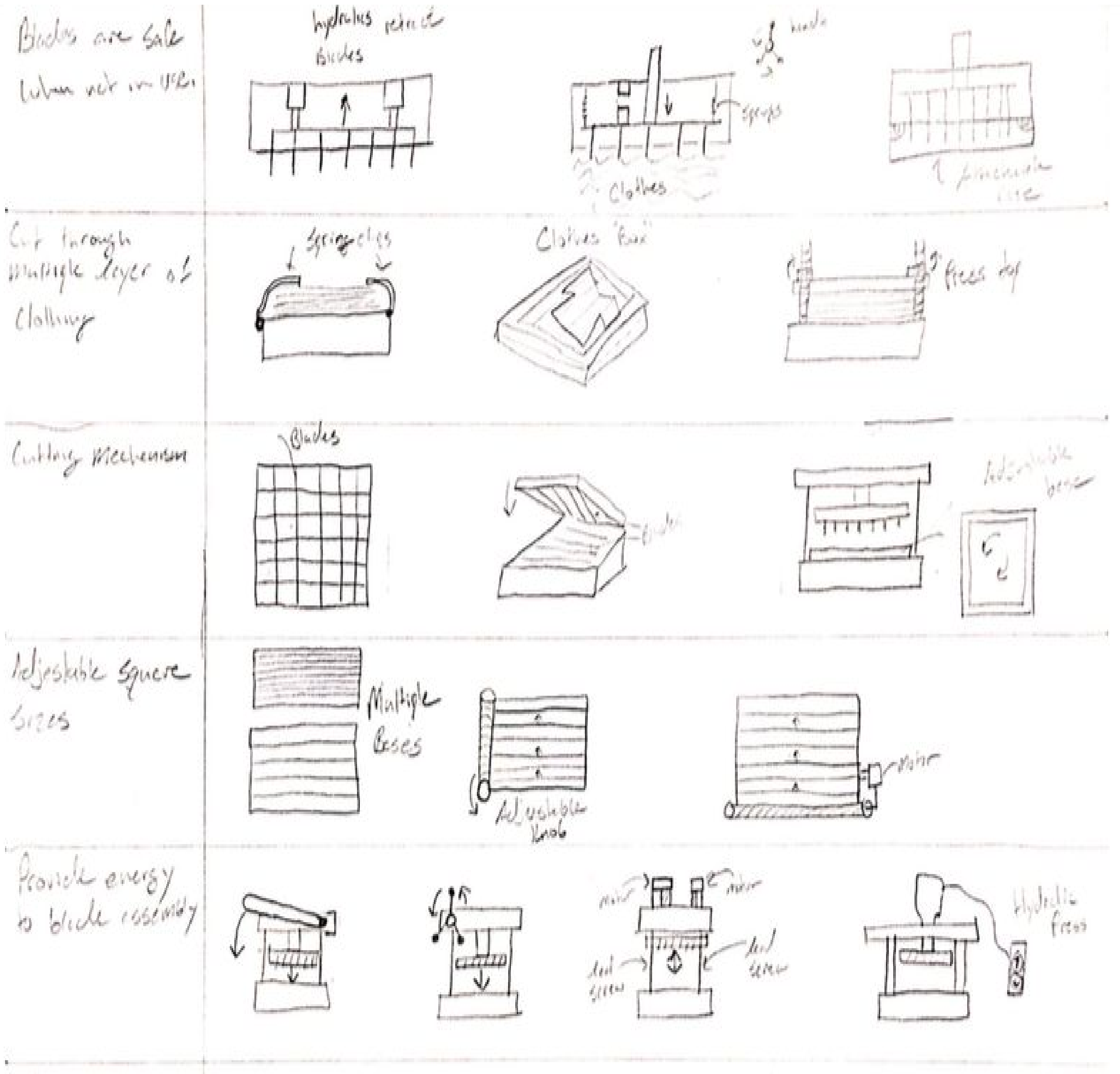


Figure 9.. Concepts proposed for the machine cutter

3.3 Alternative Design Concepts

Figures 10, 11, and 12, below show some concept design by each individual group member. These concept designs were then ranked using the criteria discussed in section 4 below.

