Abstract

Team LeGo MaNiAcS chose to work with Tri State Industries, a company that exclusively employs physically and mentally disabled persons. Workers are assigned to a variety of jobs, including the process that we selected to improve, the cutting of aluminum screen circles. The circles are used in a plastic cap to filter an industrial sealant. The design intent is to increase production, reduce customer fatigue, eliminate dexterity issues and incorporate workers with more severe functionality problems.

The development of our design started with evaluating the current process Tri State used for cutting the screens. Apparent problems included extremely low production, poorly cut circles, sharp edges and the use of scissors without protection. Some of the cut circles failed the only quality check, which is the insertion of the screen circle into a cap to ensure a snug fit.

The final prototype design cuts 10 - 2.5 inch circles per cycle while reducing material handling. The device tackles a variety of technical challenges to improve the quality and production rate of the screen circles.

We believe that the design will open this task up to lower functioning workers because it is a simple, two step operation that requires only the use of scissors which they are already proficient with. This is a significant improvement over the multi-step hand cuts that workers were previously performing. This would mean that lower functioning workers would not be limited to only certain jobs at Tri-State and this would be of great value to the company.

Final Design
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1.0 Introduction

People enjoy contributing to society and fulfilling meaningful tasks. What does this mean for people that struggle to perform everyday task at the workplace? It means that engineers can help to improve their working capability and help people with disabilities to contribute to society just as normal functioning people. “Disability is a lack of ability relative to a personal or group standard or normality” (Wikipedia). The types of disability vary from mental, physical, sensory, and cognitive. With the help of organizations as well as engineers, people with disabilities will be able to work and complete tasks as the everyday normal person.

Ohio University has created teams to help advance the technology of people with disabilities. The goal of each team is to seek out an individuals or groups that have difficulty completing or executing normal work tasks. The Ohio University Senior Design Class of 2009 will test their ability to design the most efficient device to enhance one’s ability.

1.0.1 Project Purpose

Employers’ Forum on Disability is an organization that provides framework for employers dedicated to developing practice in the employment of disabled people. Organizations such as these allow lower functioning people to have opportunities just as other people in society. The company has a list of 10 action points or guidelines that help guide employers in aiding individuals with disabilities. Employers’ Forum list many facts that show how important it is to understand people with disabilities and work. There is a need for improvement in helping people with the advancement of technology (Employers’ Forum on Disability).

According to the Employers’ Forum on Disability:

- There are at least 650 million disabled people worldwide.
- In 2002 roughly 51.2 million or 18% of Americans stated they had some form of disability.

From these statistics it can be seen that a high number of individuals in the United States are disabled. In order to make the workplace more accessible to individuals with disabilities, assistive technologies must be developed to facilitate these individuals in the workplace.

People without disabilities have a much greater rate of employment percentage. The percentage is 36% versus 74% percent of employment for those with and without a disability (2006 American Community Survey). The number of 36% shows that there is a need for help.
1.0.2 Project Purpose

The objective of this project is to develop an assistive technology device that will enable individuals with severe disabilities to excel in the workplace. This will be done by identifying and understanding a process where a need for improvement exists and designing a device from the ground up to satisfy this need. The main focus will be improving productivity, job performance, and access to employment for individuals with severe disabilities.

1.0.3 Project Scope

The scope of work is to locate a consumer, develop ideas, brainstorm, design, and fabricate a device for a person with disabilities. The design team will undergo several phases to complete each part of the project. The group will begin by researching several companies where there are potential individuals who face challenges due to disabilities. The team will narrow down the prospects to a single customer and meet with them to identify one particular area where a need for assistive technology exists. The customer will then provide a list of needs and limitations for the particular project or individual performing the process.

During Phase 1, the team will then develop an initial needs statement from the customer needs and a list of target specifications for the design. Benchmarking will be completed to research for existing designs or patents particular to the target specifications to ensure a unique design. The team will brainstorm a list of several different ideas and choose the idea that seems the most feasible and effective to best satisfy the customer needs.

In Phase 2, the design team will develop a “big picture” design of the project chosen and break the project down to a component level. This will allow the team to design, model, and analyze components using computer aided design tools to understand their engineering capability. Next, an assembly model will be developed using computer aided design tools and refinement of the components will be completed as necessary to ensure the best assembly and functionality.

The fabrication of the prototype will be completed in Phase 3 along with the finalization of the design. During the fabrication phase, the prototype will be produced in the machine shop and the design will be refined and altered as needed. To complete the project, the prototype will be tested both in house as well as in the workplace to identify and fix any issues previously overlooked. The project will then be delivered to the customer for permanent use in the workplace.

1.1 Initial Needs Statement

There is a need for assistive technology devices that enables persons with severe disabilities to overcome workplace obstacles, enabling them to improve productivity, overall job performance, and access to employment. Devices are needed to address environmental accommodation, functional assistance, and mobility issues for people with cognitive disabilities, developmental disabilities, and physical impairments (vision, hearing and mobility). (NISH, 2008)
2.0 Customer Needs Assessment

Team LeGo MaNiAcS is working with Tri-State Industries, of Coal Grove, Ohio. The customer’s needs were assessed via a facility tour and interviews with the Workshop Director, Josh Tackett. Notes from the tour and interviews are included in Appendix A. Initially we observed the entire production area, the areas of interest included: Sample Booking Making, Sample Roll Making, Foam Sheet Counting, Screen Cutting, and Labeling of buckets and jugs. After considering the information obtained during the tour and interviews, the team will be focusing its efforts on resolving the problems associated with the screen cutting process. A list of the customer’s needs was compiled based on these observation and is included in Table 2.0.

2.1 Revised Needs Statement

Tri-State Industries Inc needs a device that will enable people with moderate to severe mental disabilities to overcome the workplace obstacles involved in their screen and cap cutting process. The customer needs state that a roll of aluminum screen be “cut” into 2.5” circular disks accurately, efficiently, and with limited waste. The stock material being cut is a 100 foot roll that is 36 inches wide. The employees performing the task are currently middle and low level mentally and physically disabled persons, capable of moderately complex tasks. The primary goal is to develop a device that will allow the low level functioning employees an opportunity to work on screen cutting. A multiple step mechanism is not an ideal design for consumers at Tri-State Industries. Safety considerations included a fully enclosed mechanism with minimal gaps at the screen insertion point. If a partially automated design is to be used then the device may include two levers or two buttons as previously mentioned. The addition of an additional lever or button will require the operator to use both hands to initiate the cutter; this type of operation is only slightly more complex and will reduce the risk of injury.

When selecting this project the following items were considered: the number of people currently required to complete the process, as well as their respective level of disability; and the required productivity rate. A list of the customer’s needs was compiled based on these observation and is included in Table 2.1.

<table>
<thead>
<tr>
<th>Efficient</th>
<th>Minimal maintenance</th>
<th>Increase productivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Improve cut quality</td>
<td>Cost less than $1,000</td>
<td>Eliminates metal splinters</td>
</tr>
<tr>
<td>Safe</td>
<td>Durable</td>
<td>Fast cutting</td>
</tr>
<tr>
<td>Minimal debris</td>
<td>Footprint</td>
<td>Protection from cutting devices</td>
</tr>
<tr>
<td>Easy to operate</td>
<td>Useable by Multiple consumers</td>
<td>Easy maintenance</td>
</tr>
</tbody>
</table>
2.2 Evaluation / Weighting of Customer Needs

Each of the customer’s needs was evaluated by the team and a weight factor was calculated using the Analytical Hierarchy Process (AHP), which can be found in Appendix B. The Analytical Hierarchy Process is a structured technique for weighting a decision based on multiple variables. The individual needs can be seen below in Table 2.2. After all calculations were completed ease of use was determined to be the most important item to consider during the design process.

Table 2.2 Hierarchal Customer Needs List with (weight factor)

<table>
<thead>
<tr>
<th>1.0</th>
<th>User friendly (0.41)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1</td>
<td>Usable by multiple consumer</td>
</tr>
<tr>
<td>1.2</td>
<td>Ease of operation</td>
</tr>
<tr>
<td>2.0</td>
<td>Safety (0.09)</td>
</tr>
<tr>
<td>2.1</td>
<td>Protection from cutting device</td>
</tr>
<tr>
<td>2.2</td>
<td>No metal splinters</td>
</tr>
<tr>
<td>2.3</td>
<td>Debris Accumulation</td>
</tr>
<tr>
<td>2.4</td>
<td>Reduce hand fatigue</td>
</tr>
<tr>
<td>2.5</td>
<td>Minimal maintenance</td>
</tr>
<tr>
<td>3.0</td>
<td>Efficiency (0.05)</td>
</tr>
<tr>
<td>3.1</td>
<td>Increase productivity</td>
</tr>
<tr>
<td>3.2</td>
<td>Fast cutting</td>
</tr>
<tr>
<td>3.3</td>
<td>Accurate cuts</td>
</tr>
<tr>
<td>3.4</td>
<td>Waste material</td>
</tr>
<tr>
<td>4.0</td>
<td>Space (0.32)</td>
</tr>
<tr>
<td>4.1</td>
<td>Footprint</td>
</tr>
<tr>
<td>4.2</td>
<td>Power supply</td>
</tr>
<tr>
<td>5.0</td>
<td>Cost less than $1000 (0.13)</td>
</tr>
</tbody>
</table>

3.0 Benchmarking, Standards and Target Specifications

The sections that follow are tools that helped the team to construct the design project. Benchmarking is a crucial step in the design because it allows the designer to compare the cost, cycle time, production or productivity, and even the quality of process (http://en.wikipedia.org/wiki/Benchmarking). Standards also impact the design of a project. Standards consist of safety and quality to make a device suitable for the customer. Within the standards, target specifications will challenge the design team to meet that customer needs.

3.1 Benchmarking

The previous method of cutting at the Tri-State facility incorporated groups of individuals using scissors to cut 500 pieces per day. Currently, the process begins with a high functioning consumer removing strips of screen from the supply roll. Each of these strips is cut to approximately 3” in width. Then a single row of circles are traced onto the strip using a 2.5”
circular stencil. Finally, the consumer uses standard household scissors to cut out the patterns along the traced lines.

Improving this method requires increasing the production rate, while still allowing the employees to take part in the process. Considerations for cutting methods range from cutting shears to a punch press. Two different types of punches are shown in Figure 3.1.1 and Figure 3.1.2.

This device is simple in operation and the lever activated cut is already known to most users. An operator needs one simple action to carry out the cut. The one step action of a lever is shown in Figure 3.1.1, where a force is applied to the lever which produces the desired effect of cutting a sheet material with minimal user difficulty:

![Figure 3.1.1: Crank Roller Paper Cutting Device US Patent 7360482B2](image)

The paper punching instrument shown in Figure 3.1.2 indicates that the size of the cutting device can be relatively small. An upright punch press could be very tall but a hand operated punch could be as small as a traditional stapler. Size is important but weighted lower than safety, complexity, effectiveness.
Figure 3.1.2: Paper Punch US Patent 6000139

The circular paper punch is used to punch craft paper or other similar thin sheets of material. Craft paper and foil may both be cut using a paper punch. The following figure, 3.1.3, reveals a more applicable circular paper punch found at arts and crafts stores.
To apply cutting devices to screen material requires assumptions that are tested in prototype construction. Screen material is considered sheet-like and may be cut using paper cutting devices. A similar device capable of cutting multiple holes across the length of material is the three-hole-punch. The three-hole-punch is shown below in figure 3.1.4.

The application of force is enhanced through use of leverage in the previously depicted devices. Another method to apply force to the cutting heads is through use of a multiple bar
linkage. The force application mechanism of interest is the 5-bar linkage utilized in the die cutting press shown below.

![Five bar linkage, Die Press (ABM, 2008)](image)

The die press product retails for roughly $600. Although it only has one die cutter, the device reveals a price range for similar die cutters using complex linkages.

3.2 Standards

Currently, the only standards to set forth by the customer are the OSHA, or the Occupational Safety and Health Administration, standards for safety. To determine which of the OSHA guidelines applied to our project the team researched regulations for a device similar to those being consider, namely punch presses. OSHA has a number of standards that could apply to such a device, including regulations concerning electrical wiring and insulation, machine guards and light curtains.


*Danger from broken or falling machinery should be minimized to maximize operator safety. Safety hazards from mechanical energy release (i.e. – broken springs) should also be minimized by the addition of covers/guards. Friction brakes, where required, should be sufficient to stop the machine motion at any point. Hand-lever-operated power presses shall be equipped with a spring latch on the operating lever to prevent premature or accidental tripping. Two handed lever-operated presses can also be utilized to minimize danger to operators. Control system should incorporate an anti-repeat feature.*

Machinery Guarding – Standard Number 1910.217 App A

*General requirements for machine guards. Guards shall be affixed to the machine where possible and secured elsewhere if for any reason attachment to the machine is not possible. The guard shall be such that it does not offer an accident hazard in itself. The point of operation of machines whose operation exposes an employee to injury, shall be guarded. The guarding device shall be in conformity with any appropriate standards therefor, or, in the absence of applicable specific standards, shall be so designed and constructed as to prevent the operator from having any part of his body in the danger zone during the operating cycle.*
Tools – Standard Number 1926.300

Belts, gears, shafts, pulleys, sprockets, spindles, drums, fly wheels, chains, or other reciprocating, rotating or moving parts of equipment shall be guarded if such parts are exposed to contact by employees or otherwise create a hazard.

Electrical – Standard Number 1910.303

Electric equipment shall be free from recognized hazards that are likely to cause death or serious physical harm to employees. Insulation should be adequate to project employees.

3.3 Target Specifications, Constraints and Design Criteria

The product target specifications have a range of acceptable values that are driven by the customer needs. Constraints from the customer and their facility also drive the target specifications.

3.3.1 Constraints

Tri State Industries has specific power limitations that must be considered for the design solution. Specifically, the device cannot be actuated pneumatically, because the facility currently does not have an air compressor. A hydraulically actuated device would require more maintenance. Due to the limited availability of technical support at Tri State, a hydraulically actuated device is undesirable.

The team initially received a needs statement from the customer, Tri State Industries. This statement called for the needs shown in Table 2.1 to be filled. The importance of each need was decided by the team in a conceptual design meeting. The relative level of importance for each of the needs along with the metric it is associated with is shown in Table 3.2.2. From the needs shown in Table 2.1 the team determined which design criteria needed to be met, along with any potential delighters.

