Specialty Work Piece Holding

Detailed Design Report

Department of Mechanical Engineering

- MECH 4860 - Engineering Design -

Group 7

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Submitted: December 9, 2020

Executive Summary

Decor Cabinets has asked for a design proposal comprehensively outlining a solution to the hazards posed to their specialty department table saw operators. Small components with awkward aspect ratios are dangerous to operate with the exposed circular saw located on a table saw. This safety concern has been realized by Decor Cabinets in the specialty department where table saws are used due to their functionality and accurate results. The objective of this design project is to increase operator safety while reducing the impact of lost time in the specialty department by transitioning problematic parts away from the table saw to the CNC mill before December 9$^{\text{th}}$ of 2020.

For this transition to be successful the design must increase operator safety, meet the current processing times, be compatible with multiple materials, safely affix the part during operation, protect the tooling, and minimize costs with a total budget of $3,000. The team worked with Decor to generate a comprehensive list of metrics capable of governing the success of the design project.

Brainstorming and research methods were used to develop conceptual ideas. This stage of the project was completed using Microsoft teams to allow for safe communication of idea's through sketches, CAD models, and supporting images. Our team developed concepts that contained many idea's capable of solving the problem faced by Decor Cabinets. This list was then reduced to the top 5 concepts by evaluating their respective strengths and weaknesses.

The final step in choosing a design concept to enter the detailed design phase is the selection process. Like a chain, the selection process is only as strong as the weakest link. The process used selected decision criteria by methodically evaluating key customer needs, using a non-biased approach to identify relationships between the criteria that dictate the weight assigned to each metric, ranking each design concept against each metric, and summarizing the results in a weighted decision matrix. This process resulted in the selection of the Combination concept for the detailed design phase.

The fixture concept selected was developed by first calculating the cutting forces generated by the tooling used to manufacture the parts. The worst case cutting loads were determined to be 8.38 $[lbf]$. This value was then evaluated in comparison to the vertical and horizontal work holding forces of 535 $[lbf]$ and 324 $[lbf]$ respectively, resulting in confidence of the ability for the fixture to hold the parts in place during operation. The fixture support system was then analyzed to ensure that the calculated value of 0.003 [in] did not exceed the maximum allowable vertical deflection of 1/32 [in]. Various manufacturing considerations were implemented to allow for Decor cabinets to manufacture this product in house.

At this point in the design it was important to validate that the detailed design of the fixture did not detract from the original objective of this project. Some final feasibility studies were conducted regarding the objectives surrounding processing time, cost, and failure modes. The final design concept has a substantial gain in processing efficiency (74%) yielding a reduction of 2.76 hours for cutting 120 pieces in a peak production day, and is well under budget at a total material cost of $343.00. All of the risks associated with the potential failure modes were deemed acceptable, not requiring further action at this point. The positive results of the feasibility studies in this section objectively determine that the design project was successful.

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1 Introduction

Decor Cabinets has connected with the University of Manitoba Innovative Design for Engineering Application Program (IDEA) to involve students in the process of developing a solution to one of their industry problems. This project aims to provide students with an opportunity to work alongside professionals, learning how to relate the technical skills developed academically within industry projects. A successful project also yields an engineered solution to the problems faced by Decor. The problem statement, objectives, customer needs, and target specifications as they relate to this project are discussed in sections 1.1 through 1.4. Section 2, Concept Generation reviews the conceptual ideas developed to solve the problem. Section 3 explains the process used to decide which concept is selected for the detailed design phase of the project. Section 5 details the design phase of the final concept including the analysis and verification procedures implemented to verify that the design is capable.

1.1 Problem Statement

Decor Cabinets' has a variety of departments that work together to create products that can be used throughout a house hold; from kitchen, to office spaces, to bedrooms, and so on. All their products are made in house and require a great amount of manual labor. For this project in particular, the team will be focused on a process in their specialty department. The specialty department is responsible for making small batch components for custom cabinet projects. Table saws have been their main method for cutting materials as they are quick to set up and simple to operate. For this reason, they are a good fit for the specialty department. This functionality has made the table saw an industry-standard in wood-shops. However, table saws are a leading contributor to workplace accidents and safety-related lost time incidents [1]. The daily operation of this equipment puts operators at risk. Decor would like to reduce this risk by transitioning parts away from the table saw.

Decor Cabinets is looking at the opportunity to improve operator safety through automation. Processes currently using a table saw to cut long narrow pieces, as seen in appendix A, amplify the risk of injury to operators manufacturing these parts. Decor currently owns a 5-axis CNC mill (computer numerical control) shown in Figure 1 below.

Figure 1: Homag Centateq P-110[2]

Decor would like to use this machine to cut the parts detailed in appendix A in place of the table saw. The automated CNC mill currently utilizes a vacuum-powered pod and rail system for work-holding that is not capable of holding narrow pieces. Decor carries two different pod sizes approximately 4"x6" and

4”x2”. Both are too large for the specified target items less than 2 inches wide. Figure 2 provides a detailed visual of the current HOMAG machine on site.

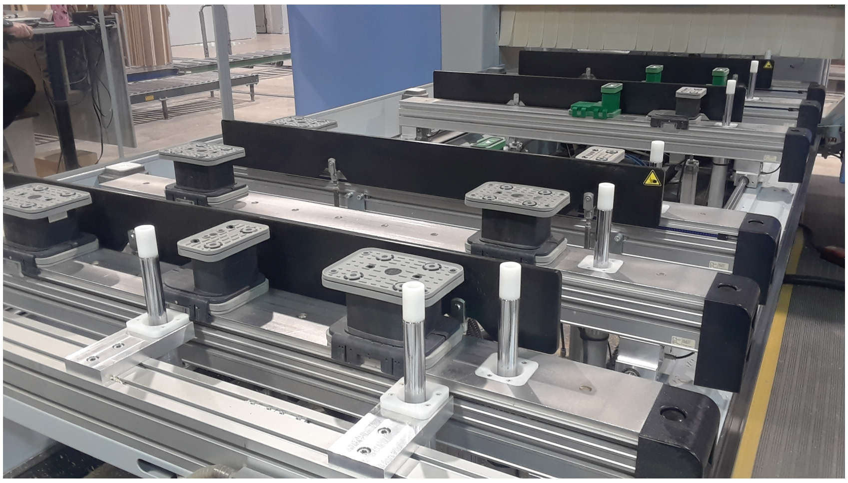


Figure 2: Pod and Rail Work-holding System [3]

1.2 Project Objectives

The objective of this design project is to design a solution capable of increasing operator safety while reducing the impact of lost time in the specialty department by transitioning problematic parts away from the table saw to the CNC mill by December 9^{th} of 2020. Along with identifying the direction of the project, the client identified the following list of requirements:

- Maximize operator safety
- Meet size specifications of technical drawings
- Meet cut quality standards (smooth, no chip out or surface damage)
- Match processing time of table saw
- Maximize material compatibility
- Mitigate damage to tooling

This list of customer needs will serve as a baseline of what to expect from the project solution. This allowed the team to outline specific metrics to objectively evaluate and rank the ability of each of the generated concepts' ability to meet the formal objective of this project.

1.3 Constraints and Limitations

Project constraints are restrictions identified as rigid by the client. They cannot be modified to accommodate solutions to the problem due to external factors that lie outside of the scope of this project. Limitations are economic restrictions imposed on the project. They are in place to reduce capital expenditure and operating expenses incurred by manufacturing these parts wherever possible. The constraints and limitations will provide baseline requirements influencing the team's design for the solution. Any concept generated must meet the quality specifications identified by the client. Design choices and the concept generation phase depends on balancing the conflicting relationships that exist between the constraints and limitations for the project, summarized in Table I below.

TABLE I: *CONSTRAINTS AND LIMITATIONS*

Constraints		
Reference Number	**Constraint**	**Description**
C1	Budget	The project currently does not have a specific budget, but it was identified that a range of up to $3000 is acceptable. If the project is to exceed the budget, a thorough cost analysis can be conducted to determine and justify the payback period.
C2	Project Time	The deadline of the project must be completed by December 9th, 2020. The project is divided into four phases with specific deliverables throughout. Details are in the project schedule section.
C3	Existing Machine	The design will be limited to the current machine and its capabilities. The CNC machine being used currently is the Homag Centateq P-110.
Limitations		
Reference Number	**Limitations**	**Description**
L1	Safety	The project must continue to comply with Decor's safety standards as they are Made Safe Certified. See ** below
L2	Quality	The project must maintain the quality standard set by the previous method (table saw).

** : Made Safe is an initiative by CME Manitoba (Canadian Manufacturers and Exporters) that provides services regarding health and safety in the manufacturing environment. They make things easier for employers and workers to have a safe workplace while maintaining productivity. [4]

1.4 Target Specifications

Metrics determined at the onset of a project communicate the parameters surrounding success in an objective format that remains unchanged. This way, the design process can focus on customer needs with a clear understanding of the decision criteria. The client has set out a number of their customer needs in the form of specifications for this project, from the equipment used to the qualitative factors used in their process. These specifications are outlined as follows in Table II below, where a value of 3 indicates the highest importance, and 1 indicates the lowest. Identifying these specifications is important when determining which concept excels in which area. The specifications will be used in the concept selection process outlined in Section 3.