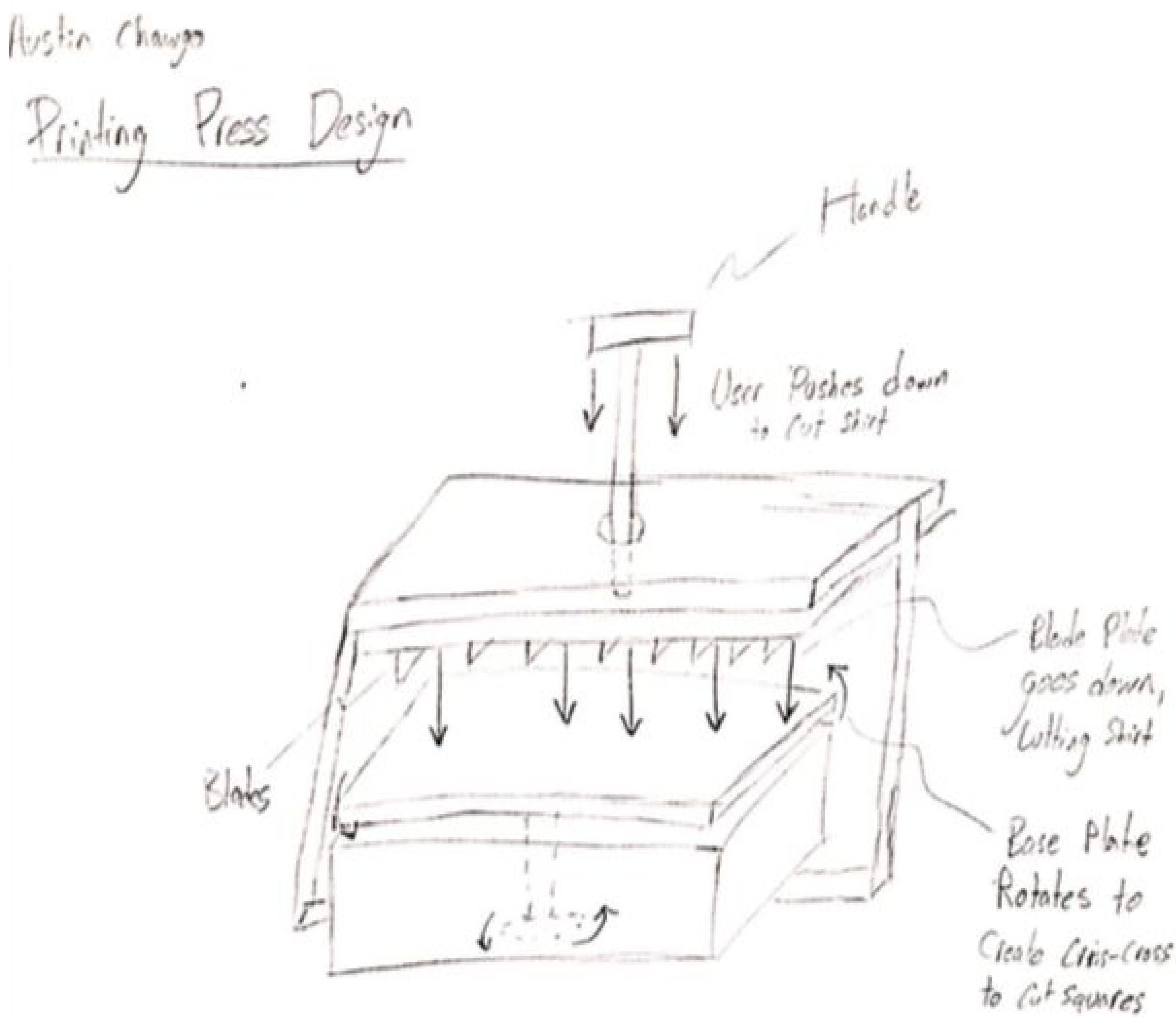


Figure 10. Austin Chawgo Printing Press Design

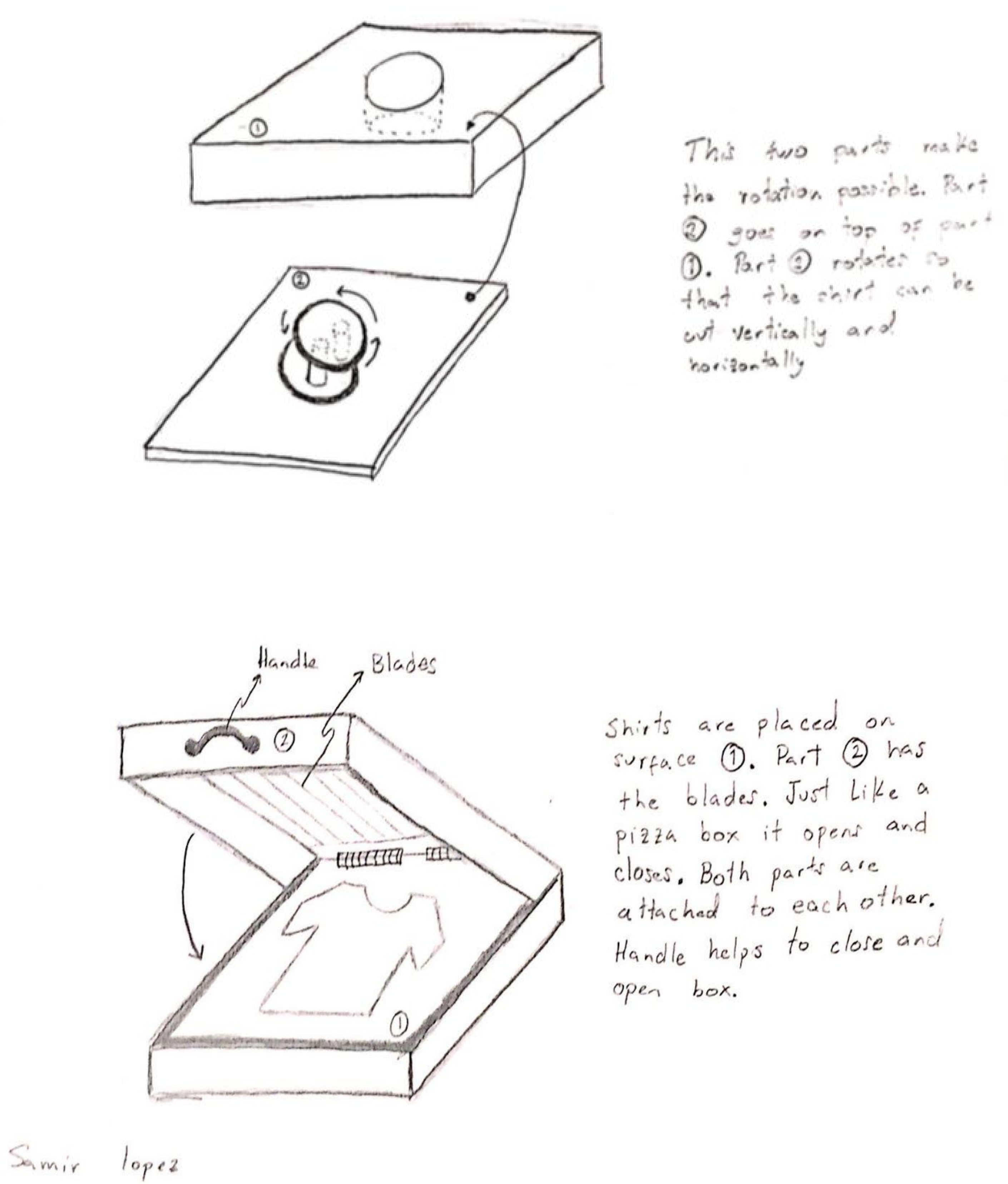


Figure 11. Samir Lopez concept model

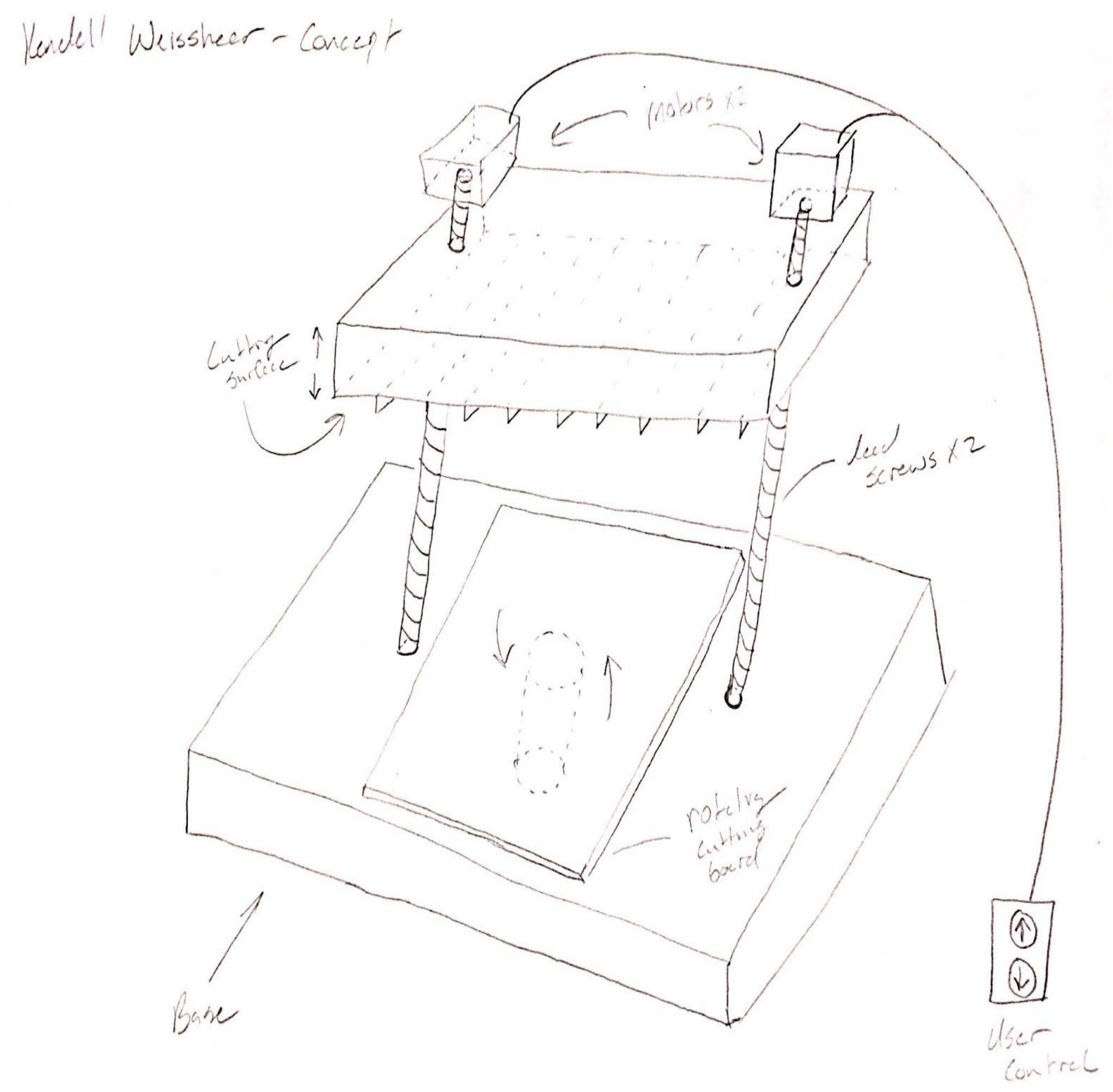


Figure 12. Kendall Weisshaar concept model

4 Concept Selection

4.1 Selection Criteria

Using the information obtained from our client meeting we were able to determine the weighted percentages to be input into the weighted matrix used for ranking the concept designs.

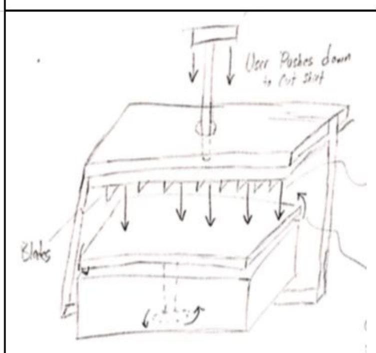
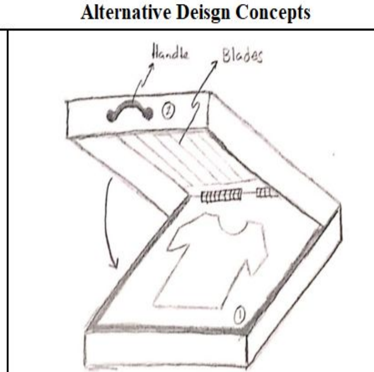
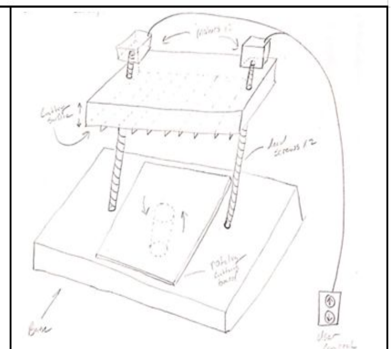
Table 5. Analytical Hierarchy Process

	Safety	Portablilty	User Friendly	Efficient	Serviceable	Adjustability	Row Total	Weight Value	Weight (%)
Safety	**1.00**	3.00	5.00	5.00	7.00	3.00	24.00	0.28	27.61%
Portability	0.33	**1.00**	0.33	0.20	0.14	0.14	2.15	0.02	2.48%
User Friendly	0.20	3.00	**1.00**	0.14	0.14	0.14	4.63	0.05	5.32%
Efficient	0.20	5.00	7.00	**1.00**	0.14	0.33	13.68	0.16	15.73%
Serviceable	0.14	7.00	7.00	7.00	**1.00**	1.00	23.14	0.27	26.62%
Adjustability	0.33	7.00	7.00	3.00	1.00	**1.00**	19.33	0.22	22.24%
						Column Total:	**86.93**	**1.00**	**100%**

4.2 Concept Evaluation

Having our three design concepts, it was time to decide which concept fit best with the needs of the user and the criterion. Table 6 shows the results and ranking of the design concepts.

Table 6: Weighted matrix for concept designs.

		Alternative Deisgn Concepts					
							
Selection Criterion	**Weight (%)**	**Rating**	**Weighted**	**Rating**	**Weighted**	**Rating**	**Weighted**
Safety	27.61	2	0.55	4	1.10	3	0.83
Portability	2.48	3	0.07	4	0.10	3.5	0.09
User Friendly	5.38	3.5	0.19	3	0.16	4	0.22
Efficient	15.73	3	0.47	2	0.31	3	0.47
Serviceable	26.62	3	0.80	2	0.53	2.5	0.67
Adjustability	22.24	2	0.44	2	0.44	2	0.44
	Total score	**2.530**		**2.657**		**2.713**	
	Rank	**3**		**2**		**1**	

4.3 Evaluation Results

From the Analytical Hierarchy Process, we determined that the top three most important criteria for assessing our designs were safety, serviceability and adjustability of the blades. Out of the three, safety was the most important, which is to be expected, as the user's safety is always the most important consideration in any design. Serviceability was also highly ranked, due to how quickly the blades wear out when cutting many layers of fabric; something that was stressed by the customer. Adjustability also scored high because the customer wanted a versatile device that could cut a variety of square sizes.

From the Weighted Matrix, we compared the three designs we developed. The best design was found to be the Powered Press design (Concept 3), which uses lead screws to move the blades. This design ranked highest, due to its high user friendliness and its nominal safety rating. The Printing Press design (Concept 1) had a low safety rating and low adjustability, which is why it ranked the lowest. The Folding Design (Concept 2) had a high safety rating, as it was the safest design, but it had a low serviceability and efficiency rating, making it ranked second.

4.4 Engineering Models/Relationships

Model 1: Shear Stress

Shear stress caused by the blades is what causes the cutting action. The shear strength (τ_{max}) is not readily available for fabrics, as the weave and blends can affect this value. However, the tensile strength (σ_{max}) of fibers is available. The shear strength is related to the tensile strength as follows, in Equation 1:

$$\tau_{max} \approx \frac{\sigma_{max}}{2} \text{ (From Mohr's Circle)} \qquad \text{(Equation 1)}$$

This model can help inform us on how much force will be required by the user (or motor) in order to cut the fabric, since normal stress (σ_{max}) is related to the applied force (F) as follows, in Equation 2:

$$\sigma_{max} = \frac{F}{A} \qquad \text{(Equation 2)}$$

Where A is the cutting area of the blade. By inputting values for tensile strength and the cutting area of the blade, we can determine the amount of force required.

Model 2: Springs

Springs are elastic bodies that exert forces and torques, absorb energy, and are used for vibration isolation. There are different types of springs: coil/helical springs, leaf springs, torsion springs, and washer/disk. For our machine cutter we would use coil/helical springs. The deflection of a coil spring is calculated with the following equation 3:

$$\delta = \frac{8FD^3N}{d^4G} \qquad \text{(Equation 3)}$$

Where *d* is the wire diameter, *D* is the mean coil diameter, *N* is the number of active coils, and *G* is the shear modulus. The spring constant rate is given by 4:

$$k = \frac{F}{\delta} = \frac{d^4G}{8D^3N} \qquad \text{(Equation 4)}$$

At any cross-section of a coil spring the torque is defined by 5:

$$T = \frac{FD}{2} \quad \text{(Equation 5)}$$

The total shear stress at the inner surface of the coil is given by 6:

$$\tau = \frac{8FD}{\pi d^3}\left(\frac{4C-1}{4C-4} + \frac{0.615}{C}\right) \quad \text{(Equation 6)}$$

Even though we investigated springs, and springs were involved with the conceptual designs, ultimately the design we chose to move forward with to produce a working prototype did not involve any springs. The use of the stepper motors was adequate and the design of the upper blade box safely enclosed the blades without the use of springs.

Model 3: Power Screws

For the Powered design, the cutting mechanism will be using power screws to move the blades up and down. This requires that the power screws experience a certain amount of torque (T) to apply the required force (W) to cut through the fabric. To calculate the required torque, Equation 7 will be used:

$$T = W\left(\frac{d_m}{2}\right)\left[\frac{f + \tan\lambda\cos\alpha_n}{\cos\alpha_n - f\tan\lambda}\right] + \frac{Wf_c d_c}{2} \quad \text{(Equation 7)}$$

and λ is defined in Equation 8, as follows:

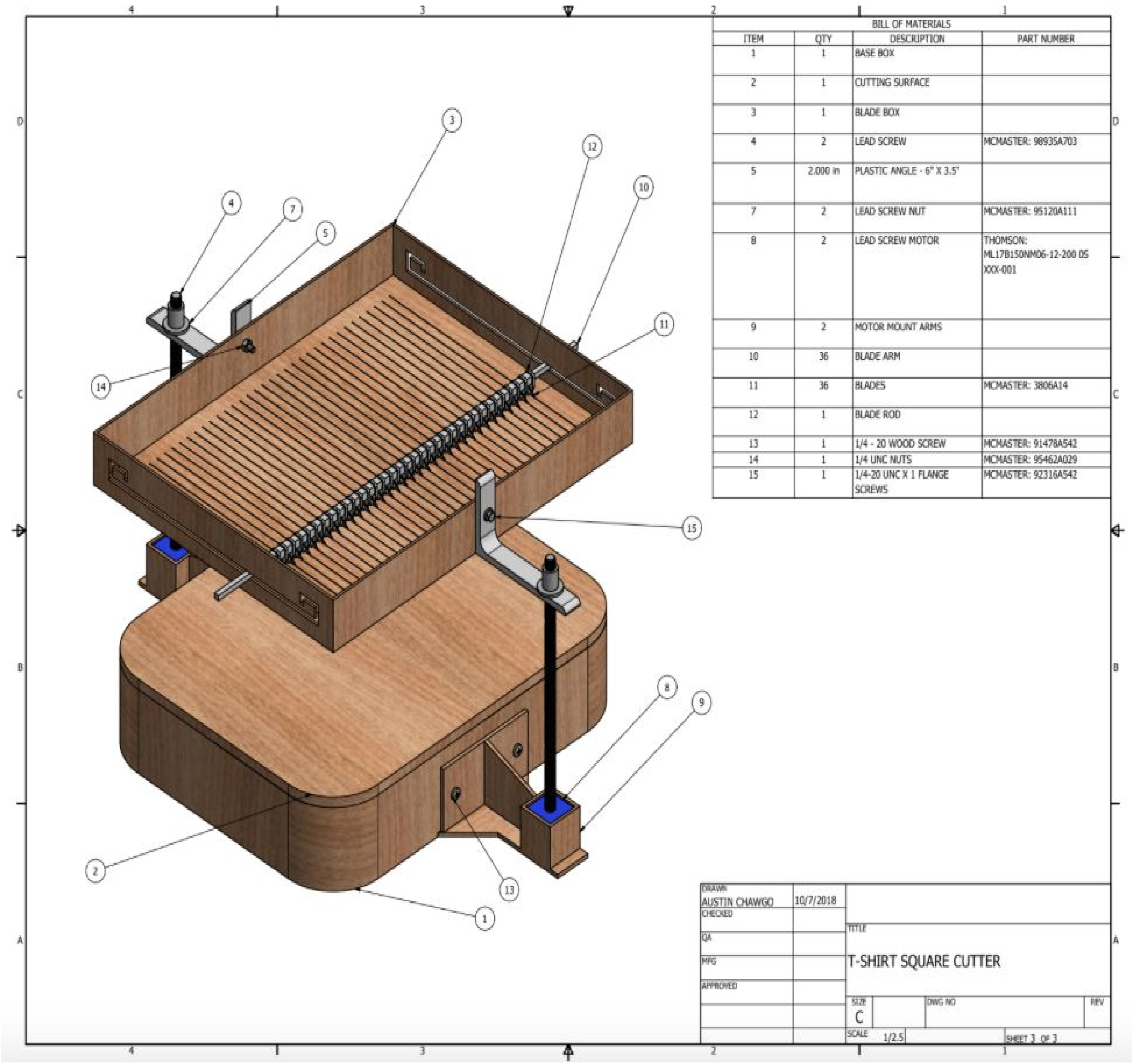
$$tan(\lambda) = \frac{L}{\pi d_m} \quad \text{(Equation 8)}$$

Where d_m is the mean diameter of thread contact, L is the lead of the threading, f is the friction coefficient, α_n is the thread angle, f_c is the friction coefficient in the collar and d_c is the mean diameter of the collar. This model will allow us to predict the torque required from the motor driving the power screw, so we can choose a correct one.