Table 3.2.2: Needs Metric List

<table>
<thead>
<tr>
<th>Metric #</th>
<th>Need #</th>
<th>Metric</th>
<th>Importance (5 high – 1 low)</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>6, 8</td>
<td>OSHA</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>5, 8, 10</td>
<td>Dimensions</td>
<td>4</td>
<td>in</td>
</tr>
<tr>
<td>3</td>
<td>2, 7, 9, 10</td>
<td>Production Rate</td>
<td>5</td>
<td>Disc/min</td>
</tr>
<tr>
<td>4</td>
<td>3, 6, 7, 9, 11, 12</td>
<td>Ease of Operation</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>4, 11</td>
<td>Footprint</td>
<td>2</td>
<td>ft</td>
</tr>
<tr>
<td>6</td>
<td>1, 3</td>
<td>Durability</td>
<td>2</td>
<td># cycles</td>
</tr>
</tbody>
</table>
3.3.2 Design Criteria

The design criteria developed by the team for the screen cutter, are listed below:

- Reliable
- Cut disks to minimize splinters
- Maximize Number of Cuts per Cycle

Other Criteria

- Reasonably comfortable for user
- Aesthetically acceptable
- Proper Safety Signage
- Easily maintainable

3.3.3 Target Specifications:

In order to determine the technical specifications the team first considered the revised customer needs statement. From this “Needs Statement” the team established several target specifications; which are listed below.

OSHA regulations – Design must meet or exceed safety levels required by OSHA

- **Disk dimensions** – Punch to cut 2.5 inch diameter circles. The customer has provided us with a “go no-go” cap to check the tolerances of the cut discs.
- **Production rate** – Minimal rate of four disks per minute, a higher rate would be a delighter.
- **Ease of Operation** – Currently mid to high functioning level customers cut the screens; these consumers have moderate to mild physical and/or mental disabilities. Our targeted operator is a low functioning consumer; or one with severe mental disabilities.
- **Footprint** - Smaller than 3’x5’ to fit on a table.
- **Weight**- The device and the combined applied force cannot exceed the maximum allowable weight for the table of 300 pounds.
- **Durability** – Design should require minimal maintenance for four hundred thousand cut discs, or a ten year production life. The maintenance on the device should not require any special tooling, lubrication, or expensive parts.

4.0 Concept Generation

4.1 Problem Clarification

The current screen cutting process at Tri-State Industries requires the use of higher functioning mentally disabled workers and has a lower than desired production rate. Currently Tri-State is having quality and productivity issues with this process; because the screens are cut manually with scissors. This requires them to assign 5 workers to cut the screen, as well as 1 person to drill the caps and 1 person to assemble the finished product. When production falls behind due to poorly cut circles, workers have to be pulled from other work areas in order to
complete the contract on time. Our primary goal is to design a new screen cutting machine that will be able to cut multiple circular screens simultaneously, with clean edges, which are 2.5” in diameter.

4.2 Concept Generation

In order to generate the initial project concepts; each team member was asked to generate several unique ideas to solve the problems that Tri-State has with its screen cutting process. These initial ideas were discussed and weighted to using two different decisions matrices in order to determine a general direction for the team to focus on. These matrices are shown in Tables 4.2.1 and Table 4.2.2. The first decision matrix shown in Table 4.2.1 was used to determine if the device being designed should utilize the entire 36” wide roll of screen or if an intermediate step would be used to cut the roll of screen into individual squares, and then cut these squares into circles. The second decision matrix show in Table 4.2.2, was used to evaluate the four primary concepts generated by the team. The most important ideas in this decision matrix were ease of operation, and design feasibility. Concept feasibility was based on potential technical hurdles that the team may face when building/operating/testing the concept, development time each concept would require, and the tooling requirements and prototype cost.

A potential delighter for the customer would be to design the machine in such a way that it could cut the screen and cap at the same time. This was discussed with Tri-State to ensure that we would not be eliminating anyone’s job. Tri-State encouraged us to pursue this option; but stated that its primary concern was with the cutting of the screens.

Table 4.2.1 shows the results for the evaluation of whether the screen cutting process should be able to use the roll of screen as it is received or if an intermediate cutting step should be used. Based on the higher score of 82 compared to 63 the team has decided that the intermediate step of cutting the screen into 2.75” squares should be avoided.

For both of the decision matrices used: Durability was based on the likelihood that a part would fail, within a 2yr span. Simplicity was determined by relative complexity of the concept machine with respect to the others. Manpower was defined as the number of people required to operate the machine, and meet the production quota.
Table 4.2.1 – Usage of Full Rolls vs. Cut Squares

<table>
<thead>
<tr>
<th></th>
<th>Cut Sheets</th>
<th>Entire Roll</th>
<th>Weight</th>
<th>Cut Sheets</th>
<th>Entire Roll</th>
</tr>
</thead>
<tbody>
<tr>
<td>Durability</td>
<td>1</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>9</td>
</tr>
<tr>
<td>Cost</td>
<td>4</td>
<td>1</td>
<td>2</td>
<td>8</td>
<td>2</td>
</tr>
<tr>
<td>Simplicity</td>
<td>4</td>
<td>1</td>
<td>3</td>
<td>12</td>
<td>3</td>
</tr>
<tr>
<td>Footprint</td>
<td>3</td>
<td>2</td>
<td>1</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>Improve Quality</td>
<td>0</td>
<td>0</td>
<td>5</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Safe</td>
<td>0</td>
<td>0</td>
<td>4</td>
<td>0</td>
<td>0</td>
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<tr>
<td>Increase Productivity</td>
<td>1</td>
<td>5</td>
<td>3</td>
<td>3</td>
<td>15</td>
</tr>
<tr>
<td>Eliminates Splinters</td>
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<td>3</td>
<td>4</td>
<td>8</td>
<td>12</td>
</tr>
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<td>Manpower</td>
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<td>6</td>
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<td>Reduce Waste</td>
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<tr>
<td>Ease of Operation</td>
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<td>4</td>
<td>5</td>
<td>5</td>
<td>20</td>
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Table 4.2.2: Concept Comparison

<table>
<thead>
<tr>
<th></th>
<th>Punch Press/Stamp</th>
<th>Stapler</th>
<th>Scotch Yoke</th>
<th>Tyler's Design</th>
<th>Weight</th>
<th>Punch Press/Stamp</th>
<th>Stapler</th>
<th>Scotch Yoke</th>
<th>Tyler's Design</th>
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<tbody>
<tr>
<td>Durability</td>
<td>4</td>
<td>4</td>
<td>3</td>
<td>4</td>
<td>3</td>
<td>12</td>
<td>12</td>
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<td>3</td>
<td>2</td>
<td>10</td>
<td>10</td>
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<td>6</td>
</tr>
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<td>Simplicity</td>
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<td>3</td>
<td>3</td>
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<td>9</td>
<td>6</td>
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</tr>
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<td>Footprint</td>
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<td>Improve Quality</td>
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<td>8</td>
<td>8</td>
<td>12</td>
<td>12</td>
</tr>
<tr>
<td>Manpower</td>
<td>2</td>
<td>2</td>
<td>4</td>
<td>4</td>
<td>2</td>
<td>4</td>
<td>4</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>Reduce Waste</td>
<td>3</td>
<td>4</td>
<td>3</td>
<td>3</td>
<td>4</td>
<td>12</td>
<td>16</td>
<td>12</td>
<td>12</td>
</tr>
<tr>
<td>Feasibility</td>
<td>4</td>
<td>4</td>
<td>2</td>
<td>3</td>
<td>5</td>
<td>20</td>
<td>20</td>
<td>10</td>
<td>15</td>
</tr>
<tr>
<td>Ease of Operation</td>
<td>3</td>
<td>5</td>
<td>2</td>
<td>3</td>
<td>5</td>
<td>15</td>
<td>25</td>
<td>10</td>
<td>15</td>
</tr>
</tbody>
</table>

63 82 119 127 95 123
Figure 4.2.1 – Scotch Yoke Screen Cutting Concept

**Scotch Yoke Concept Operation:** The concept shown in Figure 4.2.1 would utilize a Scotch Yoke mechanism to drive the punches through the screen. The input action would require an operator to turn the hand crank which would drive the rest of the mechanism. The crank could alternatively be powered using an electric motor if desired. The primary advantage for this concept is its ability to cut multiple screen disks simultaneously. A roll feeding mechanism is being considered for this concept of further increase productivity.

Figure 4.2.2 – Stapler Style Screen Punch

**Stapler Style Punch Operation:** This concept shown in Figure 4.2.2 would operate like a single whole punch, or stapler. It is operated using a lever style action which is driven by the force applied by an operator. The team is considering adding a force multiplier similar to the one used in the “Staples One-Touch stapler”, (patent number: 7,299,960 B1). The punch would cut the screen via a shearing force as it passes through the die face. This concept idea could be adapted to include multiple punches similar to the concept shown in Figure 4.2.3.
Multiple Punch Press Operation: The concepts shown in Figure 4.2.3 and Figure 4.2.4 would be approximately 37-42” wide and accommodate the entire width of the rolled screen. They will use a manually powered roll feed system consisting of roll stand to support the screen, this will allow the screen to be manually fed through the machine as required by the operator. The machine will consist of a work table that will support the cutting mechanism as shown in Figure 4.2.3. The cutting mechanism consists of multiple punches attached to a levered mechanism with mechanical advantage. The mechanical advantage will reduce the amount of force the operator is require to supply on the lever. As the screens are cut by the shearing force of the punch passing through the die face the cut screens will fall out and into a tilted tray which will feed the cuts disks to the front or side of the work table as decided by the customer, Tri-State.
**Punch Design:** The team is currently considering two types of round punches for cutting the screen. As shown in Figure 4.2.5 the two possibilities being evaluated are a solid flat punch and punch which has had some of the center stock milled out. Currently the team has performed a test using a ¾” solid punch and die to cut a sample of screen. These tests revealed that this type of die is capable of providing clean circular cuts when the appropriate amount of force is provided. However, if insufficient force is supplied to the punch then the screen is not cut cleanly and the shape becomes distorted and the edges of the cut screen fray. The exact amount of force required has not been quantified yet this will be done when the 2-31/2” solid punch is tested. The team has also conducted test using a 1-3/4” milled out punch. These tests were performed on standard notebook paper cutting though in excess of 20 sheets. These tests revealed that this design of punch and die required little input force to cut through large amounts of material. Further testing will be done on the screen material using this punch and die. During these test the team will be looking to see if the edges of the screen are cut cleanly, what effect if any the screen material has on the punch tool life.

After it was decided that the screen cutting process should not require the use of individual screen squares, the remaining concept ideas were evaluated using the decision matrix show in Table 4.2.2. The scores for each of the concepts being compared were relatively close with the exception of the Scotch Yoke mechanism, which is shown in Figure 4.2.1. The resulting decision matrix scores were close because, each of the 3 highest scoring concepts shared multiple commonalities. These common features included: Lever style input operation and a punch and die style cutting mechanism. For this reason the team has chosen to pursue an integrated design concept that will include: a manual screen feeding system; and a die and punch cutting mechanism with some type of a force multiplier to provide the operator with a mechanical advantage while cutting the screen. The final design concept may resemble the stapler concept shown in Figure 4.2.2 if only one punch is utilized. The team designed a machine that was similar to the Punch/Press Stamp machine shown in Figure 4.2.3 as well as Figure 4.2.4. The type of punch that will be utilized will be determined based on further testing of the two styles being considered, solid, milled with a bevel.
The selected design for the input action for the machine is a push/pull lever action which provides mechanical advantage. Since the primary disability that we are concerned with severe mental disability this input should be safe and simple enough for the lower functioning, more severely mentally disabled workers to use.

5.0 Concept Screening and Evaluation

5.1 Concept Screening

After reviewing these concepts with Tri-State Industries, we determined that a feed system was not required if the additional cutting operation is sufficiently simple and still allows for increased production. The following additional feedback was obtained.

5.1.1 Customer Feedback

The screen cutter was modified to a final design with the feedback from Tri-State Industries. The group engaged in a teleconference that allowed for the current and latest design.

- Steel Frame-The frame of the device must be stable and not allow tipping. It should also be design to fit a 3’x4’ table because this would allow it to fit all their tables at each work station.
- Ease of Operation/User Friendly- The device will allow for a two person work station: The first person will cut 36” strips of screen at the rear while the second worker takes the strips and feeds them into the cutters.
- Quality- The ability of the device to produce quality circles is a customer priority. The device must allow a disabled person to successfully produce circular discs.
- Weight of the Device - The design weight is restricted by the maximum allowable weight of Tri-State’s work table.
- Ease of Maintenance – Due to limited tooling, the designed device must be made of readily available parts that can be easily repaired or replaced as needed.

5.2 Data and Calculations for Feasibility and Effectiveness Analysis

5.2.1 Feasibility

Feasibility, with respect to the design team and project, was determined based on its ability to meet the needs of the customer as well as the ability to effectively implement the intended design concept. The screen cutting device needs to be capable of cutting five-hundred screens a shift, needs to meet the size specification, and have a person of low functionality be able to operate the unit.

5.2.2 Effectiveness

Effectiveness, with respect to the design team and project, is being able to complete the task at hand and having a greater output from the given input. The input of the system is a push from the lever. This in turn will create ten circular screens. The quality along with quantity will be important to the design in order to reach the needs of the customer.
5.2.3 Calculations, Simulations, Research, and other Analysis

Using calculations, simulation, and means of analysis it can be determined if the device will be feasible and effective for the customer. The feasibility of the system will be determined by allowing the smallest force for a person of low functionality to push a lever. The input force will be a human who will manually push a lever downward and this will allow for the cutter to move down cutting the screen material.

5.2.3.1 Cutter Analysis

In order to understand the function of the cutters, two experiments were conducted. One analysis used to calculate the force exerted on the lever was an experiment to find the actual weight need to pierce one cutter through the screen material. In this experiment weight was added to the cutter until it broke through the screen creating a 2.5” diameter circular screen cutout. Table 5.2.1 shows the results for cutting the screens with different number of springs and the force needed to exert the cutter down. The cutters themselves consist of four springs in which are located on each corner to allow the cutter to bounce back to its original position. It can be seen that less force is needed when the springs are totally eliminated. This experiment is an application of Hooke’s Law, where the force is equal to the spring constant multiplied by the length. The springs used on the cutters will create an additive spring force, thus requiring a higher input force. The analysis revealed that the weight needed to cut one screen using the maximum of four springs would be approximately 60lbs.

<table>
<thead>
<tr>
<th>Cutter Force Test</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amount of Springs</td>
</tr>
<tr>
<td>No Springs</td>
</tr>
<tr>
<td>2 Springs</td>
</tr>
<tr>
<td>4 Springs</td>
</tr>
</tbody>
</table>

Another experiment was conducted to analyze the fatigue of the cutters based on a continuous punching operation. During the experiment five-hundred x 2.5” diameter circular screens were cut using a single experimental cutter. The cutter was examined both visually and tactilely before and after the experiment; and it was found that there were no changes to the shape, sharpness, or cutter itself. This experiment was implemented to see if fatigue, dullness, or fracture would occur. All circles punched during this experiment passed the customer’s quality check.