TABLE II: *TARGET SPECIFICATIONS*

Customer Need	Measure	Target	Unit	Importance
Operator Safety	Workplace Injuries	Injury free	Injuries per year	3
Production Capacity	Elapsed processing time	Equivalent or reduced from current table saw times	Seconds	2
Quality	Rejection rate	Meets current capability of the table saw to hit specified tolerances	Dimensions	3
Interchangeable Feed Materials	Amount of materials which the fixture is compatible with	The target is for the fixture to be primarily compatible with maple and melamine	Number of Materials	3
Ergonomics	Operator Feel and comfort level	Operators are comfortable and confident using the fixture	Qualitative	3
Cutting Loads	Forces created by the cutting action of the tool	Loads exerted on the material should be directed in a fashion that complements the quality of the cut	Newton (N)	2
Tool-life	Cost per part produced	Most economic tool will be chosen based on cost per part	\$CDN/part	2
Part Protection	Quality parts otherwise damaged	Damage caused by handling parts is minimized	Parts per day	1
Tool Protection	Number of tools damaged in processing parts	Tools are not damaged by routing into fixture	Tools per month	1
Cost Reduction	Operating Expense	Reduce mfg. cost of the fixture to a maximum of \$3,000.00 CDN	\$CDN	2

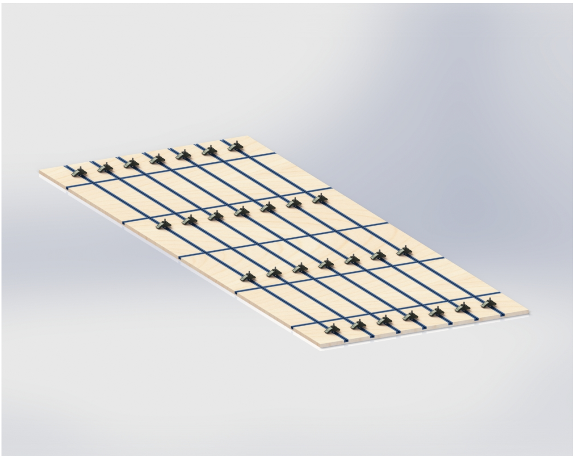
2 Concept Generation

The following section highlights concepts that were generated by our team. Each subsection contains one concept idea that will give a brief high-level description of the operating principle along with the expected benefits and challenges. Brainstorming generated preliminary design concepts by focusing on the direction, specifications, constraints, and limitations. All ideas that were not feasible were quickly eliminated without the need to invest further or create a decision matrix. Additionally, all ideas that were similar were grouped together. The top five concepts were selected from this list, placing a priority on the quality of the design concept selected. Each concept is evaluated in Section 3 based on important criteria outlined by the client described in sections "1.1: Problem"" through "1.3 Constraints and Limitations".

Preliminary research familiarizes the team with the current technology used in the industry. When researching typical work holding methods, examples included: top clamping, edge clamping, vacuum clamping, vises, direct fastening, double sided tapes, and glue [5]. These methods would then be implemented in systems such as pod and rail machines, work tables, or T-slot systems which are present in the industry currently. Integrating the vacuum system from the pods into the fixture is frequently implemented for custom applications as the system currently exists in the machine. Other methods researched were evaluated to try and source efficient and repeatable alternative systems. All of the concepts found would need modification to suit the solution to our problem. The concepts generated have influence from the research but no product satisfies the objectives laid out. Additionally, after generating concepts, the team conducted a quick research on existing patents and found no complications.

2.1 T - Slot

The team wanted to develop one concept that placed a priority on simplifying the problem by eliminating complexity wherever possible in the fixture. The typical engineering theory used methods that are currently available on the market. Integrating countersunk aluminum T-slot extrusions into a large piece of organic material is an effective solution used in wood-working. Existing T-slot products in the market are capable of manufacturing a variety of specified parts due to its versatility; This is important because it allows the two specified by our client to be manufactured. Figure 3(a) below shows the bevel cut T-slot extrusions (coloured blue) integrated into a work-holding table that allows for placement of clamps on the T-Slot matrix. Figure 3(b) gives a closer look at the top clamps that would be used. Matrix spacing is optimized based on factors such as cutting loads, feed width, and manufacturing capacity for this design.



(a) Overview

(b) Detail

Figure 3: T-Slot Spoil Board Concept

Advantages:

- Several types of clamping methods available (end, toe, toggle, etc).
- Forward compatible allowing for design revisions to specified parts.
- Aluminum T-slot rails can be cut with tooling designed for wood.
- Simple and inexpensive to manufacture out/in-house.

Disadvantages:

- Reduction in operator efficiency due to increased setup requirements.
- Potential damage to tools if contact is made with the fixture clamps.
- Component is heavy and awkward to lift and place onto machine deck.
- Difficult to stabilize horizontal loads on the triangular part.

2.2 Vacuum

The potential need for specifying a stand-alone vacuum system left the team considering a design that expanded the capability of the existing pod and rail vacuum system. The current pod and rail system uses large pods that do not allow for tool clearance limiting the machine to making large components. Figure 4 shows the concept developed by our team that uses two laminated sections of organic material to "transfer" the suction from the factory vacuum system to the designed working-holding surface. The suction matrix will be optimized based on the feed dimensions and would allow for the non-utilized area to be disabling from the vacuum supply.

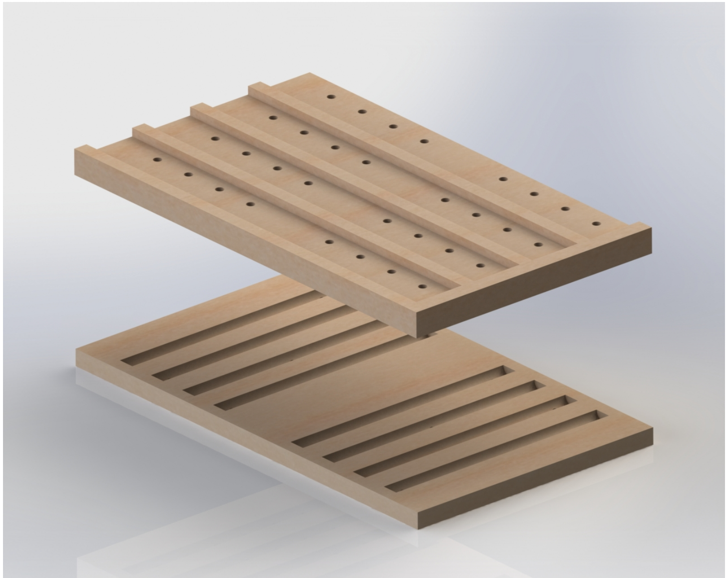


Figure 4: Routed Vacuum Fixture

Advantages:

- Chip-out prevented by uniformly supporting down cut surface.
- Organic material construction mitigates damage to tooling and machine.
- Cost reduced by utilizing the stock vacuum system.
- Inexpensive to manufacture.

Disadvantages:

- Fixture must be consistently loaded into machine to prevent premature failure.
- Accurately verifying vacuum requirements based on flow analysis of the internal flow network.
- Component is heavy and awkward to lift and place onto machine deck.

2.3 Vacuum T-Slot

The team wanted to maintain simplicity while addressing the challenges presented by the first T-Slot concept by altering the design to integrate both the countersunk T-slot extrusions and the routed vacuum system. Holes connect the routed channels to the stock vacuum system and a T-slot matrix to allow for variation in the clamping procedures. The concept combats the challenge of laterally stabilizing parts, by providing extra holding force along the length of the blank material. This also allows for forward compatibility on a vacuum-based design. Dimensions for the matrix and the vacuum system will be determined by factors such as cutting loads, feed width, and manufacturing capacity.

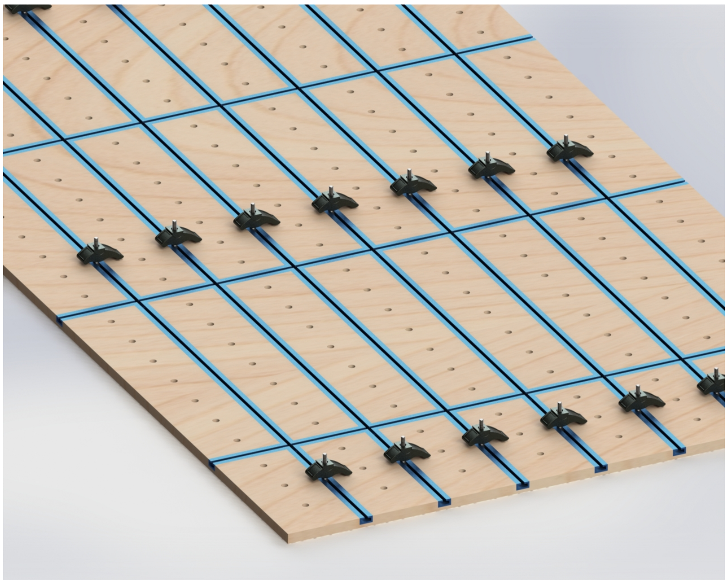


Figure 5: Vacuum T-Slot Table

Advantages:

- Several types of clamping methods available (end, toe, toggle, etc).
- Forward compatible allowing for design revisions to specified parts.
- Aluminum T-slot rails can be cut with tooling designed for wood.
- Vacuum applies primary work-holding force to stock material.

Disadvantages:

- Component is heavy and awkward to lift and place onto machine deck.
- Meshing pre-existing vacuum system increases complexity and cost.
- Fixture must be consistently loaded into machine to prevent premature failure.

2.4 Elevated Fingers

This concept focused on the economic aspect of the customer's needs. The advantage of this fixture is holding the component in space above the fixture plane. The fingers would be made out a soft metal so that the saw blade would not be damaged. The fingers would also be hollow to route to the existing vacuum system. The fingers are optimized to allow for off-cuts to fall into a safe recessed area, protecting them from binding with the saw or the tooling. The concept uses an array of clamps at the end of the fixture to hold the feed materials in place. This fixture trades adaptability in favor of processing efficiency. Figure 6 below shows the elevated work-holding surface as well as the justification blocks included in the bottom corner to help the operator locate the parts in the fixture.