5 Concept Embodiment

5.1 Initial Embodiment

Figure 14 below shows the final cad drawing with bill of materials. Some slight differences between this cad drawing and the final prototype is how the lead screw arms are attached to the upper blade box. In the drawing it can be seen that a bolt and nut are used but in the finale prototype the arms were attached simply by gluing them on. Figure 15 shows the exploded view of the prototype.



BILL OF MATERIALS			
ITEM	QTY	DESCRIPTION	PART NUMBER
1	1	BASE BOX	
2	1	CUTTING SURFACE	
3	1	BLADE BOX	
4	2	LEAD SCREW	MCMASTER: 98935A703
5	2.000 in	PLASTIC ANGLE - 6" X 3.5"	
7	2	LEAD SCREW NUT	MCMASTER: 95120A111
8	2	LEAD SCREW MOTOR	THOMSON: ML17B150NM06-12-200 0S XXX-001
9	2	MOTOR MOUNT ARMS	
10	36	BLADE ARM	
11	36	BLADES	MCMASTER: 3806A14
12	1	BLADE ROD	
13	1	1/4 - 20 WOOD SCREW	MCMASTER: 91478A542
14	1	1/4 UNC NUTS	MCMASTER: 95462A029
15	1	1/4-20 UNC X 1 FLANGE SCREWS	MCMASTER: 92316A542

Figure 13. assembly view of the concept embodiment with a completed BOM

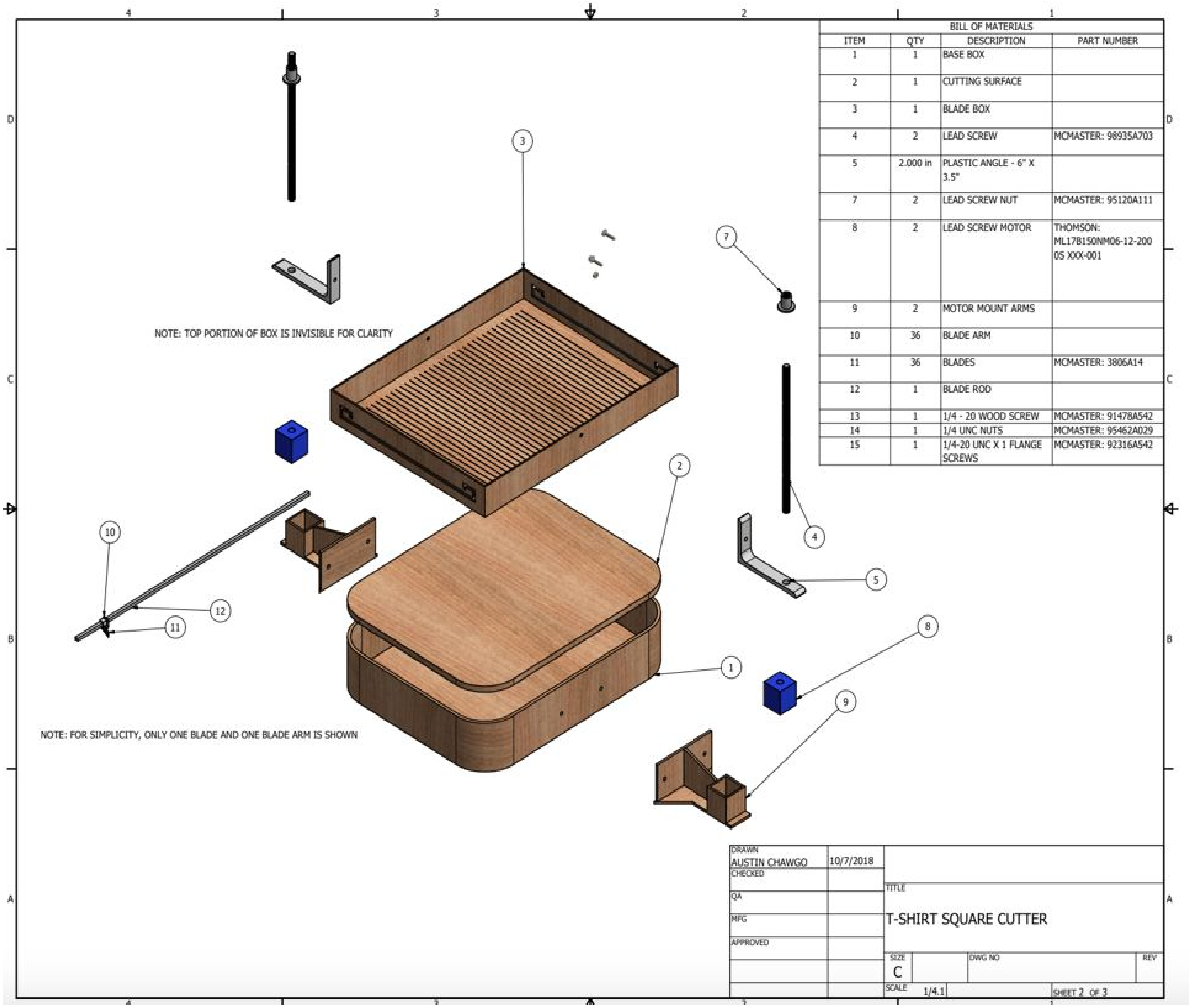


Figure 14. Exploded view of the concept showing each component (with balloon callout)

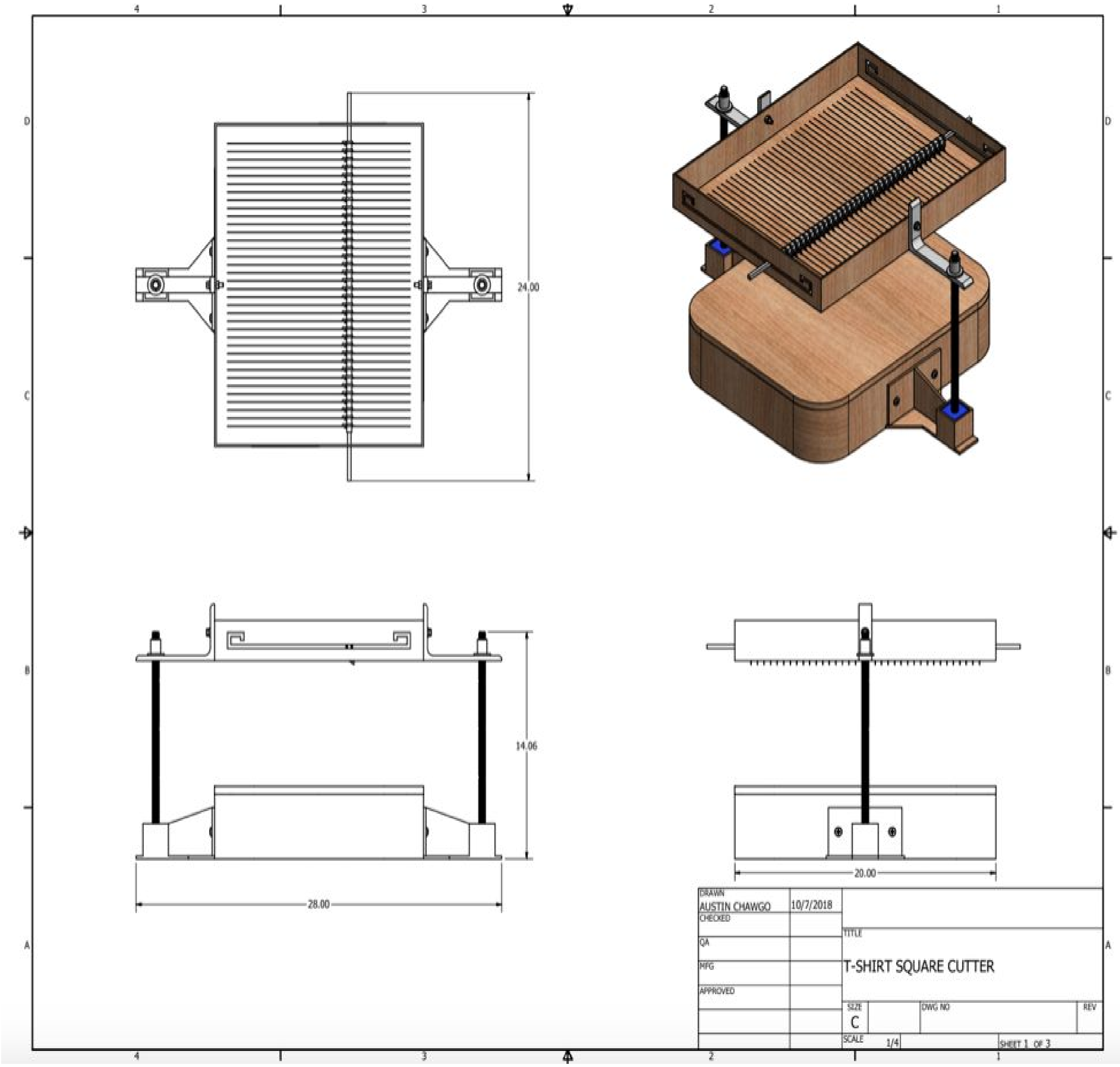


Figure 15. *Drawing of the concept embodiment showing top, right, and side views, and basic overall dimensions*

Table 7 organizes and names the parts used to build the machine cutter. It also lists its price and where it was purchased from.

Table 7. T-shirt Cutter Parts List

Part	**Source Link**	**Supplier Part Number**	**Color, TPI, other part IDs**	**Unit price**	**Quantity**	**Total price**
Stepper Motor with 28cm Lead Screw	Pololu	2268	Black/Silver	$49.95	2	$99.9
Utility Knife Blades	McMaster	3806A14	Silver. 3 Holes	$2.08	5	$10.4
Pine Sanded Plywood	Lowe's	N/A	Plytanium 1/4 CAT PS1-09	$19.02	2	$38.04
Hex Head Screw for Wood	McMaster	91478A542		$6.18	1	$6.18
Medium-Strength Steel Hex Nut	McMaster	95462A029		$4.40	1	$4.40
High-Strength Grade 9 Steel Hex Head Screw	McMaster	92316A542		$8.46	1	$8.46
Carbon Steel ACME Lead Screw	McMaster	98935A703		$6.00	2	$12.00
932 Bearing Bronze ACME Flange Nut	McMaster	95120A111		*	*	*

5.2 Proof-of-Concept

Prototype Performance Goals:

1) **Less than 10 seconds of debugging time during a 5 minute test.**

If the blades become tangled or caught on loose fabric it should take less than 10 seconds to free the blades safely.

2) **Cut 20x as many shirts over a 5 minute test**

The main goal of the machine cutter is to speed up the process of cutting the shirts into small squares. The machine should optimize time and cut 20 times more shirts than when doing it manually with scissors.

3) **Cut 20 shirts before a blade change is required**

This requirement ensures the blades will have a long enough lifetime to make the design viable and not require constant blade changes.

Design for PoC rationale components:

Utility blades were chosen for the cutting blade because they are readily available and make servicing the machine a safer and simple process. The blades chosen were specced from McMaster-Carr, specifically because they are designed to cut fabric and have holes that will be used to secure the blades when in use.

A custom 3D printed piece (Blade Arm) was designed to align the blades with their respective slots in the bottom of the plate, and ensure proper spacing between the blades. Due to the complexity of this part, 3D printing was the choice method of manufacturing.

Another major component of our model is the motorized lead screw which combines a hybrid stepper motor and a precision lead screw together. This motor converts rotary motion into linear motion. By using it we are able to lower and rise the upper bed containing the blades that will cut the shirts. This type of motor is used on 3D printers, medical devices, and more. Using this motor will make the mechanism and maintenance of the machine cutter simpler.

A concern for our design is that when the pressure is applied by the lead screw/motor, the upward force will bend the rod holding the blades. The bending will cause a deflection, which could push the blades inside the box, meaning they won't cut. Using a simplified system, with two fixed ends and a single point force at the center, the following Equation 1 can be used to calculate the deflection at the center of the rod (where it will be highest).[2]

$$\delta = \frac{PL^3}{48EI} \qquad \text{(Equation 9)}$$

[2] Gere, James M.; Goodno, Barry J. *Mechanics of Materials* (Eighth ed.). pp. 1083–1087.

Where I is the area moment of inertia, and is defined in Equation 10 for a square rod, P is applied force, L is the length of the rod, E is the Young's Modulus of the material and I is the area moment of inertia, and is defined in Equation 10 for a square rod.[3]

$$I = \frac{1}{12}e^4 \qquad \text{(Equation 10)}$$

Where e is the length of the square edge.

We chose to use aluminum, steel, wood and PLA, as those are readily available materials for our project. Using the values shown in Table 8, below. The force chosen was based off the specifications from the Pololu lead screw/motor chosen above.