5.2.3.2 Lever Analysis

The main movement of the design consists of a four-bar mechanism (rocker-rocker). A four-bar mechanism has the mechanics of a closed loop kinematic linkage. They are used
because the simple linkages are unique in that the mechanism is able to produce complicated as well as wide variety of motions. A four-bar mechanism is comprised of a ground link, a coupler link, input link, and the follower link. The ground link is important to the mechanic because it is fixed and never moves. (http://en.wikipedia.org/wiki/Four_bar_linkage).

Prior to constructing the mechanism the force required and the output force was estimated using the following free body diagram (FBD). In order to simplify the analysis the ground link and the coupler link were assumed to be parallel.

An analysis was conducted using Matlab to understand the feasibility of the 4-bar linkage system. The position, the velocity, and the acceleration were found, also the appropriate dimensions and forces were added, and the simulation was conducted on Matlab. The kinematic analysis was performed to verify the angles of the output link in order to determine output force relative to the user input, see Appendix E.
5.3 Concept Development, Scoring and Selection

Key features of the design were compared and contrasted to better determine feasibility and effectiveness. Two key items were identified as potential design drivers; these were the feeding operation, and the type of punch used. These two items are detailed below.

<table>
<thead>
<tr>
<th>Table 5.3.1 Continuous Feed vs 2-Step Feed</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Pros</strong></td>
</tr>
<tr>
<td>One operation</td>
</tr>
<tr>
<td>Increased Production</td>
</tr>
<tr>
<td>Scissors not required</td>
</tr>
<tr>
<td>Reduces Waste</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 5.3.2 Pre-Manufactured vs Manufacturing Punches</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Pros</strong></td>
</tr>
<tr>
<td>No Manufacturing</td>
</tr>
<tr>
<td>Low Cost</td>
</tr>
<tr>
<td>Easily Replaced</td>
</tr>
<tr>
<td>Safe</td>
</tr>
<tr>
<td>Low Maintenance</td>
</tr>
<tr>
<td></td>
</tr>
</tbody>
</table>
5.3.1 Scoring

The team has brainstormed and generated many ideas in order to successfully design the device. The selections have been narrowed down and each was analyzed in table 5.3.1 and 5.3.2. The two comparisons tables will allow for a general scoring and team selection. The selection will have a general number system that will weigh the pros and cons of each selection. This will decide the most feasible and effective design for the team. The ranking scale used will be 1-5 with one being most desirable and five being least desirable.

Table 5.3.3 Feature Evaluation

<table>
<thead>
<tr>
<th>Design Feature Evaluation</th>
<th>Safety</th>
<th>Cost</th>
<th>Productivity</th>
<th>Manufacturability</th>
<th>Maintenance</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Continuous Feed</td>
<td>3</td>
<td>5</td>
<td>1</td>
<td>3</td>
<td>4</td>
<td>16</td>
</tr>
<tr>
<td>2-Step Feed</td>
<td>2</td>
<td>2</td>
<td>3</td>
<td>1</td>
<td>2</td>
<td>10</td>
</tr>
<tr>
<td>Pre-Manufactured Punches</td>
<td>1</td>
<td>3</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>9</td>
</tr>
<tr>
<td>Manufacturing Punches</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>4</td>
<td>2</td>
<td>12</td>
</tr>
</tbody>
</table>

Based on this evaluation process the final design concept should consist of a 2-step feed system and pre-manufactured punches. These design features will allow for optimized safety, cost, productivity, maintenance, and manufacturability.
6.0 Final Design Concept

The final design concept that was most feasible and effective in the team’s selection is shown in Figure 6.0.1. This design is intended to be mounted to a three foot wide table provided by Tri-State Industries. After the device has been securely mounted to the table, the customer will remove the supply roller hanger rod, by sliding it out of the frame from the left side. The user will then position the supply roll of screen between the two roll hanger support bars and reinsert the rod so that it passes through the core of the supply roll. Then the device is ready for operation. The device is comprised of simple parts that allow it to be easily used, durable, and maintained.

- **Steel frame**-It is designed to withstand repetitive usage as well as a downward force exerted on the front of the machine. The integral welding will allow for the steel frame to resist this force.
- **Side plates**-The plates are made of steel and used to support the linkage force. This is critical because the force needed to actuate the cutter is substantial. The side plates are also designed to resist the repetitive force just as the steel frame.
- **Linkage system**-The system was analyzed to achieve a much greater output force than the given input force. It was simulated, analyzed, and designed to be effective in the usage that is provides for the device.
- **Cutters**-The cutters were purchased from a manufacturer. This will allow for easy maintenance and a productive way to maintain alignment.
- **Cover/Guide**- The cover and guide are both made of high impact polycarbonate. The guide is used to allow for maximum safety to protect the operator and to protect the machine from interfering object that can either fall into the device or be placed into it. The guide is used to allow the operator to accurately cut strips of screen the can be placed into the cutter system for a finished product.

The overall design is effective, feasible, and successful. The device has a few sub assembles that can be refined to help improve the cost, wear, weight, and overall simplicity. The final design can be refined and few of these areas are addressed below.

<table>
<thead>
<tr>
<th>Table 6.0.1 Cost Reduction Potential</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Guard Material</strong></td>
</tr>
<tr>
<td>Current</td>
</tr>
<tr>
<td>Polycarbonate</td>
</tr>
<tr>
<td>Guard Fasteners**</td>
</tr>
<tr>
<td>Bolts</td>
</tr>
<tr>
<td>Frame Material</td>
</tr>
<tr>
<td>Steel 12ga</td>
</tr>
<tr>
<td>Frame Fasteners**</td>
</tr>
<tr>
<td>Welding</td>
</tr>
<tr>
<td>Total</td>
</tr>
</tbody>
</table>

* Further validation is required prior to implementation
** Includes estimated labor cost

The final design concept was determined to have met the following required specifications:

- **OSHA Safety regulations**
  - Front Guard
- **Quality**
  - Passed “Cap fit” Check
  - Clean Edges
- **Production Rate**
  - 1 cycle = 10 disc
  - Cycle Rate > 1/min
- **Ease of Operation**
  - Simple 2 stage Operation
- **Weight**
  - 174 lb < 300 lb
- **Durability**
  - Minimal Cutter Wear
  - Paint to Control Rust
- **Cutter Alignment**
  - Additional Guide Plate
7.0 Final Design

FMEA

The original design was evaluated using FMEA, or Failure Mode and Effects Analysis. Three areas were identified for closer scrutiny; cutting head alignment, cutting head retraction and the lever system. Alignment of the cutting head was considered critical because if it were out of position it could bind and break, thereby preventing the punches from cutting the material. Retraction of the cutting head was also considered due to the feed problems that would incur from a failure to retract. Finally, we considered the welding of the box beam to the frame as another point that was likely to fail.

Figure 7.1.1: FMEA Inspection

To consistently rate the modes of failure we developed a method for quantifying the FMEA, shown in Table 7.1.1. It was split into two halves, one side for failures that would result in only prototype failure and the other for breakages that would cause physical harm in addition to a prototype failure.

<table>
<thead>
<tr>
<th>No Physical Harm</th>
<th>Physical Harm Possible</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Low Risk, No Physical Harm</td>
<td>6 Low Risk, Minor Physical Harm</td>
</tr>
<tr>
<td>3 Moderate Risk, No Physical Harm</td>
<td>8 Moderate Risk, Moderate Physical Harm</td>
</tr>
<tr>
<td>5 High Risk, No Physical Harm</td>
<td>10 High Risk, Major Physical Harm</td>
</tr>
</tbody>
</table>
Table 7.1.2 shows how we rated each failure for severity, probability of occurrence and detection and prevention. The Risk Priority Number is the product of the previous three ratings – higher RPN’s determine which failure deserved closer scrutiny. As a team we decided that any RPN > 75 would require a full FMEA to be completed.

<table>
<thead>
<tr>
<th></th>
<th>Severity</th>
<th>Probability of Occurrence</th>
<th>Detection and Prevention</th>
<th>RPN</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cutting Head Alignment</td>
<td>5</td>
<td>2</td>
<td>8</td>
<td>80</td>
</tr>
<tr>
<td>Cutting Head Jammed</td>
<td>5</td>
<td>3</td>
<td>8</td>
<td>120</td>
</tr>
<tr>
<td>Complete Lever System</td>
<td>9</td>
<td>4</td>
<td>10</td>
<td>360</td>
</tr>
<tr>
<td>Lever Arm Weld</td>
<td>9</td>
<td>4</td>
<td>7</td>
<td>252</td>
</tr>
<tr>
<td>Lever Flange Weld</td>
<td>9</td>
<td>4</td>
<td>10</td>
<td>360</td>
</tr>
<tr>
<td>Frame Bending</td>
<td>5</td>
<td>2</td>
<td>2</td>
<td>50</td>
</tr>
<tr>
<td>Failure to Feed</td>
<td>5</td>
<td>4</td>
<td>3</td>
<td>60</td>
</tr>
</tbody>
</table>

For the cutting head alignment the team recommended action was to ensure the cutter only retracted as far as to allow screen feed. Also suggested was to find a way to ensure only normal force was applied to the cutters. The recommended action for reducing the likelihood for cutter head jamming was to make the punch system rigid enough to resist bending, or to redesign the system. While working on the lever system FMEA, the team determined that there were two welds that would be the most likely areas for failure. Both were redesigned to greatly reduce the possibility of weld failure – a larger weld area was created due to the redesign of parts.

From the recommended actions the team implemented several changes and redesigns, all aimed at reducing the Risk Priority Number. For the alignment we eliminated the top plate and used a steel bar to actuate the pre manufactured cutters. A steel bar was selected because it deflected less than the aluminum bar originally selected. The redesign incorporated the purchased cutters as modular, drop in units - if one were to break then it could easily be replaced. This also guaranteed that the cutter alignment and jamming were no longer issues.

**Design Analysis**

Throughout the design process we performed several analyses to validate our ideas. Some of the methods utilized were Algor Finite Element Analysis, hand and beam deflection calculations. We also performed a tolerance calculation to determine the tolerance needed to punch the screen circles, galvanic corrosion calculations between the zinc cutters and steel, and finally we checked the adhesive wear characteristics for the pins and the actuator bar. Data from each of the test performed along with analytical calculations can be found in Appendix C.
FE Analysis

The team selected machine parts that could have failed during normal operation of the device; based on potential stresses and deflections. The T-Bar was selected for analysis due to the high forces applied at each end from the linkage system. The FE analysis was used to determine if the selected material could withstand these forces with minimal deflection, as well as to calculate the factor of safety for the part. The cutter plates were selected for analysis to verify that the steel plates would not undergo significant deformation. Each arm in the linkage assembly was analyzed to verify that they would not deform or buckle. The lever arm was analyzed to verify that it would not break when the device was operated for safety purposes.

*Note: All FEA loading and constraint figures use following guideline: Green arrows indicate applied load, and the small green circles on the surfaces represent the applied constraints.*

T-Bar

Finite element analysis performed on the aluminum T-bar was used to determine the deflection and maximum stress that will be seen under normal operating conditions. The entire part was forty two inches long, which would have made any small mesh practically impossible to complete. Therefore the part was cut symmetrically along both the x-axis and the y-axis, reducing the number of nodes significantly. Each of the cut faces were constrained accordingly. To make the analysis faster the bar was cut again, this time six inches from the end, and a 1500 pound force couple was added to simulate the moment. Due to the two symmetrical cuts the 600 pound load was halved twice, resulting in a 200 pound surface force in the positive y-direction. The half hole in the square linkage used pinned constraints to simulate the bar under load. The T-Bar loading is shown in Figure 7.1.2.

![Figure 7.1.2: T-Bar FEA Forces and Constraints](image)
After the analysis was completed a von Mises stress of 20,250 psi was found. The yield strength of the aluminum is 30,000 psi. Deflection of the beam was found to be approximately one tenth of an inch. The resulting stress can be seen in Figure 7.1.3 below.

![Figure 7.1.3: T-Bar Results](image)

Cutter Plate FEA

There are 10 Cutter Plates fixed directly to the Front and Rear Crossbars on the frame. The thickness of the 1018 Steel plates is 3/16 inch and the yield strength is 53.7 kpsi. The plates are 4.5 × 3.5 inch rectangles and at their center is a 2.5 inch diameter hole. The plates span the crossbars and must resist the downward force of the Cutters on the screen material. An FE Analysis was performed to check for significant deflection.

Failure scenario:

The maximum force occurs at the moment before the Cutter punctures the screen material. For the FE analysis, the peak force applied by each cutter was 60 lbs and it was applied to the top edge of the 2.5 inch hole. To get a fine mesh on the part it was cut into quarters. Also, a protrusion was modeled to represent the box beam Crossbars. A surface boundary condition was applied to the bottom of the protrusion and symmetric constraints were applied where the plate was cut. The quarter part was given an edge load of 15 lbs. The forces and boundary conditions are in the next figure.
The convergence check was performed using a number of mesh sizes. The mesh size, number of nodes, von Mises stress, and deflection are shown in the table below.

**Table 7.1.3: Cutter Plate convergence results**

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>0.05000</td>
<td>7483</td>
<td>1079.6</td>
<td>0.000167</td>
</tr>
<tr>
<td>0.04000</td>
<td>14205</td>
<td>1117.4</td>
<td>0.000168</td>
</tr>
<tr>
<td>0.03125</td>
<td>26843</td>
<td>1187.6</td>
<td>0.000169</td>
</tr>
<tr>
<td>0.02800</td>
<td>36335</td>
<td>1239.3</td>
<td>0.000170</td>
</tr>
<tr>
<td>0.02500</td>
<td>48341</td>
<td>1296.9</td>
<td>0.000170</td>
</tr>
<tr>
<td>0.02400</td>
<td>56177</td>
<td>1314.4</td>
<td>0.000170</td>
</tr>
</tbody>
</table>

Element type: Bricks, Tetrahedral, Pyramids, and Wedges

The stress and deflection converge as the number of nodes increases. The maximum stress, 1314 psi, is 2.5 % of the yield strength. The maximum stress occurs on the edge of the hole at the point furthest from the support.
Figure 7.1.5: Cutter Plate Stress (von Mises)

The magnitude of deflection had a maximum value of 0.00017 inches which occurs in the top edge of the 2.5 inch circle. The deflection is not significant but it is shown magnified in the image below.