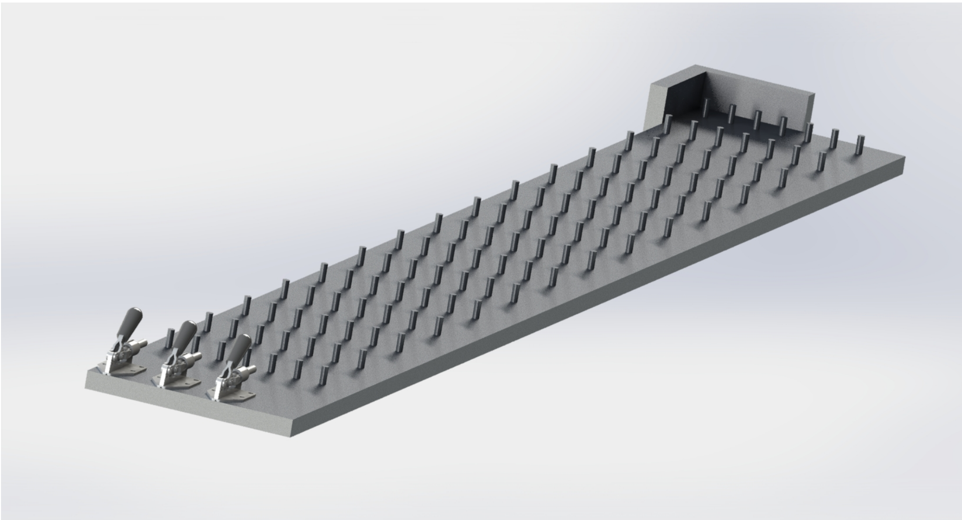


Figure 6: Elevated Finger Concept

Advantages:

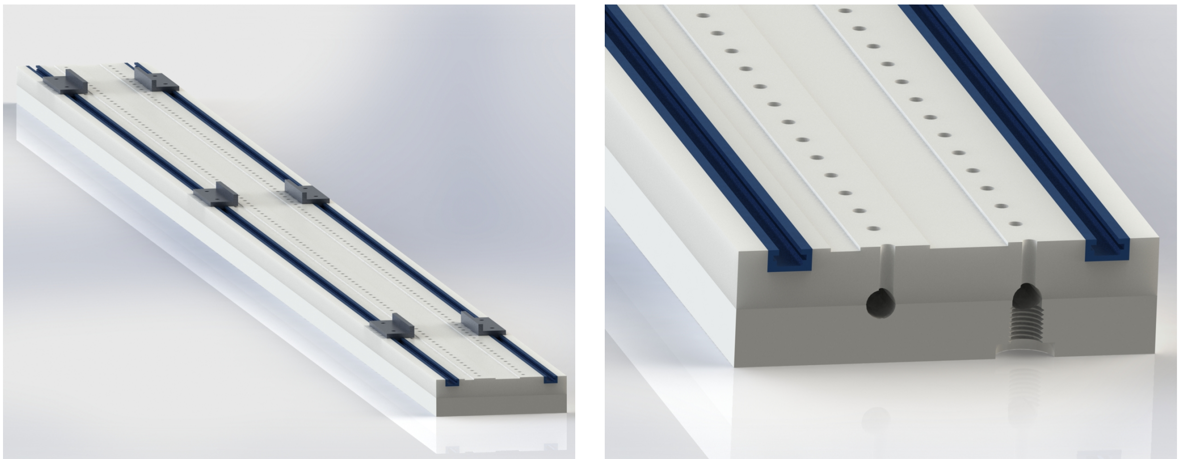
- Reduction in processing time through increased ergonomic efficiency.
- Clamp location mitigates damage to machine tooling.
- Tooling does not interfere with the fixture during normal operations.

Disadvantages:

- Poor lateral stabilization along the length of the blank material.
- Vacuum force susceptible to failure in presence of eccentric loads.
- Concern about the stability of the 'fingers' to hold material.

2.5 Combination

At this point in the concept generation phase, the previous concepts were presented to the client for feedback on the details in Sections 2.1 through 2.4. The feedback and information gained from the client resulted in revisiting the concept generation phase. This led the team to develop a design concept that incorporates key design elements from the previous concepts to meet all the customer needs. Attributes added include; Vacuum as the primary work-holding force, flush mount T-Slot rails are mounted with tool clearance to provide bump stops to make loading parts ergonomic and repeatable. One-piece raised section preventing the need for contact between the blade and the fixture in comparison to 'fingers'. Each side of the fixture holds one of the parts specified by the client. Figure 7(a) gives an overall look at the concept while 7(b) gives a detailed view. It shows the T-slots (coloured in blue) along with a cut view of the vacuum holes and channels.



(a) Overview (b) Detail

Figure 7: Combined Concept

Advantages:

- Reduction in processing time through increased ergonomic efficiency.
- Vacuum system configuration effectively stabilizes blank.
- Tooling does not interfere with the fixture during normal operations.
- Modular Vacuum system increases confidence in routing stock vacuum system.

Disadvantages:

- Awkward size to store safely when not in use.
- Vacuum system increasing points of failure for design.
- Increased manufacturing cost and complexity.

The designs from Sections 2.1 to 2.5 have been analyzed on a qualitative basis for advantages and disadvantages but will need to be decided via a selection process. This will be conducted in the next section of the report.

3 Concept Selection

The value in concept generation techniques allows the team to generate a variety of meaningful concepts. It stretches the team's creativity by relaxing the constraints placed on the project. The selection process is responsible for taking the list of concepts and selecting the best option before proceeding to the detailed design phase. The selection process is similar to a chain since a selection is only as strong as the weakest link. This section explains the system used for selecting a concept.

3.1 Criteria Selection

The objectives identified for this project are in the list below. This list was provided to the team by the client and inspired the team to determine metrics used to evaluate the design concepts. Focus is placed on the selection process on meeting customer needs by picking the design that meets the requirements of the problem statement.

- Operator safety
- Meet specifications
- Meet quality standards
- Processing time can match the current benchmark
- Compatible with a variety of materials (focused on maple and melamine)
- Mitigate damage caused by fixture on tooling and feed material
- Not exceed $3'000 CDN. to manufacture one unit

Table III below shows the metrics identified in the left column and the operational definition of these metrics in the right column. The correlation between the metrics and the project objectives is tight. The only requirement not explicitly stated in Table III is safety. From an engineering ethics perspective, our team feels that no matter which design is chosen, safety for the operators is a fundamental requirement of the solution. Safety is the focus of this project; moving from the table saw to the CNC is inherently a safer operating standard. The CNC process removes the hazards associated with operators directly interacting with dangerous tooling such as a table saw. A concept with a higher capability of producing parts to specification within allowable tolerances increases the safety of the operator.

TABLE III: *SELECTED EVALUATION CRITERIA*

Metrics Considered	Definition
Tolerance	The ability for the design to meet the tolerances specified in the part drawings to quality standards.
Materials	Ability to make parts from a variety of materials to the listed quality standards.
Ergonomics	Ease of use for the operator
Cycle Time	Time required for the operator to load individual components into the fixture.
Cost	Capital required to produce one unit of the design.
Tool Protection	The ability of the design to protect tooling from damage in the event that the fixture is accidentally routed.

3.2 Criteria Decision Matrix

The primary objective for using a decision matrix to evaluate the weight assigned to individual criteria is reducing bias in the decision process. The decisions in this table identify relationships that exist between two specific criteria and the impact of this relationship through a binary ranking system. This matrix reflects concept suitability for fulfilling the constraints of the project, and ultimately the success of the final design. For example, in cell A-B of Table IV (comparing Tolerance and Materials), "A" was selected because the fixture needs to be able to meet specified tolerances more than being able to make parts from a variety of materials. Note that this selection is also not to discredit the importance of designing a fixture to hold a variety of materials. Similarly, cell C-D was evaluated as "D", since a design with good Cycle Time ranking would inherently incorporate good Ergonomics.

TABLE IV: *CRITERIA WEIGHT DECISION MATRIX*

		A Tolerance	B Materials	C Ergonomics	D Cycle Time	E Cost	F Tool Protection
A	Tolerance		A	A	A	A	F
B	Materials			C	B	B	F
C	Ergonomics				D	C	C
D	Cycle Time					D	D
E	Cost						E
F	Tool Protection						
	Number of Hits	4	2	3	3	1	2
	Weight (%)	27%	13%	20%	20%	7%	13%

Table IV shows that the most important criteria used in evaluating the feasibility of a design is the ability to hit the specified tolerances to acceptable quality standards. It would not be feasible to assign this weight distribution to the various criteria with the same accuracy without performing this evaluation.

3.3 Criteria Based Ranking System

The last step in evaluating the design concepts is assigning values to each design concept based on their capability of satisfying each criterion. Our team decided to use a ranking system to reduce the bias created by the assignment of arbitrary specifications to the design concepts. This system identifies trends in the design principles to rank them in order from 1 (best) to 5 (worst). Ranking according to cycle time resulted in a three-way tie for first. Since all three designs use the same loading technique, the team saw no reason to set either of the three concepts above the rest. Before entering the Weighted Decision Matrix, metric categories were normalized, ensuring even distribution of weight under each criterion. The only bias created as a result of the tie was the diminished result of achieving the best design in this category due to the reduced total score assigned to the cycle time metric.

TABLE V: *RANKED CONCEPT RESULTS TEST*

	Metric Rank					
Concept	Tolerance	Materials	Ergonomics	Cycle Time	Cost	Tool Protection
T-Slot Spoil Board	5	5	5	5	2	4
Routed Vacuum T-Slot	2	1	4	3	4	3
Elevated Fingers	3	4	3	1	3	1
Routed Vacuum	4	3	1	1	1	5
Combination	1	2	2	1	5	2

3.4 Weighted Decision Matrix

The role of the Weighted Decision Matrix (WDM) is to tabulate the results from the decision criteria evaluated in sections 3.1 through 3.3 to identify the best concept. Equation 1 below normalizes the rank value to the category being evaluated. This equation is what allows for the same rank to be given to multiple concepts in the same category. Equation 2 sums the score for each design and the total associated with each concept is shown in the score column.

$$Normal_{Inv} = \left(\frac{Rank}{Total\ Assigned}\right)^{-1} \tag{1}$$

.

$$Score = \Sigma_1^n(Normal_{Inv,i} \times Weight_i) \tag{2}$$

Table VI below shows the normalized ranks for each concept based on the criteria category that it was assigned. These are the resulting values from equation 1. The score column on the far right of this table is the result of equation 2.