Table 8. Material deflection values.

Material	Force (lbs)	E (psi)[4]	Moment of Inertia (in^4)	Deflection (in)	Notes
Aluminum	70	1.00E+07	0.00033	2.61	Too high, blades would be inside box
Steel	70	3.00E+07	0.00033	0.87	Blades still exposed, good material
PLA	70	2.90E+05	0.00033	90.09	Very high deflection
Wood (along grain)	70	1.88E+06	0.00033	13.90	High deflection

From this analysis and our design, it is clear we need to use steel the material for our rod. Wood and PLA would not be useful, as they would deflect far too much, and would most likely break with the applied force. Aluminum deflects less, but the deflection would result in the blades being pushed inside the box. Steel would deflect a significant amount, but not enough to render the blades useless.

The rod holding the blades will also experience torsional loading which could deform or break the rod. Equation 11 is used to calculate the torsional the rod will experience when cutting the shirts;[5]

$$\tau = \frac{Tr}{J} \qquad \text{(Equation 11)}$$

In equation 3, T is the Torque, r is the half of the total length , and J is the polar moment of inertia. In order to cut 5 shirts an approximate of 5 pounds force are required. The square rod we will be using has sides of 0.25 inches. When this values are plugged into equation 3, the following results are obtained.

$$\tau = \frac{(5\ lb)(\frac{1}{8}\ in)(6)}{(\frac{1}{4}in)^4}$$

$$\tau = 960\ lb - in^3$$

Before a full size prototype is created we tested our key components to see if our concepts would be feasible. Figure 16 below shows how the blade assembly will fit inside the top portion of the cutter. Originally 36 blades would be needed to

[3] https://www.engineeringtoolbox.com/area-moment-inertia-d_1328.html
[4] https://www.engineeringtoolbox.com/young-modulus-d_417.html
[5] MEMS 3110, Spring 2018, Machine Elements Stresses Presentation.

cut a shirt but after this concept review it was decided to fold the shirts in fourths to cut down the number of blades and reduced the overall size.

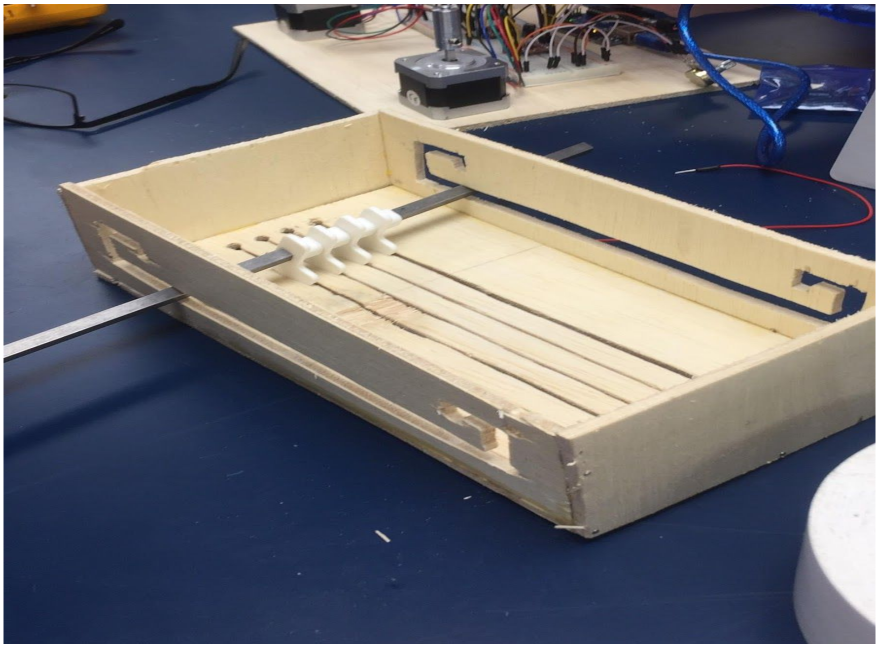


Figure 16. *Blade assembly concept.*

Another major component tested for feasibility was the circuit and motors that will be used to raise and lower the blade assemble box. Two NEMA 17 motors will be used along with an Arduino microprocessor. Figure 17 shows an earlier design including a potentiometer with three button inputs controlling the motors direction. The final circuit has eliminated the potentiometer as well as one of the buttons. The motors will operate either up or down depending on which button is pressed.

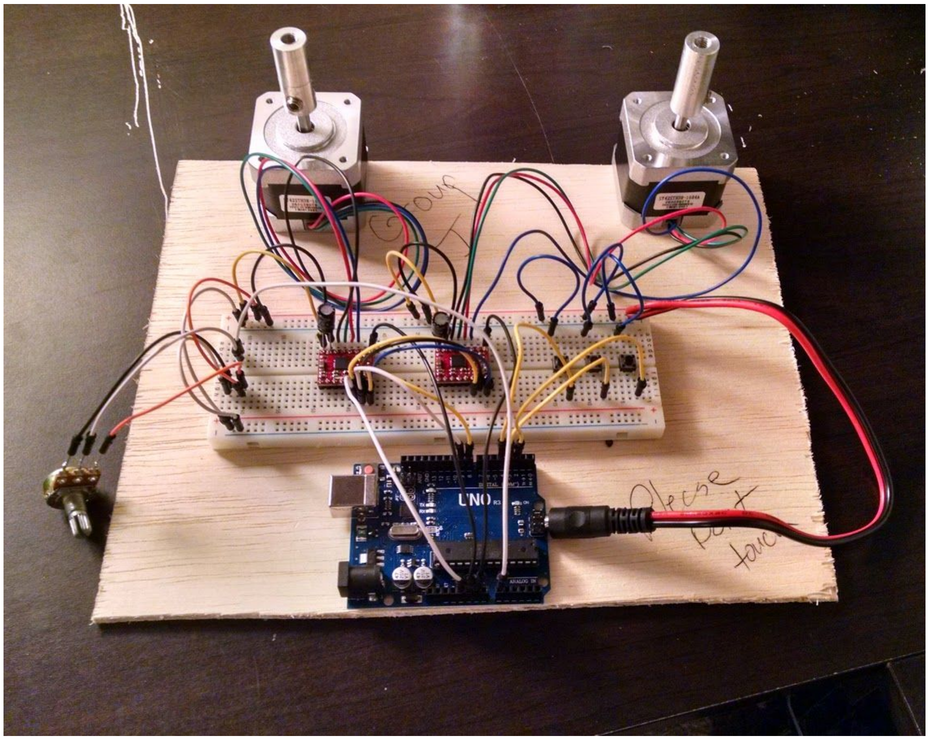


Figure 17. *Circuit and motors concept.*

6 Working Prototype

6.1 Overview

From the Proof of Concept, multiple changes were made. The first major change was scaling up the design to cut a full t-shirt. From our initial design, we had a 32 blades cutting the shirt. Due to the difficulty of cutting at the center of the bar, it was decided that we would reduce that to a 22-blade design. We also redesigned the blade arms to allow for the change in spacing of the blades. We also integrated the stepper motors and lead screws into the blade box and base box. This was done via 3D printed arms with steel nuts embedded in them. Additionally, the cutting surface had grooves cut in it, to allow the blades to slice the fabric, instead of just cutting over it.

6.2 Demonstration Documentation

Figure 18 shows the CAD model created for the working prototype, created in AutoDesk Inventor.

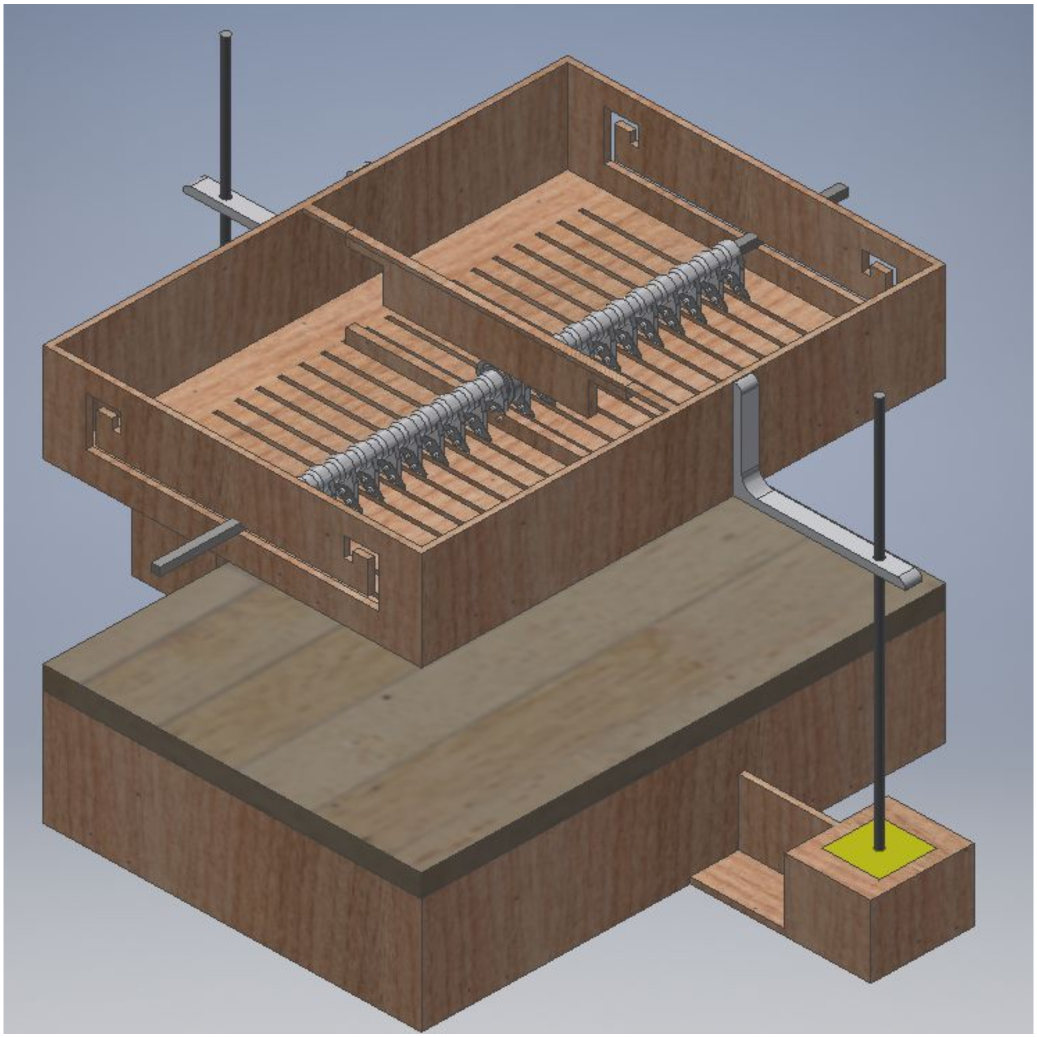


Figure 18 . Final CAD Model

Figures 19, 20, and 21. Show the final working prototype. There were alignment issues with the blade slots and the grooves cut into the cutting board. Because of these alignment issues we were only able test 5 blades instead of the 22 blades we were supposed to install.