Figure 7.1.6: Cutter Plate Max Stress (von Mises)
The deflection in the x-direction is $8.64 \times 10^{-6}$ inches and it occurs on both sides of the 2.5 inch hole. The diameter at the top edge was reduced by less than 0.001%. Small tolerances for manufacturing do not get that precise. The Cutter Plates are very strong and resist deflection.

**Top Link Deflection:**

All of the linkages are made out of 1018 cold rolled steel. According to matweb.com, 1018 cold rolled steel has yield strength of 53.7ksi and a tensile strength of 63.8ksi.

The top linkage was meshed and loaded two different ways to compare results from each case. The static results of the reaction forces can be found in Appendix C. The first load case can be seen below in Figure 7.1.7. The part was meshed at sizes of 0.1, 0.08, 0.05, 0.04, and 0.03 inches in both cases and a convergence study was performed. A pin was used inside the middle hole with surface contact set between the outside of the pin and the inside of the hole. This situation most closely resembles the contact between the pin and the outside of the hole. The pin was chosen to be put in the middle hole because this is the area where the highest reaction forces are seen. The hole on the right was constrained and a 300lb edge force was applied upward to the hole on the left. A surface load would be more accurate here but the way the surfaces were meshed did not allow for this. Therefore the edge load is equivalent and the artifacts from this force had to be hidden when analyzing the stress. The pin was constrained on one side only to resemble how it is used in the linkage.

**Load Case 1:**

![Figure 7.1.7: Top Link Load Case 1](image)

The results of the case 1, the convergence results, and the FE model can be seen below in Table 7.1.4, Figure 7.1.8, and Figure 7.1.9.
Table 7.1.4: FEA Results for Top Link Case 1

<table>
<thead>
<tr>
<th>Mesh Size (in)</th>
<th>Nodes</th>
<th>vonMises Stress (psi)</th>
<th>Displacement (in)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>5979</td>
<td>10066</td>
<td>0.0004</td>
</tr>
<tr>
<td>0.08</td>
<td>9722</td>
<td>12254</td>
<td>0.0004</td>
</tr>
<tr>
<td>0.05</td>
<td>31426</td>
<td>21245</td>
<td>0.0004</td>
</tr>
<tr>
<td>0.04</td>
<td>59177</td>
<td>27453</td>
<td>0.0004</td>
</tr>
<tr>
<td>0.03</td>
<td>131980</td>
<td>29535</td>
<td>0.0004</td>
</tr>
</tbody>
</table>

Figure 7.1.8: Convergence Results for Top Link Case 1.

The model converged nicely at around 30ksi as seen in Figure 3. This gives a safety factor of around 1.8 until yield occurs and a safety factor of around 2.1 until fracture occurs which means the results are satisfactory. It can be seen in Figure 7.1.9 that the highest stress is seen in the inside of the center hole which was to be expected because the highest reaction forces are seen here. The displacements in this case are very low and almost negligible.
Figure 7.1.9: FEA Results for Top Link Case 1

Load Case 2:

In case 2, the pin in the center hole remained but the fixed hole and the hole with the force applied were switched as seen below in Figure 7.1.10. In case 2, the reaction force applied was calculated to be 200lbs.

Figure 7.1.10: Top Link Load Case 2
The results of this case are seen below in Table 7.1.5, Figure 7.1.11, and Figure 7.1.12.

**Table 7.1.5: Convergence Results for Top Link Case 2**

<table>
<thead>
<tr>
<th>Mesh Size (in)</th>
<th>Nodes</th>
<th>Stress (psi)</th>
<th>Displacement (in)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>5979</td>
<td>8254</td>
<td>0.0006</td>
</tr>
<tr>
<td>0.08</td>
<td>9722</td>
<td>9430</td>
<td>0.0006</td>
</tr>
<tr>
<td>0.05</td>
<td>31426</td>
<td>13750</td>
<td>0.0006</td>
</tr>
<tr>
<td>0.04</td>
<td>59177</td>
<td>15060</td>
<td>0.0006</td>
</tr>
</tbody>
</table>

**Figure 7.1.11: Convergence Results for Top Link Case 2**

![Graph showing convergence results](image_url)
Case 2 shows the maximum stress in the same area it was seen in case 1, on the middle hole. It can be seen that the results for case 2 began to converge at a slightly lower stress than in case 1 and therefore case 1 was used to validate the design.

**Back Link Deflection:**

The back link is the linkage within the system that sees a 200lb compressive load under nominal operation. To load and constrain the part in ALGOR, a pin was used in one hole with surface contact set between the inside of the hole and the outside of pin. This pin was also fixed on one end to simulate how it would be pinned to another link. A surface load of 200lbs was applied to the inside surface of the other hole to simulate the axial compression load. Figure 8 shows the loads and constraints of the back link.

![Figure 7.1.12: FEA Results for Top Link Case 2](image)

![Figure 7.1.13: Back Link Loads and Constraints](image)
The results can be seen below in Table 7.1.6, Figure 7.1.14, and Figure 7.1.15.

Table 7.1.6. FEA Results for Back Link

<table>
<thead>
<tr>
<th>Mesh Size (in)</th>
<th>Nodes</th>
<th>Stress (psi)</th>
<th>Displacement (in)</th>
<th>Aspect Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>8690</td>
<td>2853</td>
<td>0.0004</td>
<td>1.42</td>
</tr>
<tr>
<td>0.08</td>
<td>17719</td>
<td>3314</td>
<td>0.0004</td>
<td>1.47</td>
</tr>
<tr>
<td>0.05</td>
<td>58501</td>
<td>4821</td>
<td>0.0004</td>
<td>1.66</td>
</tr>
<tr>
<td>0.03</td>
<td>261941</td>
<td>5910</td>
<td>0.0004</td>
<td>2.56</td>
</tr>
</tbody>
</table>

Figure 7.1.14: Convergence Results for Back Link
Figure 7.1.15: FEA Results for back Link

This was a very accurate model as seen by the convergence of the stress and the low aspect ratios. The highest stress is around the hole where the pin was placed. The stress converges at around 6000 psi which gives a safety factor of around 9 for yielding and over 10 for fracture which are both very satisfactory. Also, a hand calculation was done on this link to determine the critical buckling load which turned out to be on the order of 10⁶ psi and therefore was not a factor. The critical buckling calculation can be seen in Appendix C.

Lever Arm Deflection:

The lever link was loaded as shown above in Figure 7.1.16, with the far left hole constrained and a constrained pin in the pivot hole. The pin was chosen to be in this hole because it is the hole that sees the highest reaction force. A 20 lb load was applied to the bottom edge of the hole on the right to simulate the force from the handle. A surface load would be more accurate here but could not be utilized due to the way the surfaces were constructed when the part was meshed.
### Table 7.1.7: FEA Results for Lever Link

<table>
<thead>
<tr>
<th>Mesh Size (in)</th>
<th>Nodes</th>
<th>Stress (psi)</th>
<th>Displacement (in)</th>
<th>Aspect Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>23226</td>
<td>5524</td>
<td>0.017</td>
<td>1.43</td>
</tr>
<tr>
<td>0.08</td>
<td>48229</td>
<td>5921</td>
<td>0.017</td>
<td>4.86</td>
</tr>
<tr>
<td>0.05</td>
<td>161483</td>
<td>6025</td>
<td>0.017</td>
<td>1.72</td>
</tr>
</tbody>
</table>

### Figure 7.1.17: Convergence Results for Lever Link

### Figure 7.1.18: FEA Results for Lever Link
In this case the highest stresses are seen on the hole with the pin in it because of the large reaction force that is present here. The results were satisfactory in that they converged at a value of around 6100 psi with relatively low aspect ratios on all of the nodes. This design is validated since safety factors of around 9 can be seen within the design. Also, the deflection is somewhat high at 0.017 inches but will not cause any problems in the design.

**Lever Rod Stress:**

Finite element analysis performed on the steel lever rod was used to determine the deflection and maximum stress that will be seen under normal operating conditions. The entire part was thirty-seven inches long and ½ inch diameter. Because the rod can be evaluated analytically as a simply supported beam, FEA was not necessary for this part. However, it was performed to further confirm the results of the hand analysis. The part was meshed using a 0.05 inch mesh. Each of the outer faces was fully constrained and the contact was set to welded. Two 20 pound point loads were applied to the top of bar eight inches from each end. Figure 7.1.19 shows the constraints that were applied to the part.

![Figure 7.1.19: Loading and Constraints for Lever Rod](image)

As shown in Figure 7.1.20, the maximum stress for the lever rod using a mesh of 0.05” was determined to be 3,808 psi; which agrees with the hand calculation of 3,863 psi, therefore no further analysis was performed. The hand analysis is shown in Appendix C.
Mock-Ups and Experiments

The initial mockup, shown in Figure 7.1.21, was a wooden device intended to test the ability of the original lever system to maintain alignment and apply the force. From the test apparatus we determined that the force application method was not robust enough to apply the needed actuation force for ten cutters. We also found that maintaining alignment became problematic due to the cutters retracting too far out of their guides. From these “revelations” the team decided to redesign the prototype to address the issues.

Based on the mock-up testing we decided that a simple lever was not an adequate enough method for force application. Therefore, a four bar mechanism was designed and implemented. The mock-up also revealed the potential severity of cutter misalignment. However the team
decided to conduct further testing to determine if an alternate method could be developed to maintain cutter alignment. Initial alignment testing with only two cutter was inconclusive.

Next, we devised a test to determine the required user input force. This was completed without the prototype being completed, therefore we determined the input force from what force was necessary to actuate one punch, then multiplying it by ten. We found the required input force from testing the springs to find the spring constant. From the test we determined the force to cut the screen was approximately sixty pounds per punch. Data and graphs from this test can be found in Appendix C.

The team conducted four separate experiments to test cutter wear, required input force, potential cutter misalignment, and a method for sharpening the cutters.

Cutter wear is important because of its significance to the machine actually working and doing the intended job. The cutter wear experiment is done in order to check if the sharp edges dull quickly and prevent the cutters from punching through the aluminum. The client would like a minimal maintenance machine, because of their lack of employees that could perform these tasks. It is also important that the sides of the cutters don’t wear away causing the diameter of the cutting heads to become too small and be unable to pass the quality check.

Due to the large input force the team decided to utilize a linkage system with a long lever arm to maximize the mechanical advantage; a force of 600 pounds is needed to actuate all ten cutters at once. Due to the linkage system this translates into an input force of only 40 pounds, supplied by the user. The mechanical advantage of 15:1 also negates some of the problems with cutter wear because only small increases in input force are needed to overcome increases due to wear.

Cutter misalignment is another issue that the experimentation intends to address. It is a critical factor in the machine operation – if one punch is misaligned then the whole system will fail. Tolerances for the bottom plate are tight enough so that even a small change in cutter alignment will cause a jam. In the case of a jam it is likely that the cutter involved will be destroyed as a result of the operator applying more force in an attempt to cut.

Determining an adequate sharpening method for the cutters is important since the cutting force will be proportional to cutter wear. As they dull and material is deposited on the cutters the force required to punch through the screens will increase, causing an increase in user input force. The suggested method, by the cutter manufacturer, for sharpening the cutters was to use around 600 grit sandpaper. This is done by cutting circles in the sandpaper with the machine; this will sand off any build up and re-sharpen the edges.

The four objectives of this experiment have a significant impact on the deliverable prototype. Two of the objectives, cutter wear and required input force, are directly related to each other since as the cutter dulls the required force to punch through the screen increases. Customers at Tri State Industries have limited strength and endurance and therefore even a relatively small increase in force can cause them to tire too quickly. The data we collect in this experiment can be used to determine a maintenance schedule for the cutters, either to replace or sharpen them.

Testing done for the significance of cutter misalignment will determine if guide pins or some other method of guide will be needed to guarantee successful punching. Any misalignment cannot be tolerated due to the damage that could occur from overload. Testing will also validate the tolerances we determined for our cutters. If the required force is too large, or if required tolerances are too tight, then the prototype is not deliverable to Tri State.
Results obtained from the experiment were plotted using Microsoft Excel. Appendix Figure 7.3.1 is the plot of the single spring results against the four spring – the slope of the line is the spring constant of the spring. The team predicted that four springs in parallel would have a spring constant close to four times that of a single spring. Instead the results indicated that the perceived spring constant was closer to 5.8 times the single spring.

\[
k_1 = 5.74 \text{ lb/in} \\

k_2 = 33.42 \text{ lb/in} \\

\text{Parallel Spring Constant} = \frac{k_2}{k_1} = \frac{33.42}{5.74} = 5.82
\]

The forecast of the four spring constant was used to verify the force needed to bottom-out the cutter head. Since the maximum travel was known to be 0.59 inches the spring force was determined to be approximately twenty pounds.

\[
Spring\ Force = k\Delta x = (32.77)(.59) = 19.3 \approx 20\text{lbs}
\]

The results from linkage return test, Appendix Figure 7.3.2, showed that a force of greater than 7 lbs would be required to return the lever handle to the up position. Also, a test was done at 6 inches away from the pivot point on the link and it was determined that a force greater than 30 lbs total would be required to return the handle. Since we will be using two springs on each link, it was determined that a spring capable of providing greater than 15 lbs of force would be required on each side.

Initially we expected the required input force for cutting with no springs to be approximately 30-35 pounds. The spring constant forecast from the four spring test allowed the team to determine that the input force should be approximately 50-55 pounds. Experimentation using the four spring set-up confirmed our initial expectations. When all four springs were used the input force required to punch through the screen increased to 55-60 pounds. Throughout the design process we have assumed the force required to punch a single cutter through the screen was 60 pounds therefore, this experiment verifies that the assumed force was correct. It was also determined that two springs capable of 15 lbs or greater of force are going to be required to return the handle to the up position.
8.0 Final Design for Production

8.1 Design Description and Operation

The full screen punching device is shown in figure 8.1.0.

Device subassemblies include the frame, punches, linkage, and safety cover. The frame is shown in figure 8.1.1.

The frame is the primary subassembly and all frame parts are steel with exception to the end caps and wooden dowel rods. Steel was used for ease of welding but it also resists deflection. The steel parts are angle iron, box beam, and the side mounting plates. Angle iron extends the surface of the box beam cross-members to support the individual punches. The extended surfaces are called mounting rails. The rear of the frame includes a plastic cutting guide made of several panels.

The plastic cutting guide is used by an operator at the rear of the device to cut $6 \times 36$ inch strips of screen material. Each pre-manufactured punch is part of the punch subsystem and is shown in figure 8.1.2.
Each punch is placed overtop of two bolts which restrict translation. Refer to the User Manual for punch servicing or replacement instructions.