TABLE VI: *WEIGHTED DECISION MATRIX*

	CRITERIA						**SCORE**
Concept	**Tolerance**	Materials	Ergonomics	Cycle Time	Cost	Tool Protection	**Total**
T-Slot Spoil Board	3.0	3.0	3.0	2.2	7.5	3.8	3.2
Routed Vacuum T-Slot	7.5	15.0	3.8	3.7	3.8	5.0	6.4
Elevated Fingers	5.0	3.8	5.0	11.0	5.0	15.0	7.4
Routed Vacuum	3.8	5.0	15.0	11.0	15.0	3.0	8.3
Combination	15.0	7.5	7.5	11.0	3.0	7.5	9.9
Weight	27%	13%	20%	20%	7%	13%	100%

Given the results of the weighted decision matrix, the Combination concept scored the highest with a 9.9. This Combination concept will be chosen as the design to move forward within the project for further analysis and detailed design. Things to consider going forward are to address the challenges mentioned in Section 2. Including overall sizing and the specific dimensions, how to incorporate the existing vacuum system efficiently, and to potentially reduce any costs. These factors are also inherently present by just examining the score for each criterion in Table VI for the Combination concept.

3.5 House of Quality

The house of quality (HOQ) represents one component of the Quality function deployment. A product planning matrix was built to showcase identified customer needs, the importance of those needs, and the engineering characteristics relevant to these needs [6]. This matrix would correlate competing products or methods, comparing the overall standing of each product and concept. Unfortunately, there were not any products discovered on the market for this application. The team used the HOQ to provide a deeper understanding of the client's needs and how each concept met the target value. This method provides a robust understanding of the relationships between the evaluation criteria used.

In appendix D, customer requirements are ranked from 1-3, lowest to highest. The top section of the matrix correlates the requirements by identifying the relationship that exists between each combination.

The meaning associated with the symbols are as follows: "+" is a positive correlation, "-" is a negative correlation, and a blank space means there is no correlation between the compared requirements. The importance rating of the functional requirements is calculated by multiplying each importance rating by the customer needs and requirements. They are then converted into a percentage. In addition, the requirements and design concepts are ranked according to their success rate of achieving customer needs. All the concepts are evaluated base on the functional requirements at the lower section of the H.O.Q. matrix. According to the discussion with clients, all the target specifications are identified and listed at the bottom and evaluated base on the technical difficulty.

In appendix D, Tolerance, cycle time, and ease of use are ranked as the top three requirements and should be considered accordingly in the concept selection and detailed design of the fixture. Technical difficulty ranking shows that tolerance and cycle time are the most challenging obstacles during the detailed design. The concepts utilizing vacuum as the primary work-holding force show a better result on the tolerance, and T-slot clamps exhibit a longer cycle time. The variety of materials the design can handle depends on the cutting and work-holding forces. Improving the power of the vacuum pump could increase the work-holding force, but the cost is prohibitive.

4 Fixture Material Selection

The material used for the construction of the fixture will be selected independent of the other design components. Creating flexibility in the material choices for the detailed components allows material properties to be tailored to the function that is required. The material selected for each feature must contribute to the designs ability to meet the target specifications for the fixture laid out in Table II, Section 1.4.

4.1 Available Materials

When researching viable materials for the fixture, the team produced a list of criteria to get a rough idea of which materials would be preferable for our application:

- Young's Modulus
- Manufacturability
- Weight
- Cost

Based on a recommendation from the client, our team researched high-density plastics such as ABS, HDPE, and Nylon. The team did not want to limit our options to only plastics, so some other commonly used materials such as MDF, and Maple were added to the selection process. Decor focuses on manufacturing wood products in their facility allowing them to easily obtain and manufacture parts based on their production team's industry knowledge.

4.2 Material Decision Matrix

Material properties and characteristics are evaluated against the requirements for the fixture construction material according to the process explained in Section 3. The decision criteria used for the material selection process are listed and defined in Table VII below.

TABLE VII: *MATERIAL EVALUATION CRITERIA*

Metrics Considered	Definition
Young's Modulus	This is a material property describing a materials ability to resist strain in the elastic region.
Manufacturability	A qualitative factor associated with the ability to form materials into a desired shape.
Weight	Weight of the material selected should be minimized.
Cost	Capital required to source materials in the desired shape and quantity.

Table VIII shows the comparative importance of each decision criteria similar to how the analysis was done in Table VI. Each criterion is compared against one another, with the criteria of higher importance winning that category. For example when A: Young's Modulus and B: Manufacturability are compared against each other, the team determined that Young's Modulus is more important; therefore, an "A" is placed in that position. This criteria weighted decision matrix allows us to evaluate each criterion appropriately when determining the ideal material.

TABLE VIII: *MATERIAL WEIGHT DECISION MATRIX*

		A	B	C	D
		Young's Modulus	**Manufacturability**	**Weight**	**Cost**
A	**Young's Modulus**		A	D	D
B	**Manufacturability**			C	B
C	**Weight**				C
	Number of Hits	1	1	2	2
	Weight (%)	17%	17%	33%	33%

A qualitative rank was assigned to the Manufacturability of the materials, and quantitative metrics were assigned to Young's Modulus, Weight, and Cost categories. Rank values determined for each material are categorically sorted according to Table IX below.

TABLE IX: *CATEGORICAL MATERIAL RANK*

	Youngs Modulus (Msi)	**Manufacturability**	**Weight (lb/ft^3)**	**Cost (\$/bdft.)**	**Legend**	
MDF	508	10	40.6	\$ 2.65	**Best**	10
Maple	551	8	30.6	\$ 12.95	**Mediocre**	5
ABS	326	6	78.0	\$ 78.79	**Worst**	1
HDP	116	4	59.3	\$ 26.76		
Nylon	435	6	69.6	\$ 100.96		

Similar to the ranks assigned to the concept selection matrix, the cost and weight categories had normal values calculated according to Equation 1 from Section 3. Since the other ranked categories place value on maximizing the values, Equation 3 shows how directly correlated ranks are normalized to their respective categories. The score column is calculated according to Equation 2. Table X below shows the results of the material selection process. MDF overwhelmingly had the highest score, making it the ideal material for the construction of the fixture frame.

$$Normal_{Dir} = \left(\frac{Rank}{Total\ Assigned}\right) \times 10 \tag{3}$$

TABLE X: *MATERIAL DECISION MATRIX*

	CRITERIA				**SCORE**
Material	**Youngs Modulus**	**Manufacturability**	**Weight**	**Cost**	**Total**
MDF	3.4	3.6	1.9	45.7	17.06
Maple	3.7	2.9	1.5	9.4	4.70
ABS	2.2	2.1	3.7	1.5	2.48
HD Polyethylene	0.8	1.4	2.8	4.5	2.82
Nylon	2.9	2.1	3.3	1.2	2.35
Weight	17%	17%	33%	33%	100%

5 Detailed Design

The following section transfers theoretical models into real design characteristics. Several aspects of the design were defined based on the analytical models allowing for confidence in their capability. A variety of parameters and constraints were considered throughout the process, ensuring that quality standards and operator ergonomics complimented the overall performance of the final design. A rendered representation of the final design is shown in Figure 8.

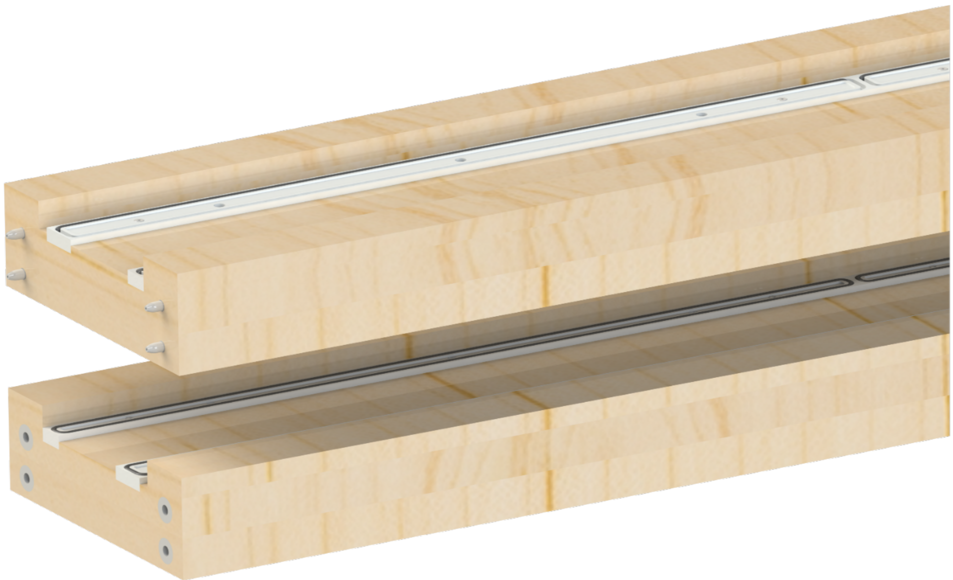


Figure 8: Final Design Render

5.1 Cutting Force

The first step to analyzing the cutting loads is determining the tool that will be used and the material being processed. Decor has specified that they intend to use two specific blades for making the parts in question (detailed below). Blade 1 will be used for making cuts in maple, and Blade 2 will be used for making the cuts in melamine. A range of values is specified for the blade Kerf since resharpening blades cause this dimension to shrink. Visual representations of the Kerf dimension is depicted in Figure 9 where the larger kerf made by a fresh blade is highlighted in red, and a resharpened tool is set inside the smaller kerf.