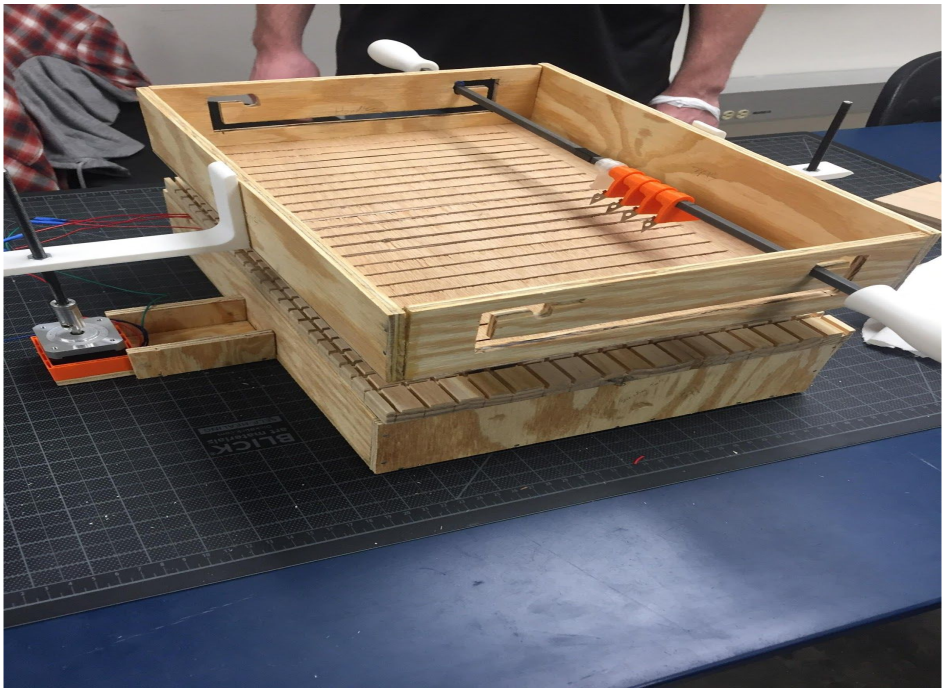


Figure 19 . Working prototype

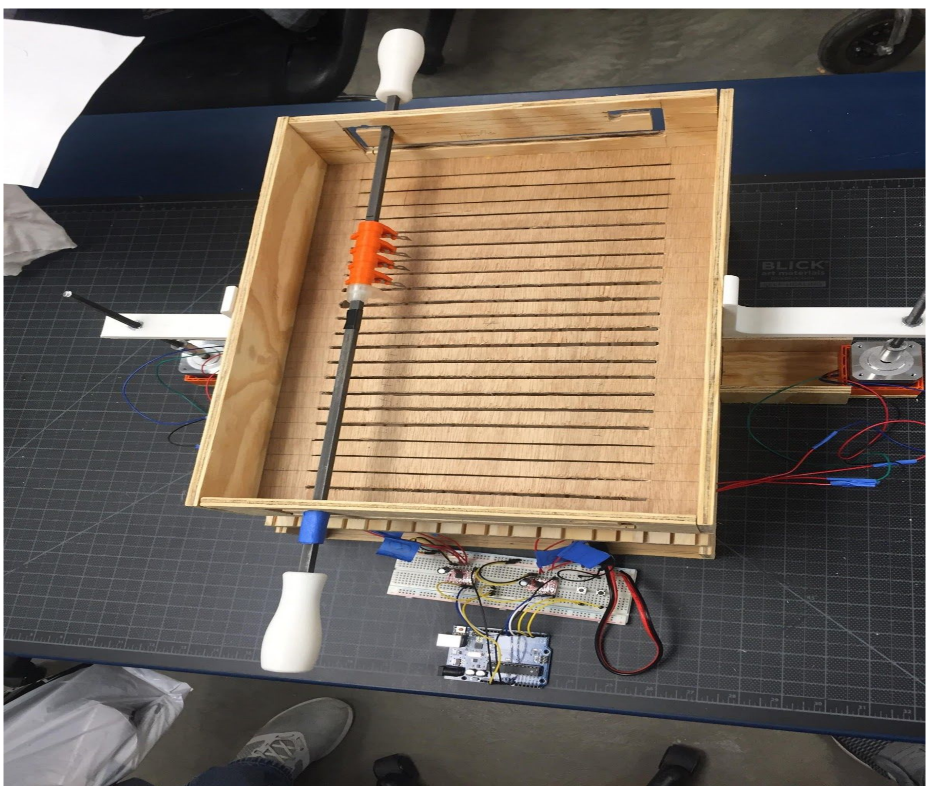


Figure 20 . Working Prototype

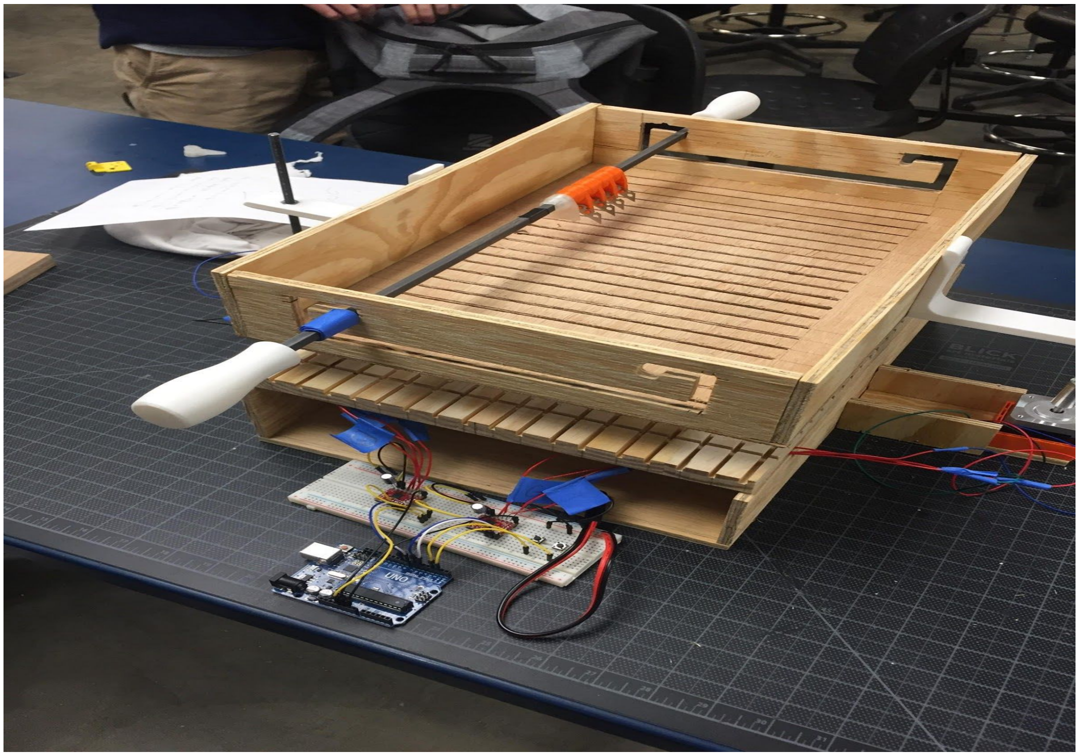


Figure 21 . Working Prototype

6.3 Experimental Results

Less than 10 seconds of debugging time during a 5 minute test.

For our first performance goal of 10 seconds of debugging time or less we were unable to fully test this requirement due to this alignment and laser cutter issues. Due to not having the laser cutter there was significantly more friction introduced to the system as a whole. At most we were able to test five blades out of the proposed twenty two. For those five blades there were no issues of debugging. If we were able to test all 22 blades there might be an issue with the fabric rolling up upon itself when attempting to cut but this issue could be fixed by using a thin metal bottom instead of wood for the blade box to help with deflection.

Cut 20x as many shirts over a 5 minute test.

The second performance goal of cutting 20x as many shirts over a five minute period was also difficult to test. Since only five blades were testable, the shirt being used for testing was folded over twice to simulate cutting through eight layers of fabric. The first attempt to cut the eight layers of fabric resulted in only the first two layers being semi-cut. With a little adjusting and added support, by us holding the motors down to stop deflection, we were able to increase our cutting ability to 3-4 layers. We theorize that using a metal bottom for the blade box may help with the shirts ability to roll or curl under the blades and increase the cutting performance.

3) **Cut 20 shirts before a blade change is required**

This requirement ensures the blades will have a long enough lifetime to make the design viable and not require constant blade changes. We were not able to test all the 22 blades that were supposed to be installed in the machine. Nevertheless the five blades installed lasted the entire semester and did not lose its sharpness. These blades were a good selection and it could cut more than 20 shirts easily before a replacement is needed. The fact that not many squares were cut deals more with the alignment of the cutting board and the upper bed than the quality of the blades. If possible it would be better to get some bigger blades so that the depth of the blades is larger and more shirts can be cut at the same time.

7 Design Refinement

7.1 FEM Stress/Deflection Analysis

For the FE analysis, we decided to look at the deflection of the blade rod when an upward force is applied to it by the shirts. Based on our estimates, an upward force of around 70 pounds will be present, due to the stepper motor torque. 70lb of force was applied at the tip of each blade and held the ends of the rods fixed. A mesh was applied with 104296 nodes and 50467 elements. We believe that this will accurately simulate actual working conditions, as the blades will be resisted upwardly by the shirts, which will cause a deflection. A large enough deflection could cause the blades to be pulled into the housing and not able to cut, rendering it useless. The boundary condition of fixed ends is realistic, as they will be held firmly in the operator's hands, making them relatively rigid throughout the process of cutting the shirts. Figure 22 shows the Mesh set up done in SolidWorks.

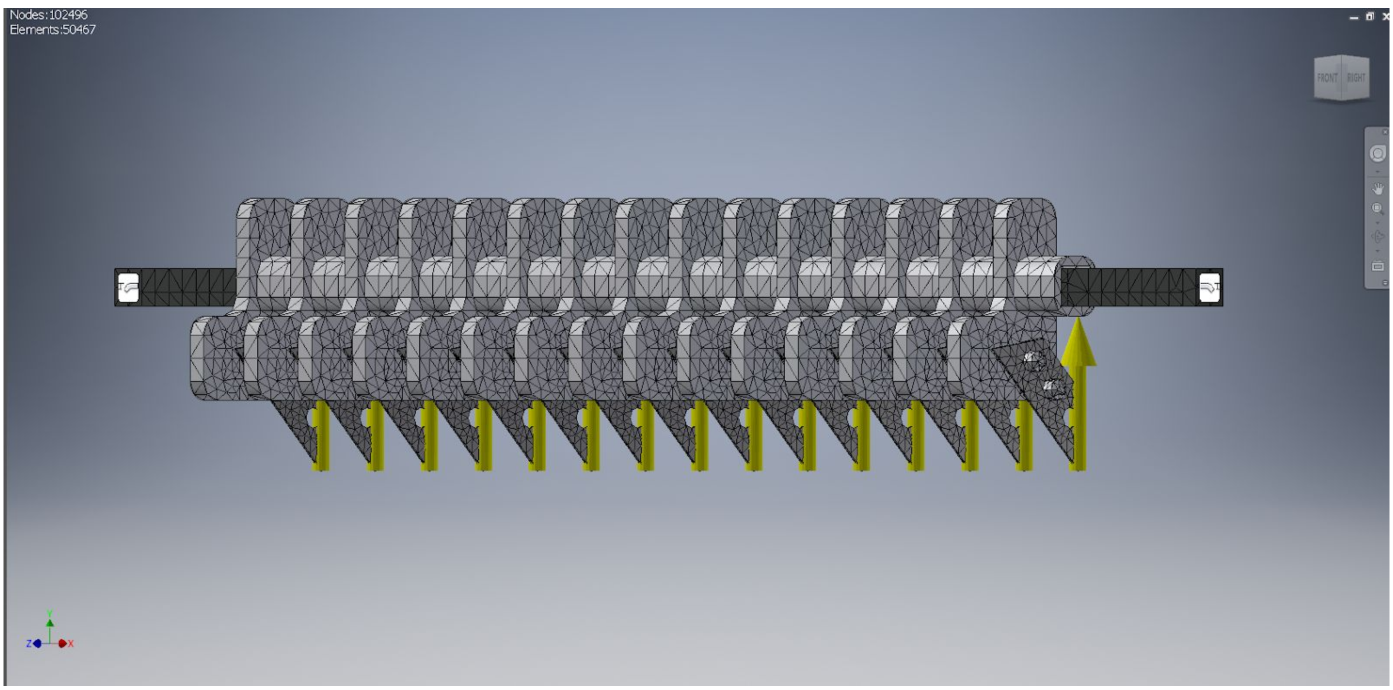


Figure 22. FEM Mesh

Our allowable displacement comes from the blades being pushed inside the box that houses them, which would be caused by a deflection of greater than ½". The maximum displacement based of the simulation is 0.02645 inches, which is well within our maximum possible allowable deflection for the blade beam. Figure 23 shows the study done to the part.

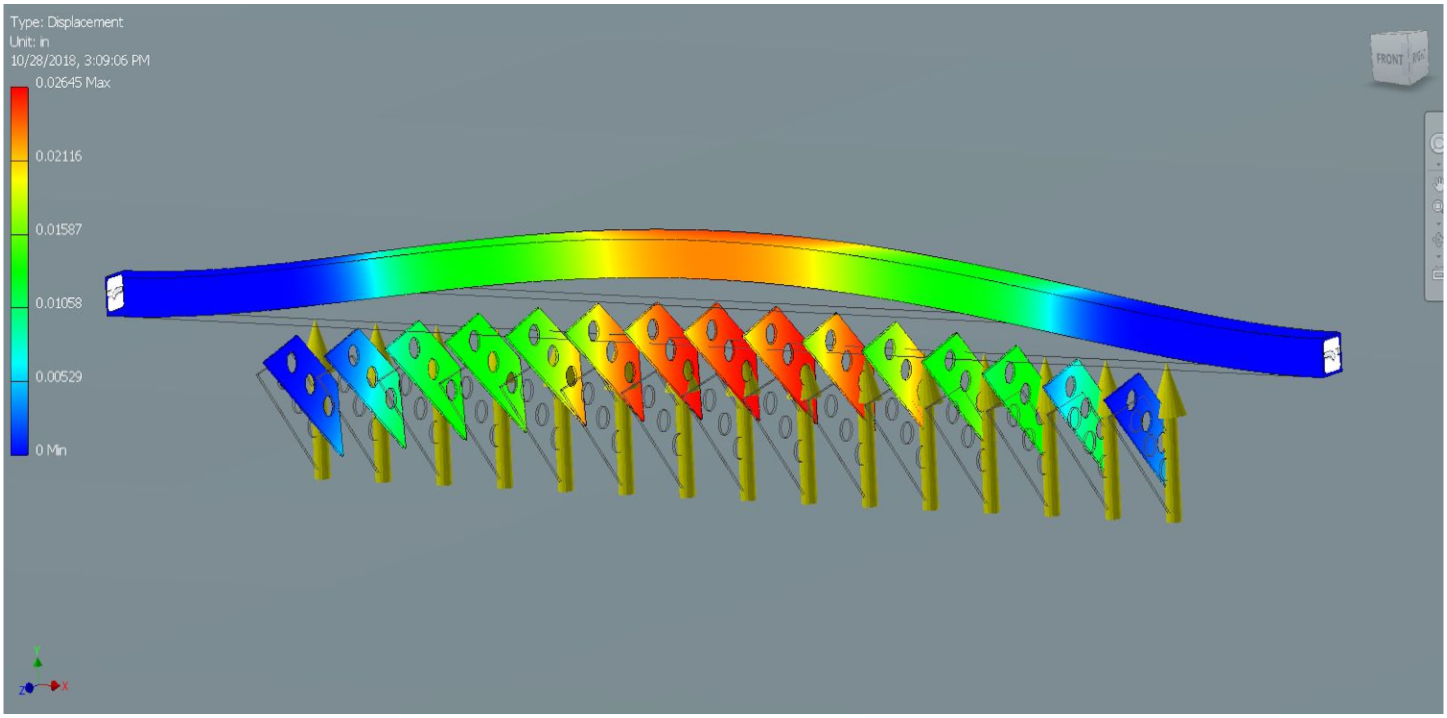


Figure 23. FEM Displacement Analysis (blade arms invisible for clarity)

7.2 Design for Safety

Risk Name: Exposed blades

Description: If the blade assembly rod would happen to break there is a possibility that sharp blades could be exposed. Also during normal operation the blades could become wedged in the upper box resulting in the user having to raise the box exposing the blades.