The linkage sub-system includes an actuator bar and tube which must be welded together before assembly. The pins and bushings are also included in the linkage subsystem as well as the operator rod. One of the linkage subassemblies is shown in figure 8.1.3.

The linkage must be assembled in the same way for both sides. Assembling the linkages symmetrically optimizes the performance. Each linkage magnifies the user input force. As the operator at the front of the device pulls the lever down, the two linkages apply a force at each side of the actuator bar. The actuator bar applies a downward force on the individual punches which completes the punching operation.
The final subassembly is the safety cover. The plastic panels guard the user against pinch and nip points as described by OSHA safety requirements for a punch press device. The safety cover is shown in figure 8.1.4.

![Safety Cover Subassembly](image)

**Figure 8.1.4: Safety Cover Subassembly**

The safety cover subassembly is made out of seven plastic panels. Adhesive is used for connections. Each plastic panel is cut from a large sheet of PVC. The template used is shown in Appendix D.

A User Manual is included in the Appendix with additional instructions and precautions.

**8.2 Manufacturing, Assembly, and Cost of an Additional Unit**

The box-beam used in the frame is cut to proper increments based part drawings in the Appendix. An assembly level drawing for the frame is also found in the Appendix. Referencing the frame assembly drawing, the box beam parts are welded in place before any other assembly operations. During the welding process, a magnetic 90° may ensure right angles. On the front of the frame there are two mounting plates. Mounting plates must be welded to the box beam frame overttop two cross-members.

Each side mounting plate must be located to promote symmetry between the left and right linkages. Properly positioning the left and right side mounting plates also effects the position of all other subassemblies. The linkage subsystem attaches to the frame with pins and bushings, the patterned punch sub-assemblies are positioned between the mounting plates, and the safety cover bolts to the top of the mounting plates. Therefore, the position of each side mounting plate determines the positioning of all other subsystems and their relative parts.

To position the side mounting plates, each side is butted up against a flat surface and clamped. The flat reference surface is represented with a red line in figure 8.2.1.
Figure 8.2.1: Reference Surface for Frame Assembly

The reference surface shown with the red line must be used to locate the side mounting plates. Constraining box beams to this surface along with using a magnetic 90° for vertical perpendicularity will ensure the two sides are assembled accurately.

For linkage assembly, pins must be driven in with a rubber mallet and a coder pin must be used to secure them in place. The two linkages must be assembled separately before installing the lever rod. If any portion of the linkage extends above the side mounting plate, it must be trimmed or ground to fit underneath the safety cover. Due to the loose tolerances used, some trimming or rounding of linkage corners may be needed.

The plastic safety cover may be assembled with screws, bolts, or an adhesive but the cost estimates are based on an adhesive connection type. Each panel must be cut from the material sheet in locations shown on the template. The template is found in Appendix D. The part drawings must also be referred to for proper dimensioning. A file may be used to clean up the edges of panels cut on the band saw. Each panel is glued together. Holes in the top panel are used to bolt the completed cover to the side mounting plates.

The Parts List is found in the User Manual. The prototype cost is found in Appendix D. The material and production costs to manufacture one additional device are also tabulated in Appendix D.
9.0 Conclusions

The objective of this project was to develop an assistive technology device for cutting circular screen sections that would aid mentally and physically handicapped workers to more easily perform this task. More specifically the main goals were to open this task up to the lowest functioning workers at Tri-State while increasing their production rate and the quality of the product. These results can be seen below.

Due to lack of customer testing, it has not been determined whether or not the design will open up this task to lower functioning workers. The device was not able to be delivered to the customer for testing because of numerous manufacturing issues that arose throughout the construction process. However, we believe the design will open this task up to lower functioning workers because it is a simple, two step operation that requires only the use of scissors which they are already proficient with. This is a significant improvement over the multi-step hand cuts that workers were previously performing. This would mean that lower functioning workers would not be limited to only certain jobs at Tri-State and this would be of great value to the company.

The production rate was significantly increased in our evaluation of our design. The production rate increased from approximately one screen/min/person to ten screens per minute per person. This greatly exceeded our goal of four screens per minute per person and increased the production rate approximately 1000%. This means it would take ten workers to do the equivalent of one worker with the new design which allows management at Tri-State to utilize these workers in other areas where they may be needed.

The quality of the cut was a major improvement over the way the screen was previously cut. When cutting the screen with scissors workers would leave loose and frayed screen edges putting the workers in danger of getting snagged or cut on them. With the use of the Marvy craft punch in our design, the quality of the cut was greatly increased with no loose or frayed edges which significantly improved worker safety over the previous method.

One significant improvement of this design would be to allow the screen to feed through the cutters, which would allow the machine to be operated by one person and would increase the productivity even more. This was the concept the team started out with but it was not followed through because of the complexity of aligning ten die and guide plates to work together. Also, an automatic screen advancer would add much more complexity to the machine but would increase the production rate even further.

At this time, there is no need for the prototype to go into production, due to lack of testing and the small product market. Tri-State industries typically receives orders for approximately 5,000 screens four times per year based on the testing that we conducted, we believe a single machine will be able to meet these orders on time, and therefore another machine is not required.
References

Amazon. 23 November 2008 <http://www.amazon.com/Swingline-Sheet-Commercial-Adjustable-Punch/dp/B00006IBKA>


Appendix A. Interview Questions and Notes
Tour Notes for Various Work Areas

1. Sample Booking Making
   a. Quality
      i. Uneven/not square cuts

2. Roll Goods
   i. Edge Alignment for rolls
   ii. Difficulty cutting and rolling sample rolls

3. Sheet Counting/Office Max
   a. Quality
      i. Cannot count sheets correctly to 10 or 100.
         1. Required high function consumers

4. Screen Cutting
   a. Quality
      i. Dimension Tolerances
      ii. Marks are left on screen
   b. Consumer Disability
      i. Dexterity issues
      ii. Screen is cut by hand.
   c. Productivity
      i. Large quantity required per order
      ii. Limited lead time (assume)

5. Labeling of Items
   a. Quality
      i. Creases and bubbles formed when label applied
      ii. Alignment
      iii. Applied by hand
Appendix A. Interview Questions and Notes

Screen Cutting Process Interview

• Brief description of how the task is currently performed
  a. Cap liner is used to draw template on screen. Consumers cut the screen with scissors

• Which customers are currently performing this task, (what level are they 1:13, etc)
  a. Mid to High Functioning consumers (without hand dexterity issues)

• What level of worker would you like to be able to perform this task when we are done
  a. Low to mid Functioning levels

• What are the specific problems they encounter with the screen cutting
  a. Screen splinters cut their hands as well as hands become sore and tired.

• What are we not allowed to change
  a. Change anything except the screen dimensions.

• What limitations do we have, i.e. power, size, space, weight, safety, etc.
  a. Power is available
  b. Size of screen cannot change
  c. Space to operate is pretty limited Job only done in one area.
  d. Weight no real limitations.
  e. Safety- must be an OSHA approved device technique

• What is their current production requirements (how many, how often)
  a. 5000 pcs 4x a year
## Appendix B. AHP Customer Needs

### Evaluation of Customer Needs

<table>
<thead>
<tr>
<th></th>
<th>User Friendly</th>
<th>Efficiency</th>
<th>Space</th>
<th>Safety</th>
<th>Cost</th>
<th>Total</th>
<th>Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Ease of Use</strong></td>
<td>1.00</td>
<td>3.00</td>
<td>5.00</td>
<td>1.20</td>
<td>4.00</td>
<td>14.20</td>
<td>0.41</td>
</tr>
<tr>
<td><strong>Efficiency</strong></td>
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<td>1.00</td>
<td>1.67</td>
<td>0.50</td>
<td>1.20</td>
<td>3.00</td>
<td>0.09</td>
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<tr>
<td><strong>Space</strong></td>
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<td>1.80</td>
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<tr>
<td><strong>Safety</strong></td>
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<td>1.00</td>
<td>3.00</td>
<td>10.80</td>
<td>0.32</td>
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<tr>
<td><strong>Cost</strong></td>
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<td>0.80</td>
<td>2.00</td>
<td>0.33</td>
<td>1.00</td>
<td>4.46</td>
<td>0.13</td>
</tr>
</tbody>
</table>
Appendix C – Design Analysis

- Hardened Steel
- 5/8” diameter
- 1” length
- Double shear strength = 79,800 lbs

Cutter + Hole Tolerances

Hole die diameter = \( D_h + 2c \)

\[ c = A_c t \]

where \( t = 0.025” \), \( D_h = 2.5” \), \( A_c = 0.09 \)

\[ c = (0.09)(0.025”) = 0.00225 \]

Therefore, hole diameter = \( \sqrt{2.50225”} \)
Beam Deflection Approximation

L = 36 in; W = 15.8 lb/in;
I = 0.10998 in^4; E = 10 \times 10^6 ksi

θ_{max} = \frac{-WL^3}{24EI} = \frac{(15.8)(36)}{2 \times (10 \times 10^6 \times 0.3078)}

θ_{max} = -0.009978°

V_{max} = \frac{-5WL^2}{384EI} = \frac{5(15.8)(36)}{384(10 \times 10^6 \times 0.3078)}

V_{max} = -0.003118 in

I = \left[ \frac{1}{2} \left( \frac{3}{16} \right)^2 \right] + \left( \frac{1}{2} \times \frac{3}{16} \times \frac{5}{16} \times \frac{5}{16} \times (\frac{3}{32} - 1) \right)

I = 0.3078 \text{ in}^4

\bar{y} = 1.05625
Pins
- Hardened Steel (HRC 47)
- Single shear strength = 39,900 lbs
  Diameter = 5/8" = 0.625" ; Length = 1.0"
  Actual Diameter = 0.625" + .0002" = 0.6252"
  Hole Size = 0.6245 - 0.625

Bushings
- SAE841 Bronze (Oilst) 
- Load \( P_{\text{max}} \) = 2000 lbs
  Nominal Diameter = 3/4" = 0.75" ; Length = 0.5"
  Outside Tolerance = +0.002" to 0.003" 
    \[ 0.752" - 0.753" \]
  Nominal Shaft Diameter = 5/8" = 0.625"
  Shaft Diameter Tolerance = +0.001" to +0.002" 
    \[ 0.626" - 0.627" \]
Spring Constant

Appendix Figure 7.3.1

\[ y = 32.767x - 0.0761 \]
\[ R^2 = 0.9865 \]

Appendix Figure 7.3.2

\[ y = 5.7423x - 0.009 \]
\[ R^2 = 0.9909 \]
# Appendix D. Cost

Initial Bill of Materials (Prototype)

<table>
<thead>
<tr>
<th>Title</th>
<th>Qty</th>
<th>Dimensions</th>
<th>Material</th>
<th>Cost/per</th>
<th>Cost</th>
<th>Vendor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frame Sub Assembly</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Box Beam 1.5&quot; 1.5&quot; x0.154&quot;</td>
<td>1</td>
<td>217&quot;</td>
<td>ASTM A 500</td>
<td>$163.00</td>
<td>$163.00</td>
<td>Central Steel</td>
</tr>
<tr>
<td>Angle 1.25&quot; x 1.25&quot; x 0.125&quot;</td>
<td>1</td>
<td>6&quot;</td>
<td>A36 Steel</td>
<td>$13.80</td>
<td>$13.80</td>
<td>McMaster Carr</td>
</tr>
<tr>
<td>Side Mounting Plates</td>
<td>2</td>
<td>0.5&quot; x 12&quot; x 8.25&quot;</td>
<td>1018 Steel</td>
<td>$33.18</td>
<td>$66.36</td>
<td>Yale Steel</td>
</tr>
<tr>
<td>Plastic End Plugs</td>
<td>10</td>
<td>1.2812&quot;-1.3438&quot;</td>
<td>Polyethylene</td>
<td>$12.20</td>
<td>$12.20</td>
<td>McMaster Carr</td>
</tr>
<tr>
<td>1/2 x 38 Wooden Dowel Rod</td>
<td>3</td>
<td>.5&quot; x 10'</td>
<td>Wood</td>
<td>$1.37</td>
<td>$4.11</td>
<td>Lowes</td>
</tr>
<tr>
<td>Safety Cover Sub Assembly</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Protective Case</td>
<td>1,1</td>
<td>4' x 4' &amp; 2' x 2'</td>
<td>PVC</td>
<td>$197.00</td>
<td>$197.00</td>
<td>McMaster Carr</td>
</tr>
<tr>
<td>Feed System Subassembly</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Drive Roller Sub Assembly</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>5/8_39 Rod</td>
<td>1</td>
<td>5/8&quot; x 6'</td>
<td>1018 Steel</td>
<td>$7.25</td>
<td>$7.25</td>
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<tr>
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<td>Neoprene</td>
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<tr>
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<td>2&quot; x 0.92&quot; x 5/8&quot;</td>
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<td>$31.59</td>
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<tr>
<td>T-Beam ***</td>
<td>1</td>
<td>1.5&quot; x 1.5&quot; x 3/16&quot; x 8&quot;</td>
<td>6061-T6</td>
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<td>$27.60</td>
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<td>Punch</td>
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<td>2.5&quot; round</td>
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<td>$100.00</td>
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</tr>
<tr>
<td>Cutter Plate ****</td>
<td>10</td>
<td>3/16&quot; x 4&quot; x 36&quot;</td>
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<td>$28.15</td>
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<tr>
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<td>1</td>
<td>0.75&quot; x 4'</td>
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<td>$13.00</td>
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<td>Steel Linkage Bars</td>
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<td>0.5&quot; x 1&quot; x 36&quot;</td>
<td>1018 Steel</td>
<td>$7.10</td>
<td>$14.20</td>
<td>Yale Steel</td>
</tr>
<tr>
<td>Mounting Pin</td>
<td>10</td>
<td>5/8&quot; x 1&quot;</td>
<td>Steel</td>
<td>$8.78</td>
<td>$8.78</td>
<td>McMaster Carr</td>
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<tr>
<td>Brass Bushing</td>
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<td>5/8&quot; x 1&quot;</td>
<td>Oilite Bronze</td>
<td>$1.10</td>
<td>$9.90</td>
<td>McMaster Carr</td>
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<tr>
<td>16 ga. Tube Actuator 1&quot; x 1&quot;</td>
<td>1</td>
<td>36&quot;</td>
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<td>$10.37</td>
<td>$10.37</td>
<td>Lowes</td>
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<tr>
<td>Bar Actuator (3/16)&quot; x 2&quot;</td>
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<td>48&quot;</td>
<td>Steel</td>
<td>$13.97</td>
<td>$13.97</td>
<td>Lowes</td>
</tr>
<tr>
<td>Test Screen</td>
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<td>36&quot; x 50'</td>
<td>Aluminum</td>
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<td>$20.00</td>
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<tr>
<td><strong>Total</strong></td>
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</table>
# Final Bill of Materials (Production of 1 Unit)