Blade 1: 350 mm diameter, 3.2-4.4 mm Kerf, 72 teeth

Blade 2: 350 mm diameter, 3.2-4.4 mm Kerf, 100 teeth

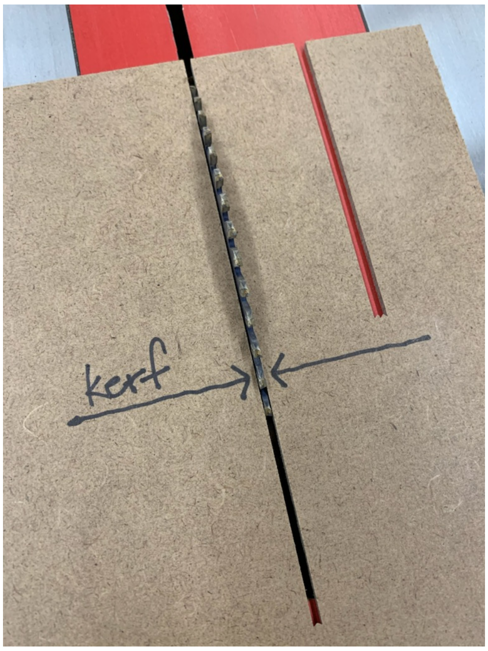


Figure 9: Saw Blade Kerf

This analysis will be conducted for the worst-case scenario that results in the largest possible cutting forces. We will be assuming that the blade kerf is 4.4 [mm] wide and the material being cut is maple. This provides the analytical analysis with the largest possible cut in the strongest material being processed by the fixture.

There is a potential for a large variation in the actual load exerted by the tool due to the following attributes: wood is an organic material with anisotropic properties, wood has a variable density, and blades become dull over time. All of these factors contribute to increasing load placed on the tool and subsequently the fixture holding the part.

5.1.1 Observed Value

The Homag machine that our design is intended for has a built-in feature that measures the spindle load. Decor has informed the team that the maximum allowed spindle loads on the machine is 12 KW. This load applied to the spindle can be used to calculate the force applied to the blank part according to Equation (4), which will produce a tangential force in Newtons.

$$F = \frac{Power\ [HP]}{Spindle\ Rate\ [rad/s]} \times \frac{1}{Tool\ Radius\ [ft]}\ [N] \tag{4}$$

The purpose of this experimental calculation is to ensure that the analytical methods produce a value of similar magnitude. Provided the intricate nature of what these models are trying to evaluate, no singular cutting force value will ensure this design is safe to operate. For this reason, a range of values will be investigated, and the most conservative value from this range will be selected for continuing with the analysis.

5.1.2 Merchant's Circle

This section determines the theoretical force needed for the specified blade to remove material from the maple board. This calculation method uses two major assumptions:

- The mechanical properties of wood will be considered uniform along the cutting direction.
- The chip is a separate body in static equilibrium with the cutting tool.

Since wood products exhibits mostly linear grain profile, the material properties are generally provided in the cutting direction that is either parallel or perpendicular to the grain growth. The following calculation is based on the Merchant's Circle shown in Figure 10 [7]; the diagram shows the force equilibrium at the tool tip.

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(a) Relationships of Friction, Normal, Shear Forces

(b) Horizontal and Vertical Cutting Force

Figure 10: Merchant's Circle

Table XI shows the known cutting parameters. Based on information provided by Decor cabinets, the cutting width of the blade remains inside the range of 3.2 - 4.4 [mm], where the 3.2 [mm] Kerf is the minimum value capable of producing a good cut. The cutting width of 4.4 [mm] was used in the analysis as it removes the largest amount of material and creates the largest loading scenario. The chip load in the calculation was the recommended value for cutting hard-wood[8]. The results for the actual chip load created by the parts in question for this process can be found in the Appendix B, Table B-I. The recommended value was selected because this value provides a more conservative analysis.

TABLE XI: *CUTTING PARAMETERS*

Parameters		Value
Static friction coefficient [μ]	[9]	0.40
Rake angle (γ_0) [°]	[10]	16.00
Width of the cut (b) [in]	[10]	0.17
Chip load (a) [in]	[8]	0.02
Shear strength (Maple) (τ_s) [ksi]	[11]	1.08

The friction angle η is related to the friction coefficient as shown in Equation (5) below.

$$\mu = tan\eta \tag{5}$$

Lee Shafer's formula provides a relationship between the rake angle of the tool γ_0, the friction angle η, and the shear angle shown in Equation (6) below [12].

$$\beta + \eta - \gamma_0 = 45^o \tag{6}$$

Also the following trigonometric relationships were used in the calculation:

$$cos(\beta + \eta - \gamma_0) = \frac{F_s}{R} \tag{7}$$

$$cos(\eta - \gamma_0) = \frac{F_c}{R} \tag{8}$$

$$sin(\eta - \gamma_0) = \frac{F_T}{R} \tag{9}$$

The shear force could be expressed by multiplying shear area A_s with shear strength of the work piece material τ_s. Shear area A_s can also be expressed as a function of the uncut chip thickness characterized by the chip-load a, shear angle β and the width of cut b shown in Equation (11) below.

$$F_s = \tau_s \times A_s \tag{10}$$

$$F_s = \tau_s \times \left(\frac{a}{sin(\beta)} \times b \right) \tag{11}$$

Table XII gives a summary of the analytical results from the Equations detailed above.

TABLE XII: *ANALYTICAL RESULTS*

Result Parameters	**Value (Metric)**	**Value (IPS)**
Friction angle (η)	21.8°	21.8°
Shear angle (β)	39.2°	39.2°
Shear force (F_s)	26.35 N	5.92 lbf
Resultant force (R)	37.26 N	8.38 lbf
Cutting force (F_c or F_{cx})	37.10 N	8.34 lbf
Cutting force (F_T or F_{cy})	3.77 N	0.85 lbf

The theoretical load was calculated to be 24.5 [lbf] while the analytical force is 8.38 [lbf]. The percent difference found between the theoretical and analytical cutting force is 98%. With that being said, the higher value will be used for a conservative approach.

5.2 Work Holding Analysis

Pulling vacuum creates a pressure differential across the surfaces exposed to atmospheric and control volume pressures; this phenomenon will be referred to as stick. The stick needs to be evaluated to ensure that the normal force acting on the part is sufficiently enhanced by the static vacuum pressure allowing the fixture to grip the part during operation. Table XIII introduces and outlines the variables and units that are used throughout the fixture analysis.

TABLE XIII: *VARIABLES DEFINITION*

Variable	Definition	Units
$\boldsymbol{A_V}$	Surface Area interfacing with vacuum pressure	in^2
$\boldsymbol{A_a}$	Surface Area interfacing with atmospheric pressure	in^2
$\boldsymbol{A_C}$	Contact Surrface Area between the fixture and the part	in^2
$\boldsymbol{P_V}$	Vacuum Pressure	PSI
$\boldsymbol{P_a}$	Atmospheric Pressure	PSI
$\boldsymbol{F_m}$	Force generated from the mass of the part	lbf
$\boldsymbol{F_a}$	Force generated from atmospheric pressure	lbf
$\boldsymbol{F_V}$	Force generated from vacuum pressure	lbf
$\boldsymbol{F_{Eq}}$	Equivalent Force	lbf
$\boldsymbol{\mu_s}$	Coefficient of static friction	N/A
$\boldsymbol{F_f}$	Frictional Force	lbf
$\boldsymbol{F\delta}$	Deflection Force	lbf
$\boldsymbol{F_C}$	Cutting Force	lbf
$\boldsymbol{F_S}$	Factor of Safety	N/A

The normal force created by the pressure applied to the work piece can be calculated as a function of the area and magnitude of pressure applied to the work piece. The equations used are shown below in Equations (12) and (13) below. The vacuum pump specifications according to the manufacturer is included in Table XIV below. It should be noted that 50 hPa converts to 0.7 PSI of absolute pressure.

$$F_v = A_v \times P_v \tag{12}$$

$$F_a = A_p \times P_a \tag{13}$$

$$F_{eq} = F_a - F_v \tag{14}$$

TABLE XIV: *VACUUM PUMP SPECIFICATIONS*

Feature	Value	Unit
Power Supply	60	HZ
Performance	2.4	kW
Speed	1800	RPM
Rated Suction Capacity	76	m^3/hr
End Pressure	.0725	Psi
Environment Temperature	12 - 40	°C

To adequately determine the force of friction acting on the work piece, the equivalent force determined in Equation (14) is added to the force generated by the mass of the part. This amplified normal force that exists between the fixture and the part shown in Equation (15) below.

$$F_N = (m_{part} \times g) + F_{eq} \tag{15}$$

$$F_f = F_N \times \mu \tag{16}$$

So long as the vertical cutting load does not exceed the equivalent vertical forces (F_{eq}), and the horizontal loads to do not exceed the frictional forces (F_f) within a safety factor on the part, the vacuum will be considered capable of sufficiently holding the part in place during cutting operations. It is important to keep in mind that this analysis assumes that a perfect seal is made between the part and the gasket.

We will be assuming that any sufficiently twisted boards will not be processed on this fixture as they would fail to pass the quality standards for Decor Cabinets. However, it would be unreasonable to assume that the blanks are perfectly straight over a 10 [ft] length. The spacing of the individual vacuum holes must be optimized based on the bending stiffness of the part blanks to prevent the internal forces created by straightening warped boards. This also prevents the blanks from lifting off of the fixture surface and breaking the vacuum seal. The moment of inertia for rectangular and triangular cross-sections about the neutral axis can be calculated according to Figure 11 (a) and (b) [13] as well as Equations (17) and (18) respectively.