Impact: 3, moderate: Having exposed blades poses an increased risk of cutting the user.

Likelihood: 1, low: The blade arm assembly bar material has been chosen to be able to handle the stresses caused by the forces of cutting a shirt without failure.

Risk Name: Blade box falls

Description: If the mechanisms holding the blade box in position fail and cause the blade box to fall the users hands may be caught in between the blade box and cutting surface. Although the blade box is lightweight if it were to fall on the user's hands there is a possibility of the blades becoming exposed and cutting the user.

Impact: 4, significant: If the blade box falls then some major component of the machine has failed rendering the cutting machine inoperable.

Likelihood: 1, low: For the blade box to fail the lead screws holding it up would have to break in two or the motors would have to lose control. The motors are controlled by drivers and the weight of the blade box is insignificant when compared to what would be required to break the lead screws.

Risk Name: Blades break/break off attachment

Description: The blades themselves are held onto the rod by 3D printed attachments. The blades may be sheared off of their attachments if an excessive amount of force is applied. This may cause the blades to fall through the openings in the bottom of the blade box or to jam the assembly altogether.

Impact: 3, moderate: If the blades were to break off the cutting mechanism jamming may become an issue. If the blades break off they may fall through the openings in the bottom of the blade box.

Likelihood: 3, medium: The attachment design is being designed to maximize the strength where the blades are secured to the attachment.

Risk Name: Exposed lead screws

Description: Two lead screws will be utilized to raise and lower the blade box. One end of the screws will be secured in the motors but the other end will be free and exposed. Having two exposed ends could lead to objects like hair or loose clothing getting caught and tangled.

Impact: 2, mild: Safety for the user is the main concern so the lead screws should only be in motion when the user is at a safe distance from the screws.

Likelihood: 2, low-medium: Since the lead screws should not be in motion when the user is cutting the fabric there is a low likelihood of objects becoming entangled.

Risk Name: Overloading/heating

Description: Whenever electrical components are used they produce a good amount of heat. These components can get hot enough to burn human skin. The electrical system for this machine will be completely enclosed within the structure so interaction with the user should be minimal. Proper ventilation will be utilized to reduce heat.

Impact: 3, moderate: The drivers used to run the motors become very hot even during normal operation. These drivers have built in protection measures to help prevent burning out.

Likelihood: 3, medium: With the high heat produced by the drivers a small fan will be used to manage heat dissipation.

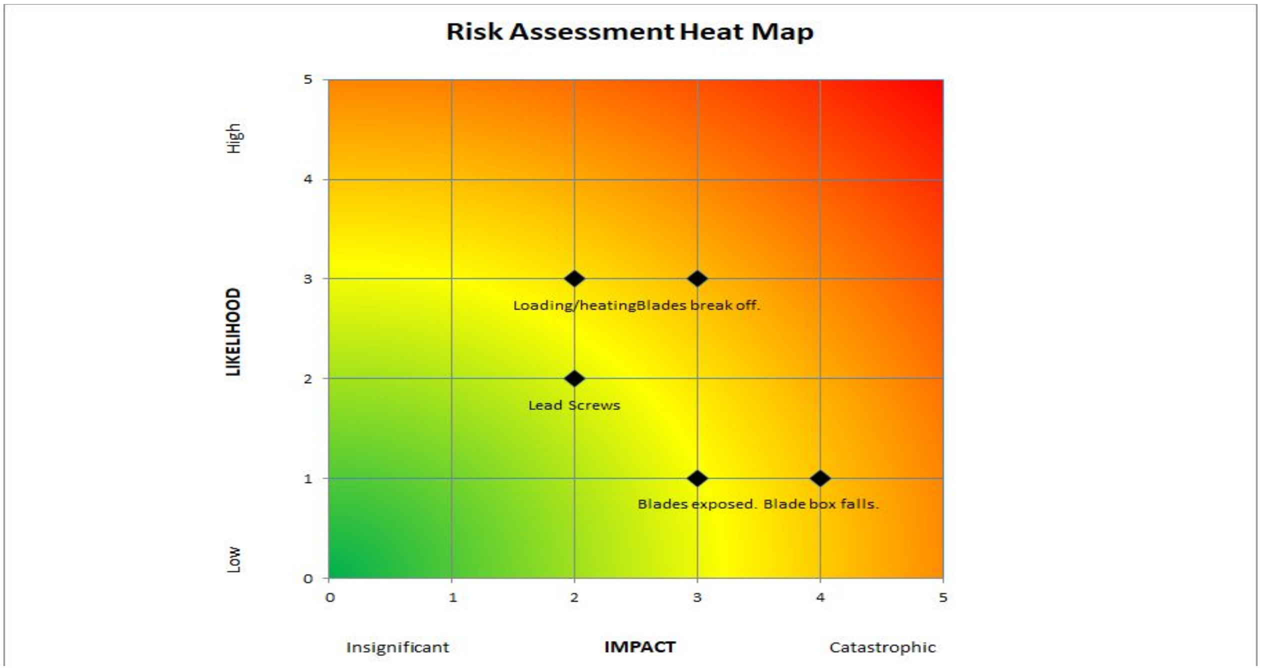


Figure 24. Risk Assessment Heat Map

7.3 Design for Manufacturing

The part we chose to make the draft upgrades was the blade arms. The main objective of the modification was to minimize the amount of yellow area present in the original part. We added a two degree angle draft to the walls which would make the process of plastic injection simpler.

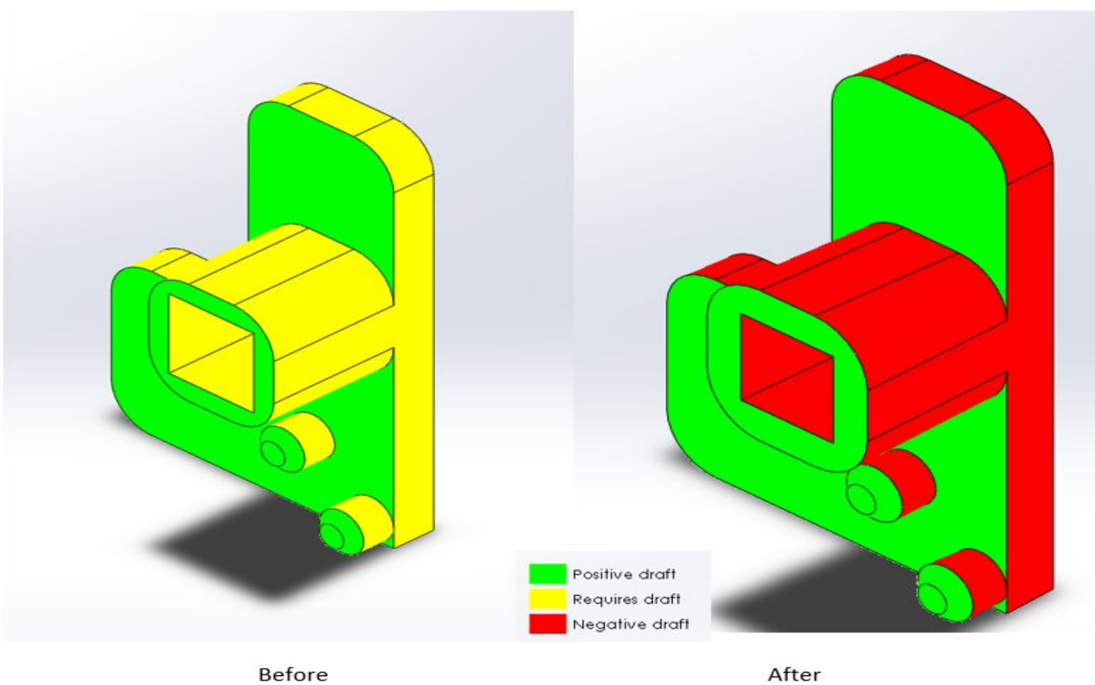


Figure 25. Draft Analysis, Before and After images from the blade arm.