<table>
<thead>
<tr>
<th>Item #</th>
<th>Title</th>
<th>Qty</th>
<th>Dimensions</th>
<th>Material</th>
<th>Cost/</th>
<th>Cost</th>
<th>Vendor</th>
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<tbody>
<tr>
<td>1</td>
<td>Box Beam 1.5” x 1.5” x 0.154”</td>
<td>1</td>
<td>217”</td>
<td>ASTM A 500</td>
<td>$163.00</td>
<td>$163.00</td>
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<td>2</td>
<td>Angle 1.25” x 1.25” x 0.125”</td>
<td>1</td>
<td>6’</td>
<td>A36 Steel</td>
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<td>$13.80</td>
<td>McMaster Carr</td>
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<tr>
<td>3</td>
<td>Side Mounting Plates</td>
<td>2</td>
<td>0.5” x 12” x 8.25”</td>
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<td>$33.18</td>
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<td>Plastic End Plugs</td>
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<td>1.2812”-1.3438”</td>
<td>Polyethylene</td>
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<td>1/2 x 38 Wooden Dowel Rod</td>
<td>3</td>
<td>.5” x 10’</td>
<td>Wood</td>
<td>$1.37</td>
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<td>6</td>
<td>Safety Cover Sub Assembly</td>
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<td>7</td>
<td>Protective Case</td>
<td>1,1</td>
<td>4’ x 4’ &amp; 2’ x 2’</td>
<td>PVC</td>
<td>$197.00</td>
<td>$197.00</td>
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<tr>
<td>8</td>
<td>Circular Craft Punch</td>
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<td>2.5” round</td>
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<td>$100.00</td>
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<tr>
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<td>12</td>
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<td>$8.78</td>
<td>$8.78</td>
<td>McMaster Carr</td>
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<tr>
<td>13</td>
<td>Brass Bushing</td>
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<td>Oilite Bronze</td>
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<td>$9.90</td>
<td>McMaster Carr</td>
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<tr>
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<td>16 Ga. Tube Actuator 1” x 1”</td>
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<td>Steel</td>
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<td>$10.37</td>
<td>Lowes</td>
</tr>
<tr>
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<td>Bar Actuator (3/16)” x 2”</td>
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<td>48”</td>
<td>Steel</td>
<td>$13.97</td>
<td>$13.97</td>
<td>Lowes</td>
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<tr>
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<td>Aluminum</td>
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## Estimated Production Cost for 1 Unit

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<tr>
<th>Time</th>
<th>Labor Rate</th>
<th>Labor Costs</th>
<th>Basic Overhead factor</th>
<th>Equipment Factor</th>
<th>Special Operation/Tolerance Factor</th>
<th>Total</th>
</tr>
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<tbody>
<tr>
<td><strong>Frame</strong></td>
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<tr>
<td>Cut stock box beam for frame</td>
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<td>12</td>
<td>$12</td>
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<td>Cut stock angle iron for frame</td>
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<td>12</td>
<td>$3</td>
<td>1</td>
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<td>Drill holes box frame</td>
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<td>12</td>
<td>$6</td>
<td>1</td>
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<td>Machine and tap holes in angle iron</td>
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<td>15</td>
<td>$23</td>
<td>1</td>
<td>0.5</td>
<td>0.25</td>
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<td>CNC mill side plates</td>
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<td>$80</td>
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<td>Set up and weld box frame, side plates, and angle iron</td>
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<tr>
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<table>
<thead>
<tr>
<th>Time</th>
<th>Labor Rate</th>
<th>Labor Costs</th>
<th>Basic Overhead factor</th>
<th>Equipment Factor</th>
<th>Special Operation/Tolerance Factor</th>
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<td>$3</td>
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<td>15</td>
<td>$15</td>
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<td>Cut bar stock for linkages</td>
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<td>15</td>
<td>$23</td>
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<td><strong>Total</strong></td>
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<td>Task</td>
<td>Time</td>
<td>Labor Rate</td>
<td>Labor Costs</td>
<td>Basic Overhead factor</td>
<td>Equipment Factor</td>
<td>Special Operation/Tolerance Factor</td>
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<td>Cut pieces from stock Poly-carbonate sheet</td>
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<td>Drill holes in PC sheet</td>
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<td>Assemble Cover and Table</td>
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<td>1</td>
<td>0.5</td>
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<td>Paint Cover and Table</td>
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<td>12</td>
<td>$12</td>
<td>1</td>
<td>0.5</td>
<td>0</td>
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<tr>
<td><strong>Total</strong></td>
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</tr>
</tbody>
</table>

Total: **$910**
Appendix E. Four Bar Analysis & Matlab Code
Insert Scan from Notebook
clc; clear;
format long
format compact

% Inputs
DR = pi/180;
g=32.2;
% All units are in Ft and degrees
r1 = (7.25/12); r2 = (2/12); r3 = (7/12); r4 = (2/12); rca = (20/12);
th1 = 91.97*DR; th20 = 346.08*DR; del3 = 180*DR; omega2=20; alpha2=0;
rlx = r1*cos(th1); rly = r1*sin(th1);

rp=(1.3/12); %length of input link p
r5=(1.945/12); % length of link 5
x=(1.625/12); % offset of T-Bar
xr=x-.125/12
ph=(.125/12);
pl=(2.625/12);
ypp=[0 -pl -pl 0];
xpp=[-ph/2 -ph/2 ph/2 ph/2];
mp=0.020;
m5=0.041;
m6=0.015;
Igzp=1.819e-5;
Igz5=1.418e-4;

th2 = 346.08*DR; % Initial Theta
dth2 = 1*DR; % Delta Theta
thf2 = (346.08+30)*DR; % Final Theta
th2 = [th2:dth2:thf2]; % Assign theta array
N = (thf2-th2)/dth2 + 1; % Number of iterations for loop

% Animate single link
anim = 1;

if anim == 1 % Animates Full Range of motion
    figure; % Give a blank graphics window
    for i = 1:N, % For loop to animate
        %position analysis for Theta4
        E(i) = 2*r4*(r1*cos(th1) - r2*cos(th2(i)));
        F(i) = 2*r4*(r1*sin(th1) - r2*sin(th2(i)));
        G(i) = r1^2 + r2^2 - r3^2 + r4^2 - 2*r1*r2*cos(th1-th2(i));
    end
end
\[ t(i) = \frac{(-F(i) + \sqrt{E(i)^2 + F(i)^2 - G(i)^2})}{G(i)-E(i)}; \]

% open branch
\[ \text{th4}(i)= 2\times \text{atan}(t(i)); \]
\[ \text{ax} = r2\times \cos(\text{th2}(i)); \quad \% \text{theta3} \]
\[ \text{ay} = r2\times \sin(\text{th2}(i)); \]
\[ \text{bx} = r4\times \cos(\text{th4}(i)) + r1x; \]
\[ \text{by} = r4\times \sin(\text{th4}(i)) + r1y; \]
\[ \text{th3}(i) = \text{atan2}(\text{by}-\text{ay},\text{bx}-\text{ax}); \]
\[ \text{bet} = \text{th2}(i) - \text{del3}; \quad \% \text{coupler point} \]
\[ \text{pcx}(i) = rca\times \cos(\text{bet}); \]
\[ \text{pcy}(i) = rca\times \sin(\text{bet}); \]
\[ \text{mu}(i) = \text{abs}(\text{th4}(i)-\text{th3}(i)); \quad \% \text{transmission angle} \]

\[ \text{thp}(i)= \pi+\text{th4}(i); \quad \% \text{theta p} \]
\[ \text{trig}(i)=\text{abs}((-xr)-r_p\times \cos(\text{thp}(i)))/r5); \quad \% \text{according to known graphical solution} \]
\[ \text{if trig}(i) > 1 \]
\[ \quad \text{tri}(i)=(\text{trig}(i)-1); \]
\[ \text{else} \]
\[ \quad \text{tri}(i)=\text{trig}(i); \]
\[ \text{end} \]
\[ \text{th5}(i)=\pi+\text{acos(tri}(i)); \]
\[ \text{h}(i)=r_p\times \sin(\text{thp}(i))+r5\times \sin(\text{th5}(i)); \]
\[ \text{hi}=\text{h}(i); \]

%Plots Position Results
\[ \text{x1} = [0 \ r1\times \cos(\text{thl})]; \quad \% \text{link1 coordinates} \]
\[ \text{y1} = [0 \ r1\times \sin(\text{thl})]; \]
\[ \text{x2} = [\text{pcx}(i) \ r2\times \cos(\text{th2}(i))]; \quad \% \text{link2 coordinates} \]
\[ \text{y2} = [\text{pcy}(i) \ r2\times \sin(\text{th2}(i))]; \]
\[ \text{x3} = [r2\times \cos(\text{th2}(i)) \ r2\times \cos(\text{th2}(i))+r3\times \cos(\text{th3}(i))]; \quad \% \text{link3 coordinates} \]
\[ \text{y3} = [r2\times \sin(\text{th2}(i)) \ r2\times \sin(\text{th2}(i))+r3\times \sin(\text{th3}(i))]; \]
\[ \text{x4} = [r1\times \cos(\text{thl}) \ r1\times \cos(\text{thl})+r4\times \cos(\text{th4}(i))]; \quad \% \text{link4 coordinates} \]
\[ \text{y4} = [r1\times \sin(\text{thl}) \ r1\times \sin(\text{thl})+r4\times \sin(\text{th4}(i))]; \]
\[ \text{xp}=[r1\times \cos(\text{thl}) \ r1\times \cos(\text{thl})+ r_p\times \cos(\text{thp}(i))]; \quad \% \text{rest of link4 coordinates} \]
\[ \text{yp}=[r1\times \sin(\text{thl}) \ r1\times \sin(\text{thl})+ r_p\times \sin(\text{thp}(i))]; \]
\(x5 = [r1 \cos(th1) + rp \cos(thp(i)) - x];\) %link5 coordinates
\(y5 = [r1 \sin(th1) + rp \sin(thp(i)) r1 \sin(th1) + rp \sin(thp(i)) + r5 \sin(th5(i))];\)

\(ht_{org}(i) = r1 \sin(th1) + rp \sin(thp(i)) + r5 \sin(th5(i));\) %Height from 0,0

% Problem was divided into two mechanisms: Four-Bar and Slider Crank
% Four-Bar Analysis
% velocity and acceleration from position analysis

%-------------------------------------------
% Matrix Solver
\(a = r3 \sin(th3(i));\)
\(b = -r4 \sin(th4(i));\)
\(d = -r3 \cos(th3(i));\)
\(e = r4 \cos(th4(i));\)
%--------------------------------
% velocity
\(c = -r2 \omega2 \sin(th2(i));\)
\(f = r2 \omega2 \cos(th2(i));\)
%--------------------------------
% Matrix Solver for velocity and acceleration
\(A = [a \ b; \ d \ e];\)
\(B = [c; \ f];\)
\(Z = \text{inv}(A);\)
%--------------------------------------
% velocity
\(X = Z \ B;\)
\(\omega3(i) = X(1);\)
\(\omega4(i) = X(2);\)
%--------------------------------
% Acceleration
\(cp = -r2 \alpha2 \sin(th2(i)) - r2 \omega2 \omega2 \cos(th2(i)) - r3 \omega3(i) \cos(th3(i)) + r4 \omega4(i) \omega4(i) \cos(th4(i));\)
\(fp = r2 \alpha2 \cos(th2(i)) - r2 \omega2 \omega2 \sin(th2(i)) - r3 \omega3(i) \sin(th3(i)) + r4 \omega4(i) \omega4(i) \sin(th4(i));\)
\(C = [cp; fp];\)
\(Y = Z \ C;\)
\(\alpha3(i) = Y(1);\)
\(\alpha4(i) = Y(2);\)
%--------------------------------
% Velocity of point CG3
\(vcx(i) = -r2 \sin(th2(i)) \omega2 - (rca \sin(bet) \omega3(i));\)
\(vcy(i) = r2 \omega2 \cos(th2(i)) + (rca \omega3(i) \cos(bet));\)
%-----------------------------------------
% Acceleration of point CG3
\(acx(i) = -r2 \alpha2 \sin(th2(i)) - r2 \omega2 \omega2 \cos(th2(i)) - rca \alpha3(i) \sin(bet) - rca \omega3(i) \omega3(i) \cos(bet);\)
\(acy(i) = r2 \alpha2 \cos(th2(i)) - r2 \omega2 \omega2 \sin(th2(i)) + rca \alpha3(i) \cos(bet) - rca \omega3(i) \omega3(i) \sin(bet);\)
\(A_{CG3}(i) = acx(i);\)
% Acceleration of point CG4
ac4x(i)=-r2*alpha2*sin(th2(i))-r2*omega2*omega2*cos(th2(i))-
   r3*omega3(i)*sin(th3(i))-r3*omega3(i)*sin(th3(i))+r4*0.5*omega4(i)*cos(th4(i));
ac4y(i)= r2*alpha2*cos(th2(i))-r2*omega2*omega2*sin(th2(i))+r3*omega3(i)*cos(th3(i))-
   r3*omega3(i)*cos(th3(i))-r4*0.5*omega4(i)*cos(th4(i))+r4*0.5*omega4(i)*sin(th4(i));
Acg4x(i)=ac4x(i);
Acg4y(i)=ac4y(i);
%-------------------------------
% Acceleration of point CG2
ac2x(i)=-r2*0.5*alpha2*sin(th2(i))-r2*0.5*omega2*omega2*cos(th2(i));
ac2y(i)= r2*0.5*alpha2*cos(th2(i))-r2*0.5*omega2*omega2*sin(th2(i));
Acg2x(i)=ac2x(i);
Acg2y(i)=ac2y(i);
%------------------------------------------
x43=r3*cos(th3(i))-rca*cos(bet);
y43=r3*sin(th3(i))-rca*sin(bet);
xy43=sqrt(x43^2+y43^2);
th43=atan2(y43,x43)+pi;
%--------------------------------------------------------
% Inverse Dynamics
%r21x=-0.5*r1*cos(th1);
r21y=0.5*r1*sin(th1);
r41x=0.5*r1*cos(th1);
r41y=-0.5*r1*sin(th1);
r12x(i)= 0.5*r2*cos(th2(i));
r12y(i)=0.5*r2*sin(th2(i));
r23x(i)=rca*cos(bet);
r23y(i)=rca*sin(bet);
r32x(i)=0.5*r2*cos(th2(i));
r32y(i)=0.5*r2*sin(th2(i));
r43x(i)=xy43*cos(th43);
r43y(i)=xy43*sin(th43);
r34x(i)=0.5*r4*cos(th4(i));
r34y(i)=0.5*r4*sin(th4(i));
r14x(i)=0.5*r4*cos(th4(i));
r14y(i)=0.5*r4*sin(th4(i));
re2x=0;
re2y=0;
re3x=0;
re3y=0;
re4x=0;
re4y=0;

m2=0.015;
m3=0.327;
m4=0.036;
Fe2x=0;  
Fe2y=0;  
Fe3x=0;  
Fe3y=0;  
Fe4x=0;  
Fe4y=0;  
Me2=0;  
Me3=0;  
Me4=0;  