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(a) Rectangular "R"

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(b) Triangular "T"

Figure 11: Beam Cross Sections

$$I_{R_{X'}} = \frac{bh^3}{12} \tag{17}$$

$$I_{T_{X'}} = \frac{bh^3}{36} \tag{18}$$

It is important to understand the following key assumptions made in this calculation:

1. Effects of curvature on the bending stiffness of the board are being ignored
2. Crown of the board must be placed upright on the table
3. Any blanks with more than 1 inch of total deflection from the table top surface over the 10 [ft] length will not pass quality standards

Internal forces created by bending a warped board into place will be evaluated using the principle of superposition. A diagram for the beam loading used in this analysis as well as the deflected shape is shown in Figure 12 [13].

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Figure 12: Beam Loading Case

The force required to create the maximum deflection in the material from a straight beam is equal and opposite to the force required to straighten a bent one. This solution is based on the arrangement of Equation (19) below in terms of $F_{\delta Max}$.

$$\delta_{Max} = \frac{F_{\delta Max} \times l^3}{48EI} \tag{19}$$

$$F_{\delta Max} = \frac{\delta_{Max} \times 48EI}{l^3} \tag{20}$$

The resulting forces can now be solved for the overall loading scenario of the fixture. The resulting component forces are calculated according to the Equations (21) and (22) below.

$$R_x = F_f - F_{Cx} \tag{21}$$

$$R_y = F_{Eq} + F_{Cy} - F_{\delta Max} \tag{22}$$

These analytical forces account for the vacuum acting on the part, internal forces created by warped blanks, and the cutting loads determined in Section 5.1. Table C-I in Appendix C summarizes the output data from the various calculations performed in this section. The important information gained from this calculation process is that the smallest safety factor observed on the fixture is just under 13.0. Meaning that even if the cutting force suddenly increased 4 times above what is believed to be a reasonable maximum load, the part would maintain its position securely fastened onto the fixture.

5.3 Fixture Support Spacing

This fixture is designed to span a specified distance over the Pod and Rail system available on the Homag machine. This section is dedicated to verifying that the fixture is capable of resisting vertical deflection ensuring cutting tolerances are inside of the quality expectations. This consideration will be made by using the principle of superposition to simplify the over-constrained beam into a statically determinant loading case.

The overall length of the beam will be divided into two 5-foot sections to allow for operators to independently load and unload the fixture from the machine safely. There are a total of six available rail systems to locate underneath of the fixture leaving three supports per 5-foot section. The pods will secure the fixture to the table with a vacuum force. The pods will emulate fixed supports because of the symmetry of the system creating an inflection point in the deflected shape at the centre of the support. By the principle of superposition the point load created by the cutting tool, and the distributed load created by the weight of the fixture can be evaluated separately and added together. Both of these loading scenarios and deflected shapes are shown in Figure 13 (a) and 13 (b) [13] below.

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(a) Point Load

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(b) Distributed Load

Figure 13: Support Loading Scenarios

The distributed load created by the mass of the fixture can be calculated by using the density of MDF and multiplying by the cross-sectional area. Equation (23) provides a unit mass per length of the fixture in $[\frac{lbf}{in}]$.

$$w = \rho \times A_s \tag{23}$$

Next, the moment of inertia for the fixture will need to be approximated. Figure 14 shows the cross-section of the fixture along the axis for which the moment of inertia is being analyzed. Because of the non-uniform nature of this cross-section, the neutral axis of the fixture was calculated according to Equation (24), where d is the centroidal distance from the bottom edge of the part, and A_n is the cross-sectional area of the section in question. The moment of inertia for a rectangular cross-section is shown in Equation (25).

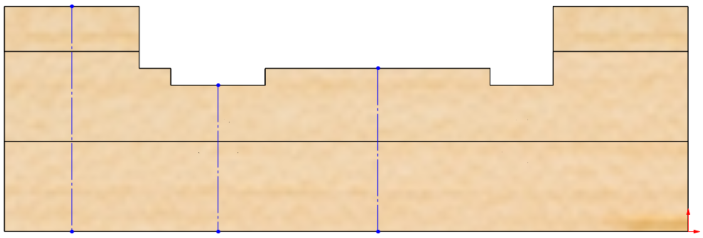


Figure 14: Fixture Cross Section

$$N.A. = \frac{(A_1 * d_1) + (A_2 * d_2) + ...}{(A_1) + (A_2) + ...} \tag{24}$$

$$I_{N.A.} = \left(\frac{b_1 h_1^3}{12} + A_1 d_1^2\right) + \left(\frac{b_2 h_2^3}{12} + A_2 d_2^2\right) + ... \tag{25}$$

For simplification purposes, the effects of the internal features will be neglected in the calculation of the moment of inertia. Deflection in the beam due to the point load can now be calculated according to Equation (26), likewise, the deflection created by the distributed load can be calculated according to Equation (27). Since the maximum deflection in these isolated scenarios occur at the same point in the beam, the two results for the maximum deflection can be added together to produce the total deflection in the fixture.

$$y_{max,p} = \frac{Pl^3}{192EI} \tag{26}$$

$$y_{max,d} = \frac{wl^4}{384EI} \tag{27}$$

$$y_{Tot} = y_{max,p} + y_{max,d} \tag{28}$$

To meet the existing cut quality tolerance at Decor Cabinets, the total vertical deflection experienced by the fixture must be less than $\frac{1}{32}$ of an inch (0.031"). The resulting value of y_{Tot} based on the calculations provided is 0.003". This is well within the provided tolerance with a safety factor of 11. The parameters and values used for this calculation are detailed in Table C-II of Appendix C.

5.4 Vacuum Pad Design

A modular part was added to the fixture specifically designed to support the work piece. This part was added to allow for increased serviceability on the fixture. If this part is damaged by the machine tool, it can be individually replaced rather than rebuilding the entire fixture. When brainstorming concepts for the modular part, the team focused on key criteria detailed in Table XV. The criteria presented were identified by the client during the Phase 3 kickoff meeting.

TABLE XV: *MODULAR PART CRITERIA*

Criteria	Description
Serviceability	Easy of manufacturing, install, and maintain.
Vacuum Seal	Surface interfaces must be sealed to reduce vacuum pressure losses.
Vacuum Force	The vacuum force must be maximized to ensure the work piece is held safely.
Cost	Cost must be minimized as this is considered a consumable component.

5.4.1 Concept 1

The team wanted to develop a simple concept that reduced complexity wherever possible. This resulted in the team generating a concept that used standard fasteners to attach to the fixture, and channels which the vacuum pressure will be routed. This concept can be seen in Figure 15 below. It would have two fasteners on each end and several vacuum holes in-between depending on the holding force. For this instance, only three are shown to represent the idea.

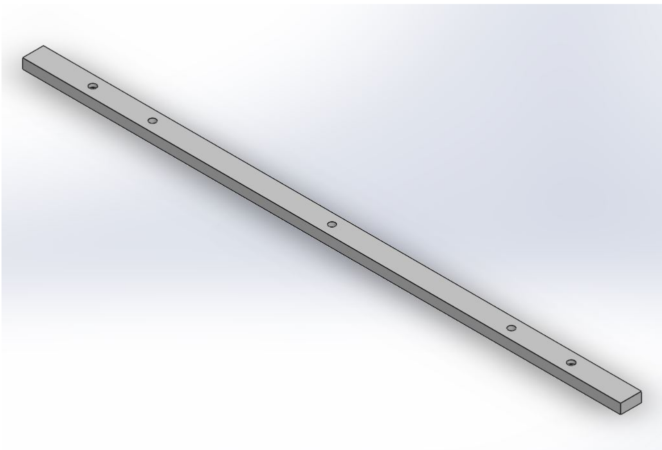


Figure 15: Initial Vacuum Pad

Benefits:

- Easy to manufacture
- Cost Effective

Challenges:

- No sealing method to prevent vacuum leaks
- Small cross sectional area exposed to vacuum

5.4.2 Concept 2

The following concept increases complexity and relates to the elevated finger design concept. Each vacuum hole would have a threaded insert that can be easily replaced if it were to get damaged. An example of this concept can be seen in Figure 16 [14]. The vacuum cup is oval to increase the area affected by the vacuum, increasing the work holding force. It is thin enough so that it remains safe underneath the finished part without interfering with the cutting blade.

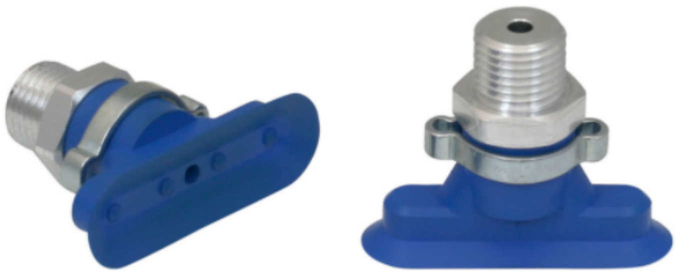


Figure 16: Oval Shaped Vacuum Cup

Benefits:

- Elevates the work piece to protect tooling
- Improved vacuum force
- Rubber cup improves vacuum seal

Challenges:

- Will require large quantity of vacuum cups
- Increased cost
- Rubber cups allow lateral and rotational deflection

5.4.3 Concept 3

The third design developed by the team was focused on the efficiency of using the vacuum forces to hold the work-piece. This concept uses a gasket to ensure a proper seal between the modular part and the work-piece. The design uses an indent where the work-piece is held to maximize the surface area of the vacuum forces. The part uses mechanical fasteners to hold them to the fixture frame, providing a fully constrained connection between the part and the fixture.