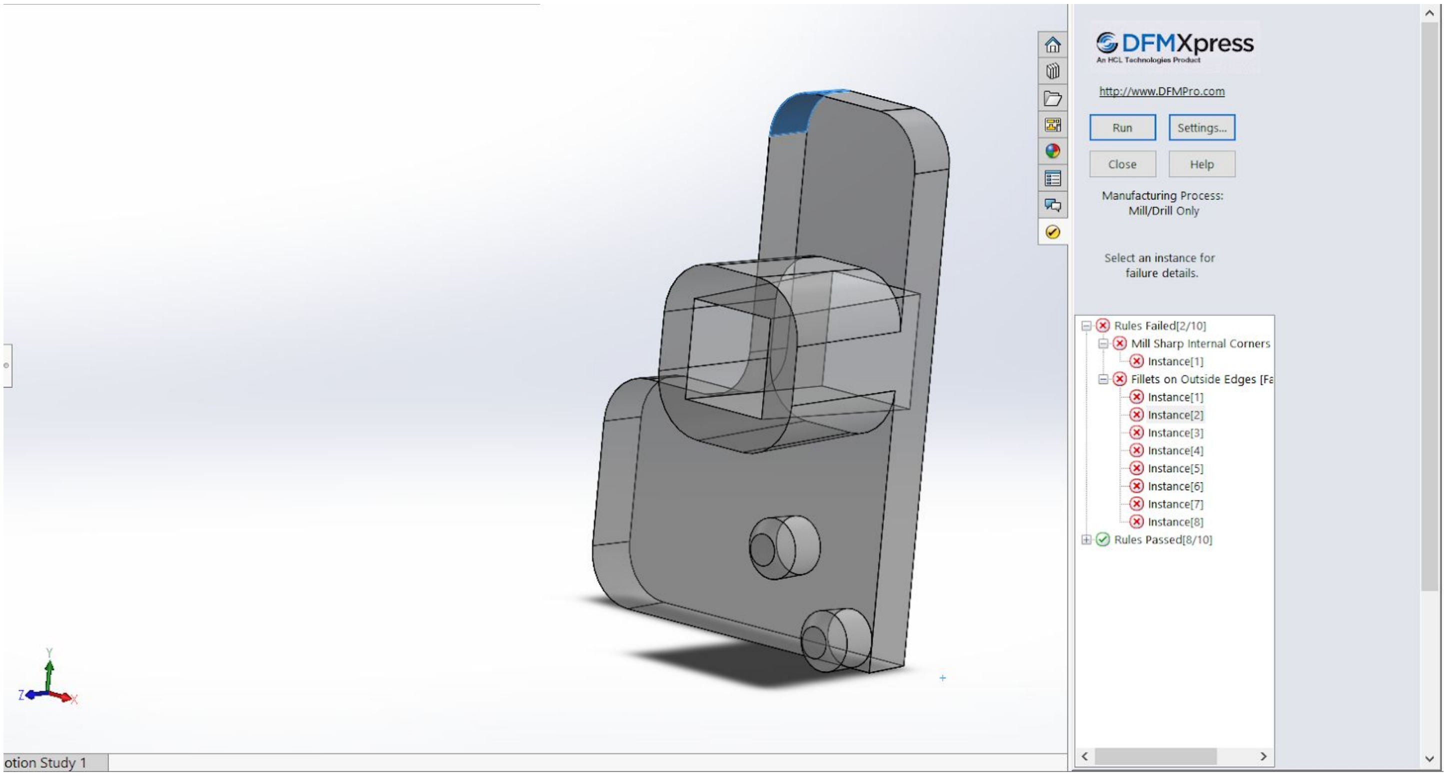


Figure 26. DFM analysis for Milling/Drilling the blade arm part

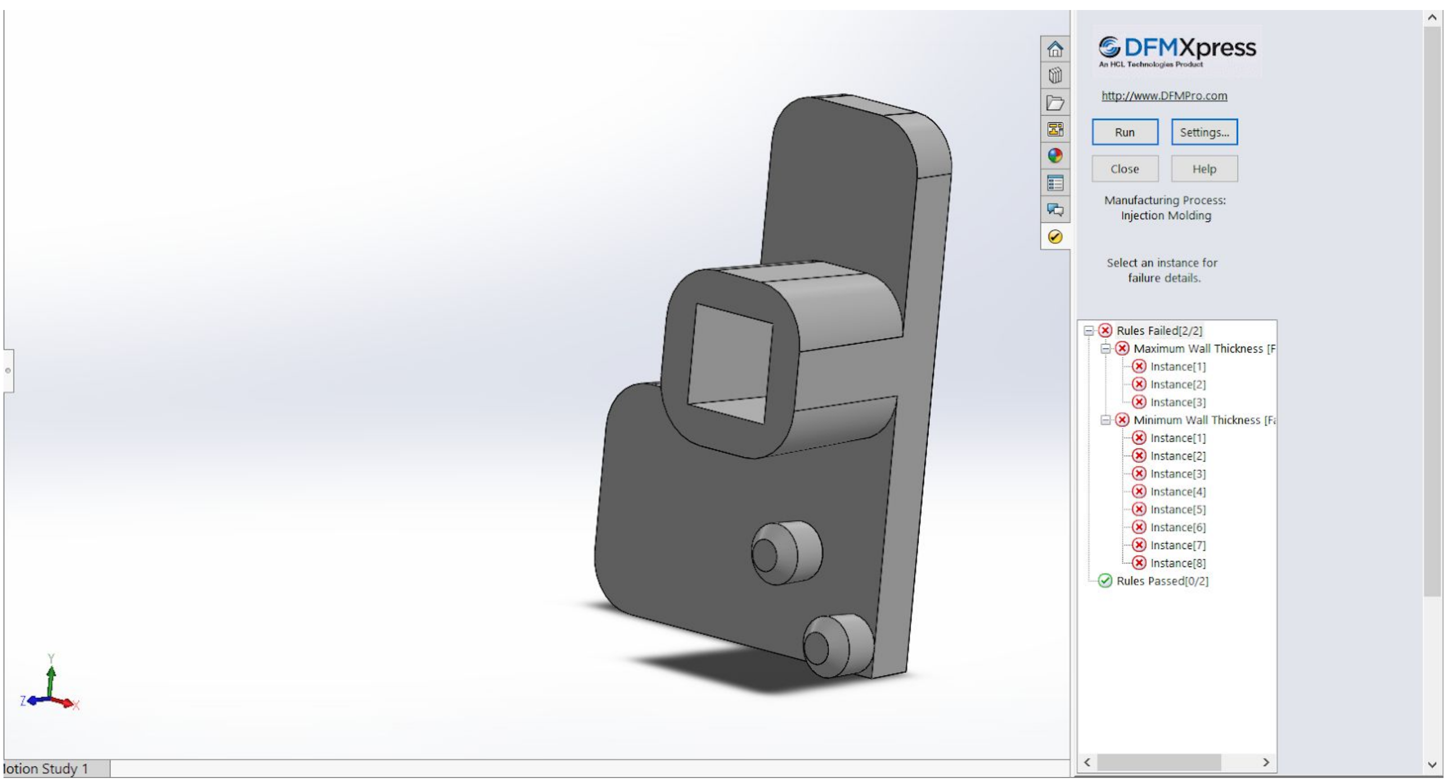


Figure 27. DFM analysis for injection molding the blade arm part

The DFM analysis was performed for milling and injection molding. From the analysis, we confirmed that this design for the blade arm would not be able to be milled/drilled to manufacture them. Our design, with some small modifications, would be readily manufactured using injection molding, especially since we need many blade arms for our overall design.

7.4 Design for Usability

Vision

If the user of the machine cutter suffers from hyperopia it might result dangerous to operate the machine. The operator needs to be able to detect when the blades are outside the box and ready to cut. Because the blades are very small and hard to visualize a person with hyperopia would be required to use the appropriate glasses or lenses to avoid injuries.

Hearing

In terms of security listening is very important to know if the machine is operating correctly. Because we are using stepper motors, it would be important that the user is able to hear when the motors are emitting unusual noises , so that the machine can be stopped and the problem can get fixed. Although not a very big limitation, if someone operating the machine cutter suffers from presbycusis it will be highly recommended to operate the machine in presence of someone else who can help if something goes wrong.

Physical

The usability of the machine cutter requires the user to exert a force to push the blades across the machine and cut the shirts. Approximately 15 pounds force are necessary to do the job. Suffering from arthritis, muscle weaknesses, limb immobilization, or other physical impairments could result in inability to operate the machine cutter.

Language

The usability of the machine cutter is very simple and language would not be a problem for operation. By just observing how the machine operates, it would be easy for a person who does not speak english to operate correctly the machine. The machine can be used by anyone if we include graphics of how to operate correctly.

Control

Operating the machine cutter as any other machine requires of the user to be one hundred percent concentrated on the task. The machine contains sharp blades that can easily injury someone. A person that suffers from distraction might forget to raise the blades after the cut is done and hurt himself or herself when collecting the shirt squares. Overall when operating a machine the person should be in perfect conditions. If the user is using certain medication that generates secondary effects such as dizziness the or she should not operate any type of machine until the side effects are completely gone. Although not required it is highly suggested that the user is always with someone else that can keep an eye and help in case of an accident.

8 Discussion

8.1 Project Development and Evolution

8.1.1 Does the final project result align with its initial project description?

Yes, the design of the machine cutter was done taking into account the project description and the necessities professor Mary Ruppert Stroescu needed for the machine. The blades were placed at a certain distance from each other so that the squares cut were one inch squared, which was one requirements from Professor Stroescu. The final working prototype matched almost exactly with the CAD embodiment. So before and during the construction of our machine we always had in mind the project description and the performance goals it needed to achieve.

8.1.2 Was the project more or less difficult than expected?

This project was more difficult than we expected, since we discovered that it is significantly more difficult to cut fabric than one would think, especially in high quantities. Additionally, information such as the yield or ultimate stress of fabrics, so calculations requiring those are pretty much impossible. Furthermore, even when we did find information, the analysis of fabrics is very different, in terms of units and setup of testing, than the engineering world, making it difficult to convert from the fabric industry units to common engineering units.

8.1.3 On which part(s) of the design process should your group have spent more time? Which parts required less time?

Although we spent a considerable amount of time in the waffle board and the bottom face of the upper bed because we did not have access to a laser cutter, we could have used other tools or techniques to make the cuts we needed. These two parts required of more time so that everything was aligned and the machine cutter worked as desired. Putting the parts together was not time consuming, so it would be a good idea to first have all the parts done and then assemble them together.

8.1.4 Was there a component of the prototype that was significantly easier or harder to make/assemble than expected?

The 3D printed blade arms were significantly more difficult and involved than we initially expected. It took of various models to finally get the blade arms we needed. The lower bed of the machine cutter which is meant to rotate was easier to assemble than what we expected. With few measurements it was possible to assemble this part very fast. Unlike the blade arms the lower bed was assembled in just one attempt. Another component of the machine we were concerned about was the handles. Luckily the handles were easy to design in SolidWorks and the 3D print came out very nice.

8.1.5 In hindsight, was there another design concept that might have been more successful than the chosen concept?

Yes, our design required of a lot of precision and expensive equipment. Some of the other designs proposed at the beginning of the semester were easier to assemble, but they were not as safe as our working prototype. A design that might have been more successful required of long blades attached to an upper bed that was lowered by hand until it reached the lower bed holding the shirts; the mechanism is similar to a paper cutter or guillotine.

8.2 Design Resources

8.2.1 How did your group decide which codes and standards were most relevant? Did they influence your design concepts?

We searched for codes and standards related to the fabric and textile industries. They weren't really relevant to our design, due to the scope of the codes being far beyond what we were doing. It did get us thinking about safety, which was a primary concern for our design, so it was relevant in that regard. Additionally, looking at codes and standards got us in the mind frame of trying to keep the design as standard/universal as possible, using common building materials, such as wood, fasteners and dimensions that are easily reproducible.

8.2.2 Was your group missing any critical information when it generated and evaluated concepts?

Aside from the lack of experience with design and fabrication, we felt that we had a good grasp on the design problem and requirements. We fill that there was no “hidden” information from us tha would have made the design process easier. With any design process there is a learning curve and depending on how intricate the project is the harder the learning curve. For example, our group had zero experience with stepper motors so a large amount time and research was spent learning how to operate the motors.

8.2.3 Were there additional engineering analyses that could have helped guide your design?

We could have done an analysis to predict the oscillations generated by lowering and rising the upper bed with the stepper motors and the threaded rods. These oscillations were just noticed when the machine was assembled. As we know vibrations are not always desired in a machine because in the long run in will make some of the components to fail. We could have also made a further study on what type of blades would not have any problem to cut fabric, but this would be difficult due to the issues with fabric analysis described above.

8.2.4 If you were able to redo the course, what would you have done differently the second time around?

If we were to do the course again, more time would have been spent researching and developing a better way to cut the fabric. This is the first time our group has worked with fabric and we didn't realise how hard it is to cut fabric efficiently. The blades we chose to use in our design would work for great for a utility knife or other single blade application, but our design uses multiple blade.

8.2.5 Given more time and money, what upgrades could be made to the working prototype?

First, we would be able to build a more robust machine so that more shirts can be cut at the same time. We would also be able to purchase bigger and sharper blades so that cutting the fabric would be less problematic. Another upgrade we could make to our working prototype is using lead screws instead of a threaded rod, which would decrease the time it takes to lower and rise the upper bed of the machine.

8.3 Team Organization

8.3.1 Were team members’ skills complementary? Are there additional skills that would have benefitted this project?

Yes, the team members skills were complementary. Every team member had a different area of expertise and together we managed to build the t-shirt square cutter. Some of the skills that would have helped during the process were to know how to correctly operate certain types of machinery. A good amount of time was spent in understanding the machines that needed to be used to build our prototype. It was also the first time for some of the group members to actually build a machine so more experience in the area would have been helpful.

8.3.2 Does this design experience inspire your group to attempt other design projects? If so, what type of projects?

This project was quite challenging. It hasn’t inspired us to pursue other design projects currently but, it has opened up the possibilities to learn more about the integrated systems used in the T-shirt cutter project. For instance our group didn’t have any experience using stepper motors or the code used to run them. It was a fun, yet frustrating process learning how to program the motors to operate the way they were intended to. Our group hasn’t had a lot of experience with electrical systems, so choosing motors adequate for our needs and the required pieces of supporting equipment was a learning process.

Appendix A – Cost Accounting Worksheet

	Part	Source Link	Supplier Part Number	Color, TPI, other part IDs	Unit price	Quantity	Total price
1	Utility Blades	https://www.mcmaster.com/3806a14	3806A14	3 Holes	$2.08	8	$16.64
2	36" - 1/4" x 1/4" Keystock	https://www.mcmaster.com/98830a836	Mcmaster 98830A836	Steel Keystock	$4.44	1	$4.44
3	12" - 1/4" x 1/4" Keystock	https://www.mcmaster.com/98830a200	98830A200	Steel Keystock	$1.48	1	$1.48
4	3ft - 1/4"-28 Steel Threaded Rod	https://www.mcmaster.com/90322a667	90322A667	Steel Threaded Rod	$10.00	1	$10.00
5	1ft - 10mm Dia. 6061 Aluminum Rod Stock	https://www.mcmaster.com/4634t36	4634T36	Aluminum Rod Stock	$2.01	1	$2.01
6	Thrust Ball Bearing	https://www.mcmaster.com/6655k13	6655K13	1/4" shaft diameter	$2.21	2	$4.42
7	Stepper Motor	https://www.pololu.com/product/22	2267	Bipolar, 2.8V, 1.7 A	$16.95	2	$33.90
8	Stepper Motor Driver	https://www.pololu.com/category/22	2966	MP6500	$7.45	4	$29.80
9	Arduino	https://www.microcenter.com/product/486799/uno-breadboard-kit	426304	Arduino Kit	$17.99	1	$17.99
10	adapters	local: Gateway Electronics		barrel jack adapters for power supply	$4.45	1	$4.45
12	power supply	https://www.microcenter.com/product/422224/power-supply-constant-voltage	846832	Wall adapter	$18.99	1	$18.99
13	Stepper Driver	https://www.pololu.com/category/22	2966	MP6500	$7.45	3	$22.35
14	Paint grade panel	Lowe's	9101	1"x12'x36"	$6.54	1	$6.54
16	Pine plywood	Lowe's	7701	1/4"x24"x24"	5.23	4	$20.92
17	#4-3/4" screw	Lowe's	57223	#4-3/4" Phillip 20ct.	2.56	2	$5.12
18	Button	Micro Center	699336	Elect. Button	1.99	2	$3.98
19	Arduino	Micro Center	422212	Arduino	7.99	1	$7.99
20	Solder Board	Micro Center	422790	Solder Boards	4.99	1	$4.99
21	Bearing	https://www.mcmaster.com/60355k505	60355K505	Bearing	6.27	1	$6.27
Total:							$222.28