Igz2=7.9*10^-6;  
Igz3=1.8*10^-3;  
Igz4=9.5*10^-5;  

%unknowns=[f21x;f21y;f32x;f32y;f43x;f43y;f14x;f14y;tau2];  

unmat=[-1 0 1 0 0 0 0 0 0;  
0 -1 0 1 0 0 0 0 0;  
-r12y(i) r12x(i) -r32y(i) r32x(i) 0 0 0 1;  
0 0 -1 0 1 0 0 0 0;  
0 0 -r23y(i) r23x(i) r43y(i) -r43x(i) 0 0 0;  
0 0 0 0 -1 0 1 0 0;  
0 0 0 0 0 -1 0 1 0;  
0 0 0 0 r34y(i) -r34x(i) r14y(i) -r14x(i) 0];  

knowns=[m2*Acg2x(i)-Fe2x; (m2*(Acg2y(i)+g))-Fe2y; Igz2*alpha2-re2x*Fe2y+re2y*Fe2x-Me2;  
        m3*Acg3x(i)-Fe3x; (m3*(Acg3y(i)+g))-Fe3y; Igz3*alpha3(i)-re3x*Fe3y+re3y*Fe3x-Me3;  
        m4*Acg4x(i)-Fe4x; (m4*(Acg4y(i)+g))-Fe4y; Igz4*alpha4(i)-re4x*Fe4y+re4y*Fe4x-Me4];  

unknowns=inv(unmat)*knowns;  
if i==7  
    unmat7=[-1 0 1 0 0 0 0 0;  
     0 -1 0 1 0 0 0 0 0;  
     -r12y(7) r12x(7) -r32y(7) r32x(7) 0 0 0 1;  
     0 0 -1 0 1 0 0 0 0;  
     0 0 -r23y(7) r23x(7) r43y(7) -r43x(7) 0 0 0;  
     0 0 0 0 -1 0 1 0 0;  
     0 0 0 0 0 -1 0 1 0;  
     0 0 0 0 r34y(7) -r34x(7) r14y(7) -r14x(7) 0];  
    knowns7=[m2*Acg2x(7)-Fe2x; (m2*(Acg2y(7)+g))-Fe2y; Igz2*alpha2-re2x*Fe2y+re2y*Fe2x-Me2;  
             m3*Acg3x(7)-Fe3x; (m3*(Acg3y(7)+g))-Fe3y; Igz3*alpha3(7)-re3x*Fe3y+re3y*Fe3x-Me3;  
             m4*Acg4x(7)-Fe4x; (m4*(Acg4y(7)+g))-Fe4y; Igz4*alpha4(7)-re4x*Fe4y+re4y*Fe4x-Me4];  
    unknowns7=inv(unmat7)*knowns7
f21xcheck=unknowns7(1);
f21ycheck=unknowns7(2);
f32xcheck=unknowns7(3);
f32ycheck=unknowns7(4);
f43xcheck=unknowns7(5);
f43ycheck=unknowns7(6);
f14xcheck=unknowns7(7);
f14ycheck=unknowns7(8);
tau2check=unknowns7(9);

Fsxcheck=f21xcheck+(-f14xcheck)
Fsycheck=f21ycheck+(-f14ycheck)
Fscheck=[Fsxcheck;Fsycheck]

Mscheck=(-tau2check)+(r21x*f21ycheck)+(r21y*f21xcheck)+(r41x*(-f14ycheck))+(r41y*(-f14xcheck))
end

------------------------------
f21x(i)=unknowns(1);
f21y(i)=unknowns(2);
f32x(i)=unknowns(3);
f32y(i)=unknowns(4);
f43x(i)=unknowns(5);
f43y(i)=unknowns(6);
f14x(i)=unknowns(7);
f14y(i)=unknowns(8);
tau2(i)=unknowns(9);

Fsx(i)=f21x(i)+(-f14x(i));
Fsy(i)=f21y(i)+(-f14y(i));
Fs=[Fsx(i);Fsy(i)];

Ms(i)=(-tau2(i))+(r21x*f21y(i))+(r21y*f21x(i))+(r41x*-f14y(i))+(r41y*-

tau2avg=sum(tau2)/31; % Divided by N
tau2sq(i)=tau2(i)*tau2(i);
tau2sumsq=sum(tau2sq);
tau2rms=sqrt(tau2sumsq/31); % Divide by N

% slider Crank analysis
%------------------------------------------
% velocity and acceleration from position analysis
ar=r5*sin(th5(i));
br=1;
dr=-r5*cos(th5(i));
er=0;
%-------------------------
% Velocity Analysis
cr=-rp*omega4(i)*sin(thp(i));
fr=rp*omega4(i)*cos(thp(i));
%------------------------------------------
% Matrix Solver for Acceleration and Velocity
Ar=[ar br; dr er];
Br=[cr;fr];
%-------------------------
% Velocity Analysis
Xr=inv(Ar)*Br;
omega5(i)=Xr(1);
xdot5(i)=Xr(2);

% Accleration Analysis
r5*omega5(i)*omega5(i)*cos(th5(i));
fpr=rp*alpha4(i)*cos(thp(i))-rp*omega4(i)*omega4(i)*sin(thp(i))- r5*omega5(i)*omega5(i)*cos(th5(i));
Cr=[cpr;fpr];
Yr=inv(Ar)*Cr;
alpha5(i)=Yr(1);
x2dot5(i)=Yr(2);

% Acceleration of point CG5
ac5x(i)=-rp*alpha4(i)*sin(thp(i))- rp*omega4(i)*omega4(i)*cos(thp(i))-0.5*r5*alpha5(i)*sin(th5(i))-0.5*r5*omega5(i)*omega5(i)*cos(th5(i));
ac5y(i)= rp*alpha4(i)*cos(thp(i))-rp*omega4(i)*omega4(i)*sin(thp(i))+0.5*r5*alpha5(i)*cos(th5(i))-0.5*r5*omega5(i)*omega5(i)*sin(th5(i));
Acg5x(i)=ac5x(i);
Acg5y(i)=ac5y(i);

% Acceleration of point CG6
ac6y(i)=rp*alpha4(i)*cos(thp(i))- rp*omega4(i)*omega4(i)*sin(thp(i))+r5*alpha5(i)*cos(th5(i))-r5*omega5(i)*omega5(i)*sin(th5(i));
Acg6y(i)=ac6y(i);
Acg6x(i)=0;

% Acceleration of point CGp
acpx(i)=-0.5*rp*alpha4(i)*sin(thp(i))-
0.5*rp*omega4(i)*omega4(i)*cos(thp(i));
acpy(i)= 0.5*rp*alpha4(i)*cos(thp(i))-
0.5*rp*omega4(i)*omega4(i)*sin(thp(i));
Acgpx(i)=acpx(i);
Acgpy(i)=acpy(i);

% Inverse Dynamics

mu=0.2; % assumed friction coefficient
r1px(i)=rp*cos(thp(i))+r5*cos(th5(i));
r1py(i)=r2*sin(th2(i))+r3*sin(th3(i));
r1p(i)=sqrt((r1px(i)*r1px(i))+(r1py(i)*r1py(i)));
th1p(i)=atan2(r1py(i),r1px(i));
r1px(i)=-0.5*r1p(i)*cos(th1p(i));
r1py(i)=-0.5*r1p(i)*sin(th1p(i));
r1px(i)=-0.5*rp*cos(thp(i));
r1py(i)=-0.5*rp*sin(thp(i));
r5px(i)=0.5*rp*cos(thp(i));
r5py(i)=0.5*rp*sin(thp(i));

rp5x(i)=-0.5*r5*cos(th5(i));
rp5y(i)=-0.5*r5*sin(th5(i));

r65x(i)=0.5*r5*cos(th5(i));
r65y(i)=0.5*r5*sin(th5(i));

r61x(i)=0.5*r1p(i)*cos(th1p(i));
r61y(i)=0.5*r1p(i)*sin(th1p(i));

repx=0;
repy=0;
re5x=0;
re5y=0;
re6x=0;
re6y=0;

Fepx=0;
Fepy=0;
Fe5x=0;
Fe5y=0;
Fe6x=-1;
Fe6y=0;

Mep=0;
Me5=0;
Me6=0;

frr(i)=-1*sign(xdot5(i))*mu; % makes sure that the frictional force is applied in the correct direction

%unknowns=[f21x;f21y;f32x;f32y;f43x;f43y;f14y;tau2];

unmat=[-1 0 1 0 0 0 0 0;
       0 -1 0 1 0 0 0 0;
       rlpy(i) -rlpx(i) -r5py(i) r5px(i) 0 0 0 1;
       0 0 -1 0 1 0 0 0;
       0 0 0 -1 0 1 0 0;
       0 0 rp5y(i) -rp5x(i) -r65y(i) r65x(i) 0 0;
       0 0 0 0 -1 0 0 1 frr(i) 0;
       0 0 0 0 0 -1 1 0 0];

knowns=[mp*Acgpx(i)-Fepx;(mp*(Acgpy(i)+g))-Fepy;Igzp*alpha4(i)-
         repx*Fepy+repy*Fepx-Mep;
         m5*Acg5x(i)-Fe5x;(m5*(Acg5y(i)+g))-Fe5y;Igz5*alpha5(i)-
         re5x*Fe5y+re5y*Fe5x-Me5;
         m6*Acg6x(i)-Fe6x;(m6*(Acg6y(i)+g))-Fe6y];

unknowns=inv(unmat)*knowns;
fp1x(i)=unknowns(1);
f1y(i)=unknowns(2);
f5px(i)=unknowns(3);
f5py(i)=unknowns(4);
f65x(i)=unknowns(5);
f65y(i)=unknowns(6);
f6y(i)=unknowns(7);
tau(i)=unknowns(8);

f16x(i)=frr(i)*f16y(i);
f61x(i)=-f16x(i);
f61y(i)=-f16y(i);

Fsxr(i)=fp1x(i)+f61x(i);
Fsyr(i)=fp1y(i)+f61y(i);

Msr(i)=(-tau(i))+(rp1x(i)*fp1y(i))-(rp1y(i)*fp1x(i))+(r61x(i)*f61y(i))-
       (r61y(i)*f61x(i));

%--------------------------------------------------------------------------

% Figure 2
figure; % Figure 2
hold all
plot(th2/DR,Acg3x,'b');
plot(th2/DR,Acg3y,'*r');
grid;
xlabel('Theta2 (deg)');
ylabel('Acg3 (ft/s^2)');
legend('Acg3x (ft/s^2)', 'Acg3y (ft/s^2)');
hold off;
set(gca,'FontSize',16);
title('Four Bar Open Branch: Acg_3');
%---------------------------------------------------
figure; %Figure 3
hold all
plot(th2/DR,tau2,'b');
plot(th2/DR,tau2avg,'*r');
plot(th2/DR,tau2rms,'xg');
grid;
xlabel('Theta2 (deg)');
legend('tau2 (#ft)', 'tau2avg (#ft)', 'tau2rms (#ft)');
hold off;
set(gca,'FontSize',16);
title('Four Bar Open Branch: Tau_2');
%--------------------------------------------------------
figure; %Figure 4
hold all
plot(th2/DR,Fsx,'b');
plot(th2/DR,Fsy,'*r');
grid;
xlabel('Theta2 (deg)');
legend('Fsx (#)', 'Fsy (#)');
hold off;
set(gca,'FontSize',16);
title('Four Bar Open Branch: Fs');
%------------------------------------------------------
figure; %Figure 5
plot(th2/DR,Ms,'b');
grid;
xlabel('Theta2 (deg)');
ylabel('Ms(#ft)');
set(gca,'FontSize',16);
title('Four Bar Open Branch: Ms');
%-----------------------------------------------------
figure; %Figure 6
hold all
plot(th2/DR,th3/DR,'b');
plot(th2/DR,th4/DR,'*r');
plot(th2/DR,mu/DR,'xg');
grid;
xlabel('Theta2 (deg)');
ylabel('Theta (degrees)');
legend('Theta3', 'Theta4', 'mu');
hold off;
set(gca,'FontSize',16);
title('Four Bar Open Branch: Theta');
%------------------------------------------------------
figure; %Figure 7
hold all
plot(th2/DR,omega3,'b');
plot(th2/DR,omega4,'*r');
grid;
xlabel('Theta2 (deg)');
ylabel('omega (rad/s)');
legend('omega3', 'omega4');
hold off;
set(gca,'FontSize',16);
title('Four Bar Open Branch: omega');
figure; %Figure 8
hold all
plot(th2/DR, alpha3,'b');
plot(th2/DR, alpha4,'*r');
grid;
xlabel('Theta2 (deg)');
ylabel('alpha (rad/s^2)');
legend('alpha3','alpha4')
hold off;
set(gca,'FontSize',16);
title('Four Bar Open Branch: omega');

%__SliderCrank______________________________________________________________
figure;
subplot(211);
plot(thp/DR, th5/DR, 'r');
xlabel('Thetap(deg)');
ylabel('Theta5 (deg)');
grid;
sample(gca,'FontSize',18);
subplot(212);
plot(th2/DR, x,'g');
grid;
xlabel('Thetap (deg)');
ylabel('Position (ft)');
%----------------------------------------------------
figure;
subplot(211);
plot(thp/DR, xdot5, 'xr');
xlabel('Thetap(deg)');
ylabel('Xdot5 (ft/s)');
grid;
subplot(212);
plot(thp/DR, omega5,'g');
grid;
xlabel('Thetap (deg)');
ylabel('Omega 5 (ft)');
set(gca,'FontSize',18);
%------------------------------------------------------
figure;
sample(gca,'FontSize',18);
subplot(211);
plot(thp/DR, alpha5, 'r');
xlabel('Thetap (deg)');
ylabel('Alpha 5 (rad/s)');
grid;
subplot(212);
plot(thp/DR, x2dot5,'g');
grid;
xlabel('Thetap (deg)');
ylabel('Acceleration (ft/s)');
figure;
plot(thp/DR,Msr,'b');
grid;
xlabel('Thetap (deg)');
ylabel('Ms(ft#)');
set(gca,'FontSize',16);
title('Slider Crank: Ms');

figure;
hold all
plot(thp/DR,Fsxr,'b');
plot(thp/DR,Fsyr,'r');
grid;
xlabel('Thetap (deg)');
legend('Fsx (#)','Fsy (#)');
hold off;
set(gca,'FontSize',16);
title('Slider Crank: Fs');

figure;
hold all
plot(thp/DR,taup,'b');
plot(thp/DR,taupavg,'r');
plot(thp/DR,tauprms,'og');
legend('taup (ft#)','taupavg (ft#)','tauprms (ft#)');
grid;
xlabel('Thetap (deg)');
hold off;
set(gca,'FontSize',16);
title('Slider Crank: Tau_p');

figure;
hold all
plot(thp/DR,Acg5x,'b');
plot(thp/DR,Acg5y,'r');
grid;
xlabel('Thetap (deg)');
legend('Acg5x (#)','Acg3y (#)');
hold off;
set(gca,'FontSize',16);
title('Slider Crank: Acceleration Link 5 CG');
User Manual for Punch Press
A. Safety Precautions and Warnings

1. Due to sharp edges and burrs it is recommended that all users wear gloves to prevent injuries.
2. When operating the device
   a. Make sure that everyone is clear of the handle.
   b. Never operate the machine without the cover on.
   c. Make sure that both hands are on the padded handle when operating the device
   d. Keep fingers clear and away from the handle pinch point.