Figure 17: Modular Part with Gasket

Benefits:

- Increased area affected by vacuum
- Replaceable gasket seal
- Low cost

Challenges:

- Custom part requiring manufacturing
- No sealing surface located between the fixture and the part

5.4.4 Vacuum Pad Selection

The three modular part designs, Sections 5.4.1 to 5.4.3, were evaluated in a simplified Weighted Decision Matrix (WDM). The WDM will use the criteria mentioned in Table XV to evaluate the three designs. Each design was ranked from 1 to 3, where 3 is the best rank and 1 is the worst. Additionally, for the sake of simplicity, each criterion carries the same weight. Each design was then summed up for a total score as seen on the right-hand column in Table XVI. Design 3 was chosen as the modular part to move forward with having a score of 10.

TABLE XVI: *MODULAR PART WEIGHTED DECISION MATRIX*

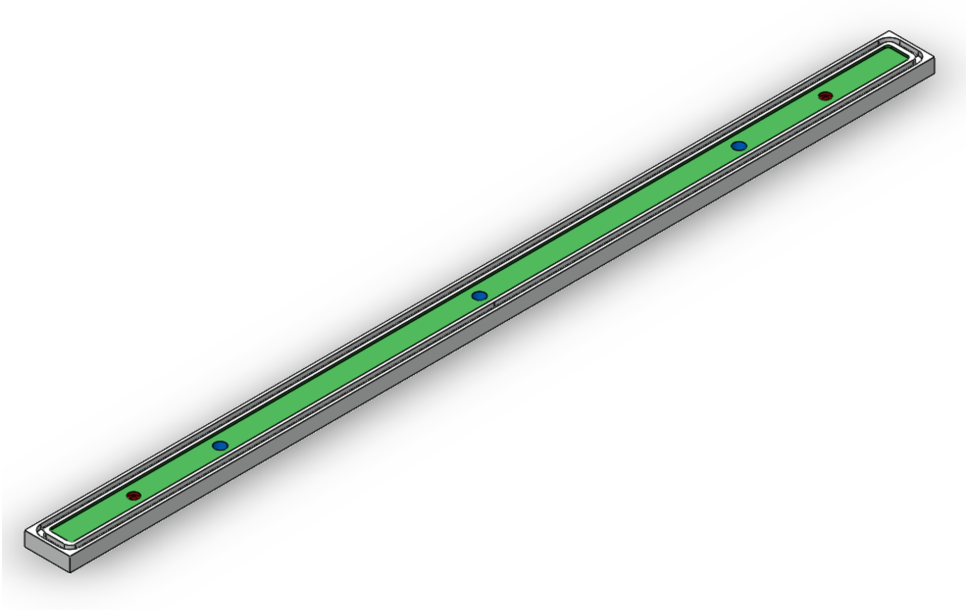
	Criteria				**Score**
Concept	Serviceability	Vacuum Seal	Vacuum Force	Cost	**Total**
Design 1	2	1	1	3	7
Design 2	3	2	2	1	8
Design 3	2	3	3	2	10

5.4.5 Vacuum Pad Detailed Design

With the focus on designing the modular part based on the criteria in Section 5.4, the design is optimized to meet the criteria. The width of the part was optimized separately for the square and triangular part holders to account for the different stock sizes and tooling clearance. Both parts are 20 [in] long meaning that six parts span the length of the fixture for one 10 foot long part. The number of parts was determined based on the six total vacuum pods currently available on the machine. This means, along the length of the fixture each modular piece is supplied with an isolated vacuum supply. This helps ensure redundancy in the design in the event that a vacuum leak is experienced due to a foreign object or a damaged gasket. Also, Decor has the ability to manufacture this part in-house reducing lead times and inventory requirements.

The modular part features three holes where the vacuum will be routed from the fixture to the top work holding surface which can be seen highlighted in blue in Figure 18 (a). These holes are routed to the top work holding surface which is indented to allow for a greater vacuum area providing a larger work-holding force applied by the vacuum. This indent can be seen in Figure 18 (b), highlighted in green.

(a) Cross Section View



(b) Isometric View

Figure 18: Highlighted Vacuum Pad Design Features

Two through-holes have been added to allow for a mechanical joint between the part and the fixture, this detail is shown in red in Figure 18 (a). A low profile socket head screw and counterbore combination was chosen to leave clearance between the top of the fastener and the work piece shown in Figure 19.

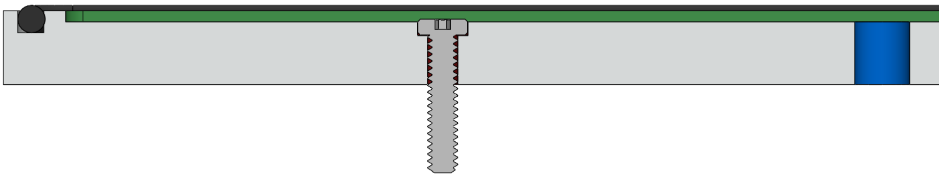
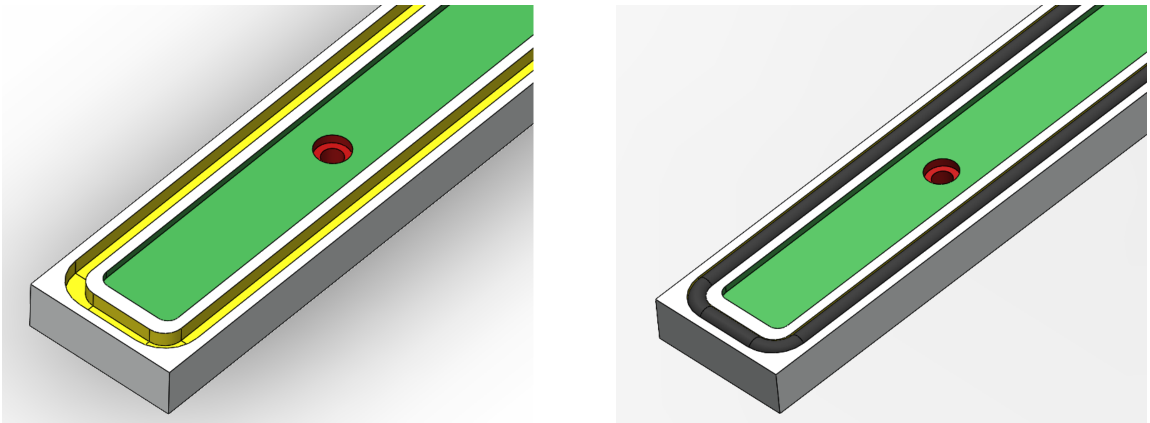


Figure 19: Low Profile Socket Head Screw Used in Modular Part

A groove was placed into the top work holding surface which allows for a gasket to be added to the part shown below in yellow. The gasket has two primary functions; ensuring a proper seal between the part and the work piece, and increasing the coefficient of friction which is critical when considering the support loads that counteract the horizontal cutting loads. The ideal gasket was determined by the team to be a 1/8" round gasket made from neoprene. This small-diameter gasket reduces the groove size, allowing for a large indented area in Figure 18 (b) to be maximized. Detailed close up of the gasket groove and the overall assembled gasket are shown in Figure 20



(a) Gasket Groove

(b) Assembled Gasket

Figure 20: Modular Part Gasket

The final design allows for a vertical holding force of 535 [lbf] and 1221 [lbf] for the rectangle and triangle parts respectively. This vertical load produces a horizontal holding force of 324 [lbf] and 202 [lbf] for the rectangle and triangle parts respectively. These values account for all six vacuum pads in total acting on the respective parts. A detailed set of calculations can be found in Section 5.2 while the parameters and results can be inspected in Table C-I of appendix C. The engineering drawings for the final design and the sub components can be found in the Drawing Package provided.

5.5 T-Slot Removal

With the newly completed vacuum pads modeled into the assembly the team realized that there was tool clearance issues between the bump stops held in place by the T-slot and the machine tooling clearance required for one side of the triangle part. For this reason the team decided to lower the vacuum pads deeper into the fixture. This solution revealed that the cut-out in the MDF sheet was providing the same function as originally intended by the T-slot bump stops. Since there was no added benefit within the design objectives for this project, the added functionality was eliminated to reduce the cost of the elements along with removing the risks presented to the machine tooling by the aluminum bump stops. Figure 21 shows a detailed sketch of the tool blade location (Shaded with black outlines) against the final design of the fixture. Since the fixture is made from MDF, the tool will be able to safely self clearance itself on the first pass of the new fixture.

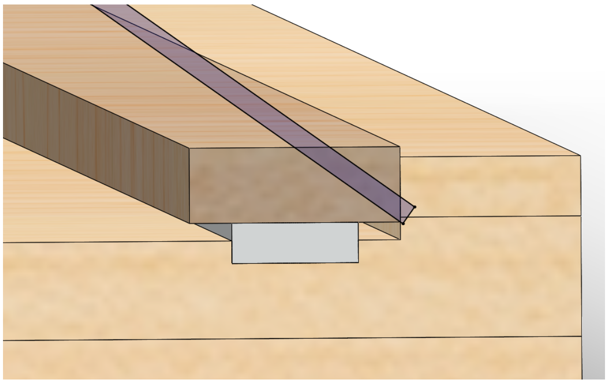
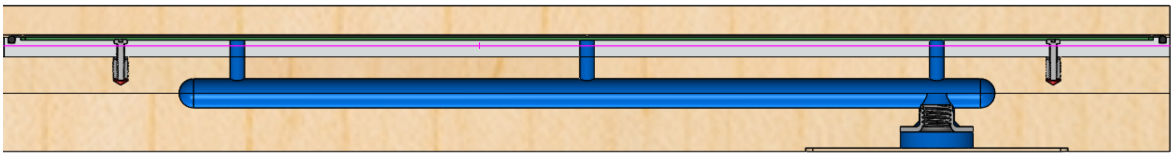