APPENDIX B – FINAL DESIGN DOCUMENTATION

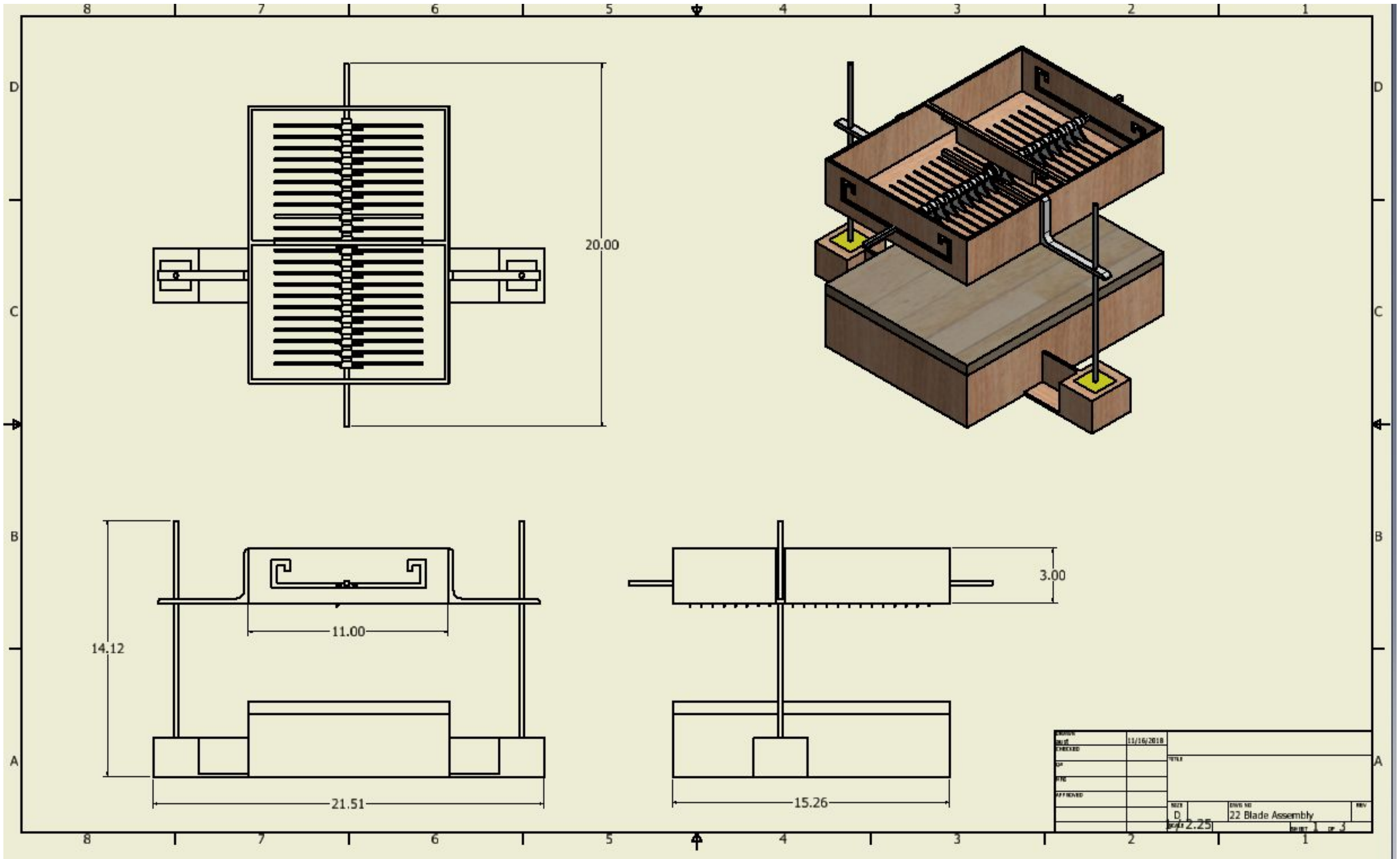
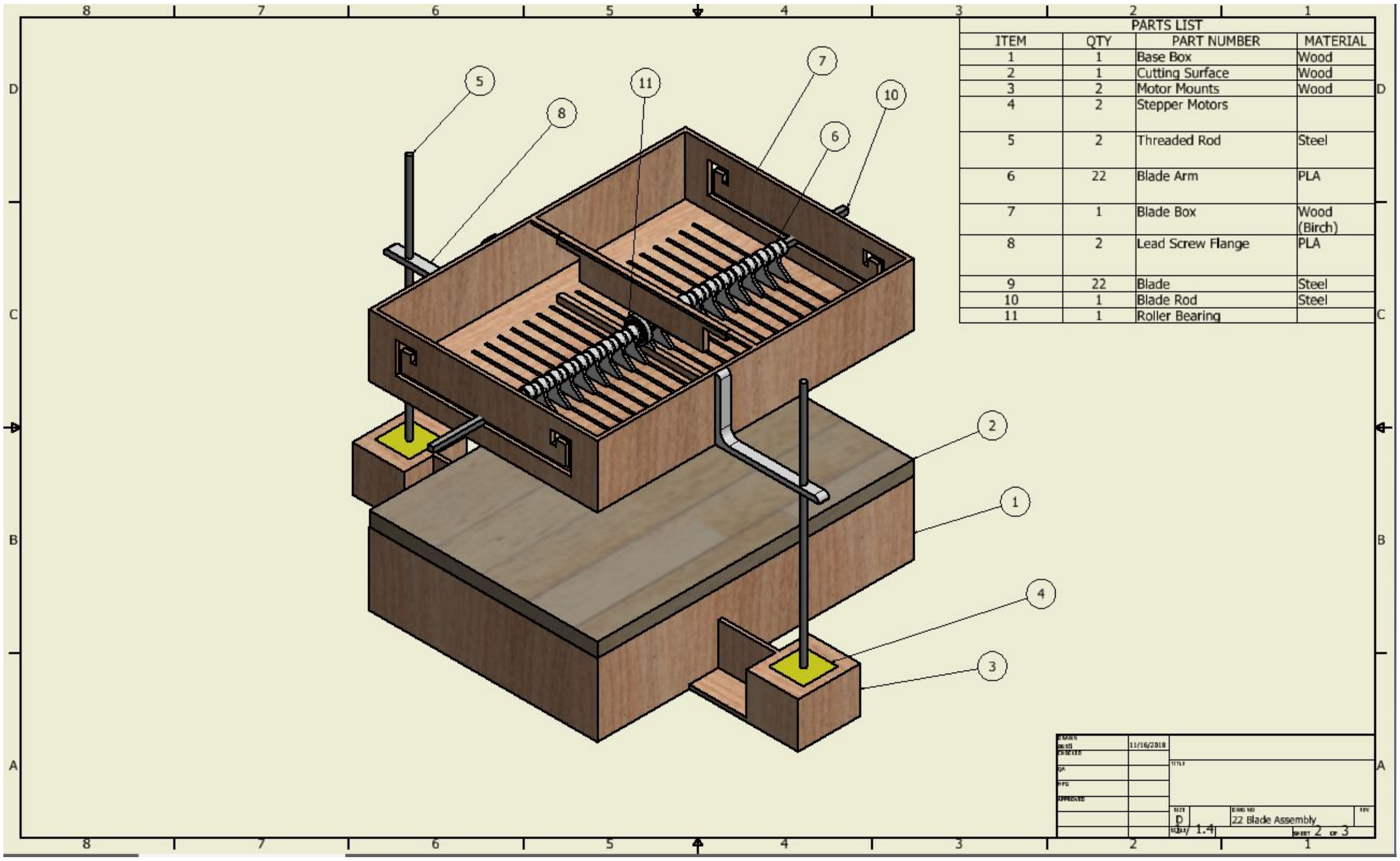


Figure B.1 - Final CAD Model 3-View



ITEM	QTY	PART NUMBER	MATERIAL
1	1	Base Box	Wood
2	1	Cutting Surface	Wood
3	2	Motor Mounts	Wood
4	2	Stepper Motors	
5	2	Threaded Rod	Steel
6	22	Blade Arm	PLA
7	1	Blade Box	Wood (Birch)
8	2	Lead Screw Flange	PLA
9	22	Blade	Steel
10	1	Blade Rod	Steel
11	1	Roller Bearing	

Figure B.2 - Final CAD Model Assembly View with BOM

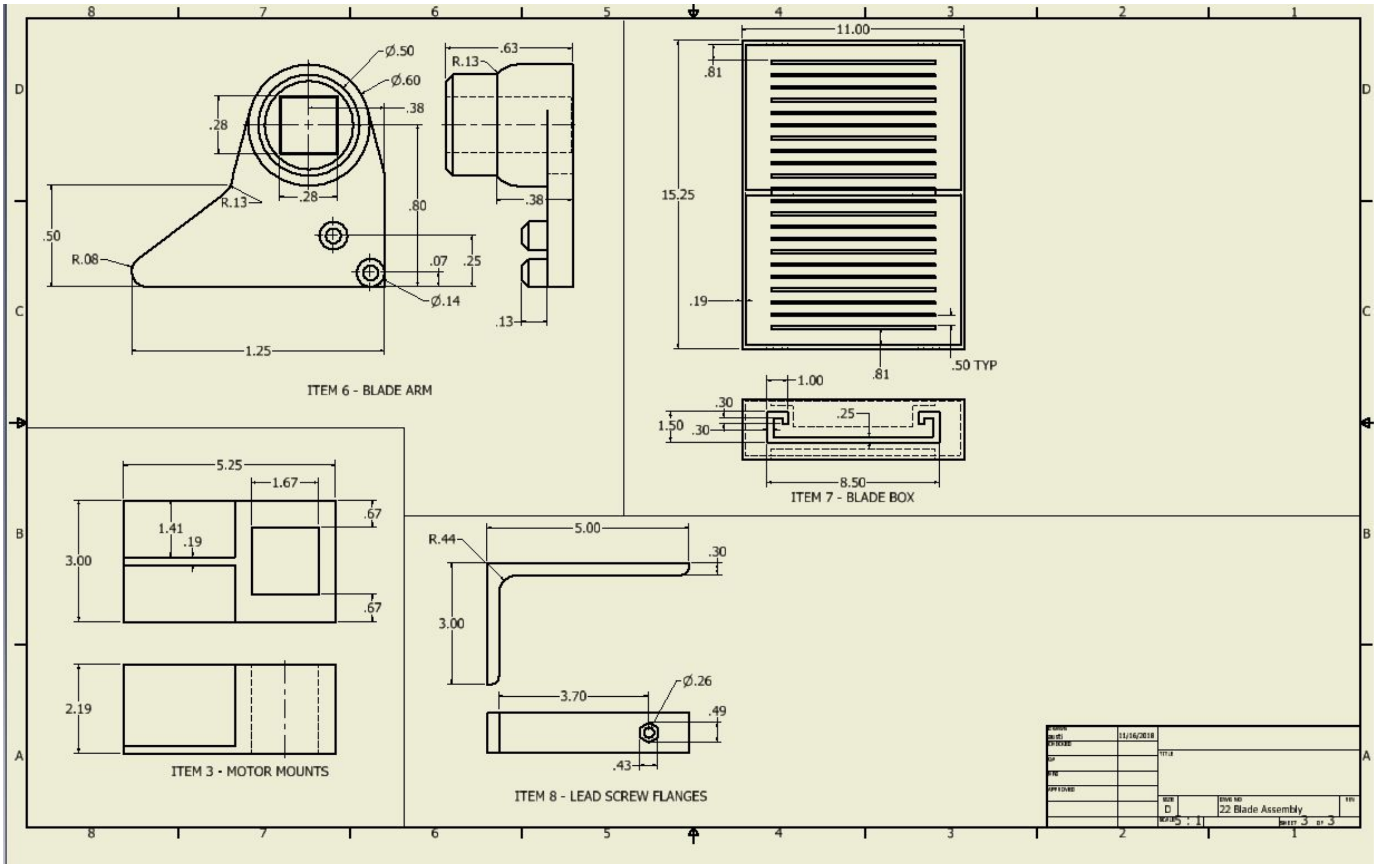


Figure B.3 - 4 Selected Part Drawings

Bibliography

Gere, James M.; Goodno, Barry J. *Mechanics of Materials* (Eighth ed.). pp. 1083–1087.

- Used to obtain an equation for beam deflection at the center of a rod.

https://www.engineeringtoolbox.com/area-moment-inertia-d_1328.html

- Used to obtain commonly known equations for the moment of inertia for various geometries

https://www.engineeringtoolbox.com/young-modulus-d_417.html

- Used as a reference for values for Young's Modulus for the materials we wanted to used for the blade bar

MEMS 3110, Spring 2018, Machine Elements Stresses Presentation.

- Used to obtain equations for springs and spring stress for possible use in our design. We ended up not needing these equations.

Hibbeler, R.C., 2014, Statics and Mechanics of Materials, 4th ed., Pearson Prentice Hall, Upper Saddle River, NJ.

Constantino. "Arduino Stepper Code – Basics." *Photo CS*, 5 Nov. 2016, photoscs.wordpress.com/2014/03/20/arduino-stepper-code-basic/.

- Constantino outlined the basic code for the task we were wanting to perform using multiple stepper motors using buttons to control the direction. This code was adapted and used to control our motors.