B. System Operating Instructions

1. Set-up Procedure
a. Remove the wooden dowel pin from the screen support beams.
b. With a helper one person hold the screen in place while the second person slides the dowel rod through the holes. This process can be seen below.

c. Feed the screen over top of the other dowel rod, around it then under the frame cross-member.
d. The screen will be pulled up to the rear cutting template.

2. Operating Procedure

a. Place the screen into the clips on the cutting template shown below.
b. Cut along the back side of the template so that the 5 ¾ inch section is cut. This process can be seen below.

Note: Make sure scissors follow along the board.

c. The 36” x 5 3/4” piece of aluminum screen can be placed on the guide table and slide into the cutters, which is shown below.
Note: Screen needs to be pushed to the guide line.

d. With the screen completely inserted actuate the cutters by pushing the handle downward until it stops, as seen below.

   ![Diagram showing the cutters being actuated](image1)

   ![Diagram showing the handle being returned](image2)

   e. Return the handle to starting position, and remove the screen and flip it over. This step can be seen below.
f. Repeat steps c. and d.
g. Remove and scrap excess aluminum and retrieve circles from the bin.

C. Trouble Shooting and Service Instructions

1. Trouble Shooting – Problems/Solutions

   a. More force is required to actuate the cutters.
      • Cutter could be dull/dirty (see section D.1.)
      • Linkage is binding (remove cover and inspect)
   b. Handle lever will not return to top of stroke.
      • Spring needs replaced (see section D. 3.).
   c. Handle moves but doesn’t cut screen.
      • The linkage could be disconnect (remove cover and inspect).
   d. Screen will not feed into the cutters.
      • Handle isn’t all the way up, spring could need replacing.
      • Check for debris in cutters.
      • Burrs on screen section.
   e. Only some cutters are cutting out the screen.
      • Cutter needs replaced (see section D. 2.).
D. Servicing the device

1. Sharpening/Clean cutters
   a. Cut a 3” x 5 3/4” piece of 160 grit sandpaper. This piece will be sufficient for two cutters.
   b. Slide the sand paper into the cutter that seems to be dull or have build.

   i. Notes:
      1. Recommended to sharpen all cutters at once.
      2. Removing the protective cover will make this process easier (operation can be seen below in the first part of “Replacing cutters” section).

2. Replacing a cutter
   a. Using a 9/16 inch socket remove the four bolts that are holding the safety cover on. This can be seen in the picture below.

   b. Removing the cover requires two people. With a person standing at each end the cover should be lifted straight up.
c. Remove the cotter pin from the top linkage where it connects to the side plate. The process can be seen below.

Notes: Bend each tail straight of the cotter pin to remove


d. Pull out the linkage pin and lay the linkage down toward the back of the machine.
e. Repeat steps c. and d. for the other side of the device.
f. Remove the actuating bar by lifting it straight up through the grooves.

g. Grab the cutter that needs to be replaced and lift straight upward as seen below.
Note: Cutters are held on by pins so no tooling needed

h. Use replacement part suggested below in section E.
i. Reassemble in reverse.

3. Replacing lever spring.
   a. Using a 9/16 inch socket remove the four bolts that are holding the safety cover on. This can be seen in the picture below.

   b. Removing the cover requires two people. With a person standing at each end the cover should be lifted straight up.

   c. While lifting the handle lever up as high as it will go lift the spring over the bolt that it is resting on. This can be seen below.
d. Repeat for other side.

e. Use replacement part suggested below in section E.

f. Reassemble in reverse.

**E. Replacement parts**

4. Parts list and sizes

<table>
<thead>
<tr>
<th>Replacement part</th>
<th>Size</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>Cutters</td>
<td>2.5&quot; dia</td>
</tr>
<tr>
<td>Safety cover bolt</td>
<td>1/4&quot;- 20 x 1&quot;</td>
</tr>
<tr>
<td>Linkage pins</td>
<td>5/8&quot; x 1&quot;</td>
</tr>
<tr>
<td>Linkage pins</td>
<td>5/8&quot; x 3&quot;</td>
</tr>
<tr>
<td>Cotter pins</td>
<td>1/8&quot; x 1&quot;</td>
</tr>
<tr>
<td>Spring</td>
<td>unknown</td>
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<tr>
<td>Wooden dowel rod</td>
<td>1/2&quot; x 4'</td>
</tr>
</tbody>
</table>

All the parts above include parts that can be purchased for replacement. All other parts will have to be manufactured by a machine shop.
F. Parts List

Figure 1: Fully Assembled Punch Press
Figure 2: Assembled Frame

Table 1: Part Description and Corresponding Number

<table>
<thead>
<tr>
<th>Number</th>
<th>Part Title</th>
<th>Sub-Assembly</th>
<th>Quantity</th>
<th>Item Number (BOM)</th>
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<tbody>
<tr>
<td>F1</td>
<td>Box_Beam_1</td>
<td>Frame</td>
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<td>1</td>
</tr>
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<td>Box_Beam_2</td>
<td>Frame</td>
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<td>1</td>
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<td>Box_Beam_3</td>
<td>Frame</td>
<td>8</td>
<td>1</td>
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<td>Frame</td>
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<td>1</td>
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<td>Feed Beam 1</td>
<td>Frame</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>F6</td>
<td>Feed Beam 2</td>
<td>Frame</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>F7</td>
<td>Mounting Plate</td>
<td>Frame</td>
<td>2</td>
<td>3</td>
</tr>
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<td>F8</td>
<td>Craft Punch Angle</td>
<td>Frame</td>
<td>1</td>
<td>2</td>
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<td>Sub-Assembly</td>
<td>Description</td>
<td>Corresponding Part Numbers</td>
<td>Item Number (BOM)</td>
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<td>Box Beam Parts</td>
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<tr>
<td>Frame</td>
<td>Additional Steel Parts</td>
<td>F7 – F9</td>
<td>2,3</td>
<td></td>
</tr>
<tr>
<td>Frame</td>
<td>Wooden Dowel Rods</td>
<td>F10</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>Frame</td>
<td>Plastic Cutting Guide</td>
<td>G1 – G3</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>Punch System</td>
<td>Craft Punch and Plastic Guide</td>
<td>P1, P2</td>
<td>6,7</td>
<td></td>
</tr>
<tr>
<td>Linkage</td>
<td>Pins/Rods</td>
<td>L3 – L5, L8</td>
<td>8,10,11</td>
<td></td>
</tr>
<tr>
<td>Linkage</td>
<td>Links</td>
<td>L6 – L9</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Linkage</td>
<td>Punch Actuator</td>
<td>L1, L2</td>
<td>12,13</td>
<td></td>
</tr>
<tr>
<td>Safety Cover</td>
<td>PVC Panel Parts</td>
<td>C1 – C7</td>
<td>6</td>
<td></td>
</tr>
</tbody>
</table>
Figure 3: Punch System Assembly

Figure 4: Linkage Assembly
### Table 3: Linkage Parts List with Corresponding Number

<table>
<thead>
<tr>
<th>Number</th>
<th>Part Title</th>
<th>Sub-Assembly</th>
<th>Quantity</th>
<th>Item Number (BOM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>L1</td>
<td>Steel Bar Actuator</td>
<td>Linkage</td>
<td>1</td>
<td>13</td>
</tr>
<tr>
<td>L2</td>
<td>Steel Tube Actuator</td>
<td>Linkage</td>
<td>1</td>
<td>12</td>
</tr>
<tr>
<td>L3</td>
<td>Brass Pin</td>
<td>Linkage</td>
<td>2</td>
<td>11</td>
</tr>
<tr>
<td>L4</td>
<td>Pin_2</td>
<td>Linkage</td>
<td>6</td>
<td>10</td>
</tr>
<tr>
<td>L5</td>
<td>Lever Pin</td>
<td>Linkage</td>
<td>2</td>
<td>10</td>
</tr>
<tr>
<td>L6</td>
<td>Top Linkage</td>
<td>Linkage</td>
<td>2</td>
<td>9</td>
</tr>
<tr>
<td>L7</td>
<td>Contact Linkage</td>
<td>Linkage</td>
<td>2</td>
<td>9</td>
</tr>
<tr>
<td>L8</td>
<td>Linkage Arm 2</td>
<td>Linkage</td>
<td>2</td>
<td>9</td>
</tr>
<tr>
<td>L9</td>
<td>Lever Arm</td>
<td>Linkage</td>
<td>2</td>
<td>9</td>
</tr>
<tr>
<td>L10</td>
<td>Rod</td>
<td>Linkage</td>
<td>1</td>
<td>8</td>
</tr>
</tbody>
</table>

![Figure 4: Safety Cover Assembly](image)

Figure 4: Safety Cover Assembly
Table 4: Cover Parts List with Corresponding Number

<table>
<thead>
<tr>
<th>Number</th>
<th>Part Title</th>
<th>Sub-Assembly</th>
<th>Quantity</th>
<th>Item Number (BOM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1</td>
<td>Cover Top</td>
<td>Cover</td>
<td>1</td>
<td>6</td>
</tr>
<tr>
<td>C2</td>
<td>Punch Shield</td>
<td>Cover</td>
<td>1</td>
<td>6</td>
</tr>
<tr>
<td>C3</td>
<td>Cover Back</td>
<td>Cover</td>
<td>1</td>
<td>6</td>
</tr>
<tr>
<td>C4</td>
<td>Cover Side Left</td>
<td>Cover</td>
<td>1</td>
<td>6</td>
</tr>
<tr>
<td>C5</td>
<td>Cover Side Right</td>
<td>Cover</td>
<td>1</td>
<td>6</td>
</tr>
<tr>
<td>C6</td>
<td>Cover Front Right</td>
<td>Cover</td>
<td>1</td>
<td>6</td>
</tr>
<tr>
<td>C7</td>
<td>Cover Front Left</td>
<td>Cover</td>
<td>1</td>
<td>6</td>
</tr>
</tbody>
</table>

PVC Template to minimize material cost
Drawing Package
Note: Purchased from Yale Steel
Part dimensions are 1.5"x1.5"x.12"
Note: Purchased from Yale Steel
Part dimensions are 1.5"x1.5"x.12"
Note: Purchased from Yale Steel  
Part dimensions are 1.5"x1.5"x.12"
Note: purchased from Yale Steel, part dimensions are 1.5"x1.5"x.12" steel tube
Note: Purchased from Yale Steel
Part dimensions are 1.5"x1.5"x.12"
steel tube
Note: Purchased from Yale Steel
Part dimensions are 1.5"x1.5"x.12" steel tube
Note: Purchased from Yale Steel
Part dimensions are 12"x8"x.5" steel plate
Note: Purchased from McMaster Carr
.5" Lexan (polycarbonate) plate
Note: Purchased from Yale Steel
Part dimensions are 1.25"x1.25"x.125" angle iron
Note: Purchased from Yale Steel
Part dimensions are 1.25"x1.25"x.125"
angle iron
Note: Purchased from McMaster Carr
.5" Lexan (polycarbonate) plate
Note: Purchased from McMaster Carr

.5" Lexan (polycarbonate) plate
Note: Purchased from McMaster Carr
.5" Lexan (polycarbonate) plate
Note: Purchased from McMaster Carr
.5" Lexan (polycarbonate) plate
Note: Purchased from Yale Steel
Part dimension is .625"
steel rod
Note: Purchased from Yale Steel
Part dimensions are 1.5"x.5"
steel bar
Note: Purchased from Yale Steel
Part dimensions are 1.5"x.5" steel bar
Note: Purchased from Yale Steel
Part dimensions are 1.5"x.5" steel bar

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Heat Treat | Material
-----------|--------
|          |

SOLID EDGE ACADEMIC COPY
Note: Purchased from Yale Steel
Part dimensions are 1.5"x.5" steel bar
Note: Purchased from McMaster Carr
Part dimensions are 3"x1" steel round
Note: Purchased from McMaster Carr
Pin meant for .625" hole
Note: Purchased from Yale Steel
Part dimensions are 2"x.1875"
Note: Purchased from Yale Steel
Part dimensions are 1.25"x1.25"x.125"
Note: Purchased from McMaster Carr
.5" Lexan (polycarbonate) plate
Note: Purchased from McMaster Carr .5" Lexan (polycarbonate) plate
Note: Purchased from McMaster Carr
.5" Lexan (polycarbonate) plate

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Athens, Ohio 45701

Heat Treat: Material

Drawn: Checked: Approved:

Scale: Weight: Sheet 1
Note: Purchased from McMaster Carr
.5" Lexan (polycarbonate) plate

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ASME Y14.5M Apply
Surface Finish

UNLESS OTHERWISE SPECIFIED

DIMENSIONS ARE IN MILLIMETERS
ANGLES ±X.X°
2 PL ±X.XX 3 PL ±X.XXX

Heat Treat Material

SOLID EDGE ACADEMIC COPY
Note: Purchased from McMaster Carr
.5" Lexan (polycarbonate) plate
Note: Purchased from McMaster Carr
.5" Lexan (polycarbonate) plate
Note: Purchased from McMaster Carr
.5" Lexan (polycarbonate) plate