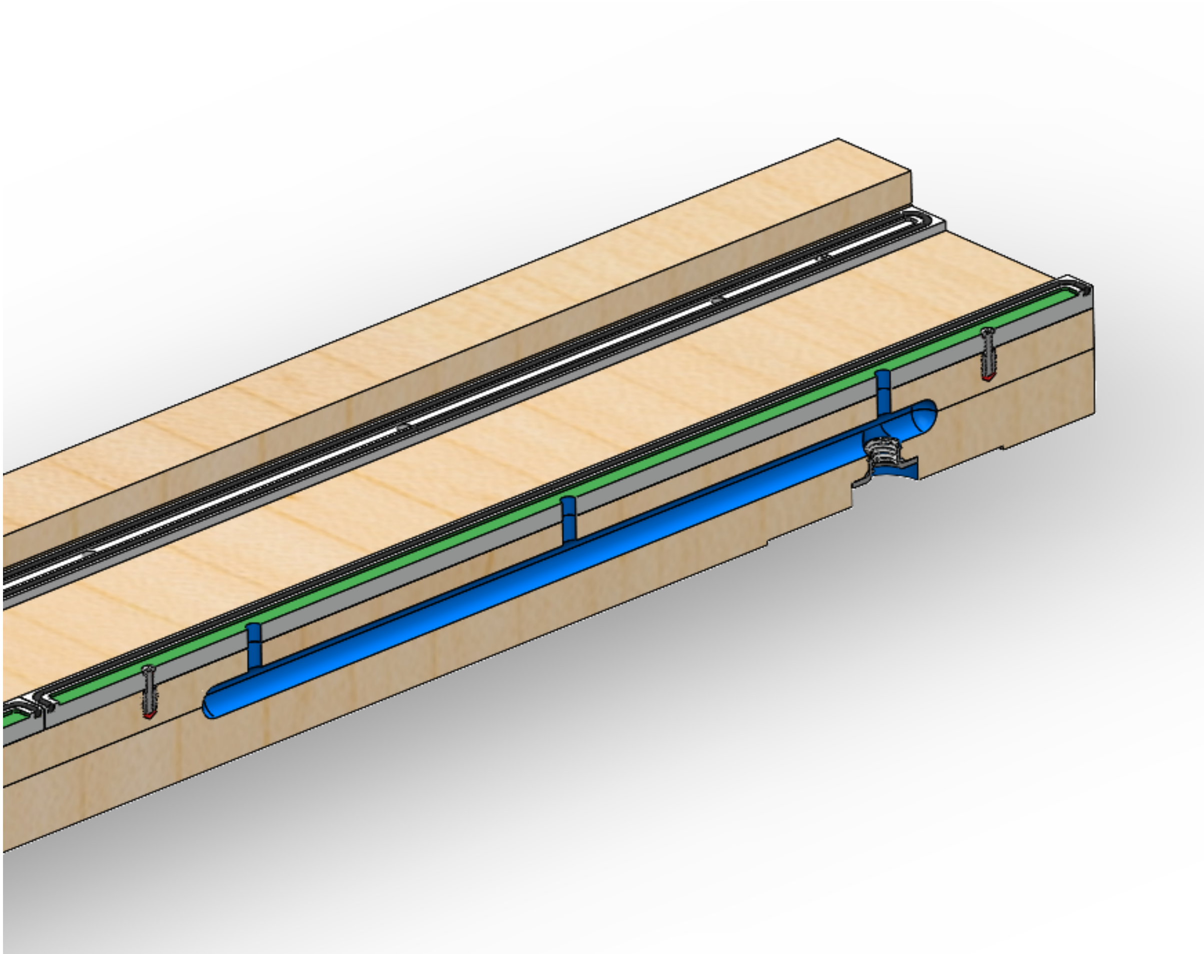
Figure 21: Fixture Tool Interference

5.6 Vacuum Channel Design

The following section is dedicated to how the design utilizes the current pod and rail vacuum system to power the fixture. The design acts as a transfer system for the current vacuum pump output to the work holding surface. The fixture is manufactured in two halves, the top and bottom before being laminated together. This allows for internal geometry to be manufactured into the center portion of the fixture as seen in Figure 22 (a). The parts have matching semi-circular cross-section profiles created by plunging a 0.5” end mill into the part. Dowel pins will be used to locate the top and bottom during the lamination phase of the manufacturing procedure so that the alignment is preserved and the internal channels are created as shown in Figure 22 below.



(a) Section View



(b) Isometric View

Figure 22: Vacuum Routing Detail

The design at this point was functional for creating both parts at the same time. Our team wanted to allow for only one part to be processed on the fixture at a time. Meaning that the operator would not have to juggle both parts if they were not required on the production line that day. Threaded inserts were added to the bottom portion of the vacuum channels so that vacuum power could be blocked from flowing to specific sections of the fixture. This allows for the fixture to be mounted onto the machine normally only requiring the desired work holding location to be covered for processing. Parts with the same geometry as the parts specified by the client can be processed up to a minimum of 20 inches long at the maximum spindle load of the machine while still being held securely in place. Figure 23 shows the exploded view of the fasteners used for implementing this functionality.

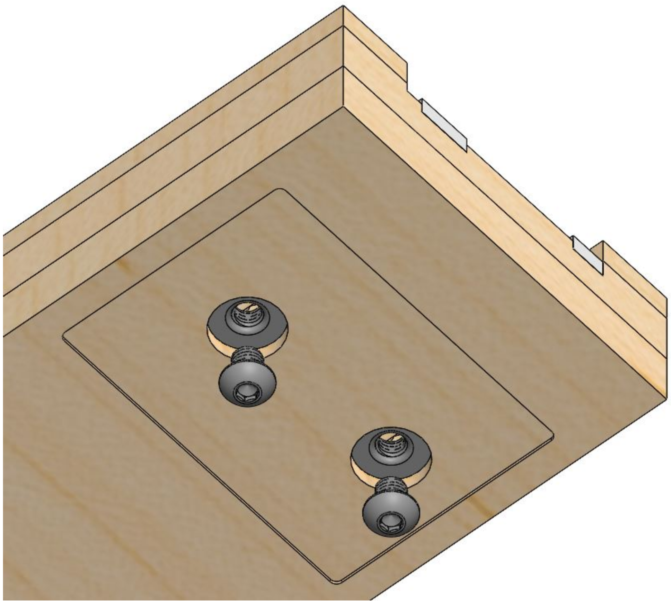


Figure 23: Locating Pod Pocket

6 Optimization

At this point in the design the fundamental aspects of the fixture performance were captured in the various design details of the product. Our team wanted to make an effort to increase the usability and ergonomics of the design along with reducing as much complexity as possible from a design for manufacturing perspective. Both of these considerations are discussed in detail below in Sections 6.1 and 6.2.

6.1 Operator Ergonomics

The length of the fixture is 10 [ft] to accommodate the clients specified parts. With the fixture being 10 feet long, it may be difficult for the operator to maneuver the fixture through the facility due to its awkward size and associated total weight of 44 [lbs]. With the help of the clients input, the team decided to separate the fixture into two 5 foot sections. This reduces the size and weight of the individual pieces of the fixture and increases the functionality by allowing the operator to use only one half of the fixture when cutting parts at or below 5 feet in length. The fixture has been designed to be held together using a basic draw latch shown in Figure 24 to ensure both halves remain seated between operation cycles when the vacuum power is turned off.

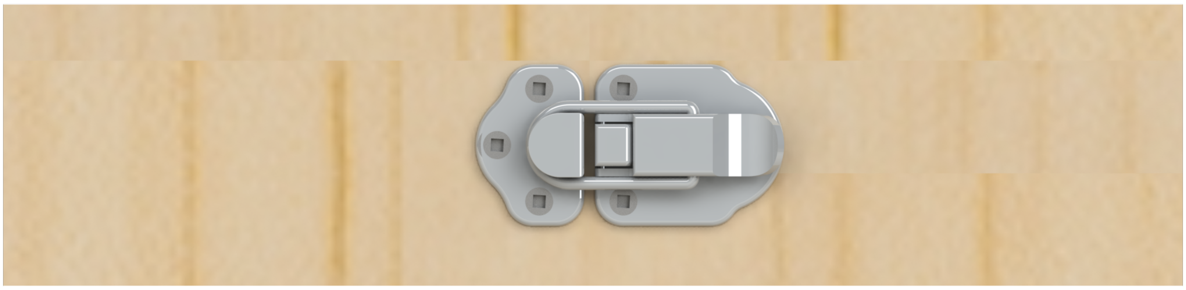
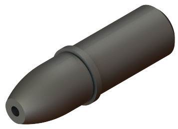
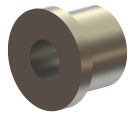


Figure 24: Draw Latch

To ensure the two halves of the fixture are aligned when installed on to the CNC mill, a combination of steel male and female locating pins, shown in Figure 25 (a) and (b), were placed into opposite sides of the fixture halves. These guides are permanently glued into place and allow for the two halves of the fixture to be quickly and easily aligned during setup on the machine deck. Figure 26 shows the components in the assembly along with the holes drilled to accommodate installation on top of one another in a cut view.



(a) Locating Dowel



(b) Tapered Guide

Figure 25: Guide System

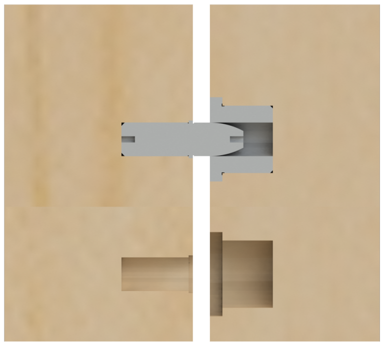


Figure 26: Guide Assembly

6.2 Manufacturing Considerations

The team wanted to ensure that the design was easy to make from a manufacturing perspective. The client expressed interest in developing and manufacturing the design in-house. Each part's dimensions were optimized to typical tooling sizes and to the available tools that Decor either has in stock or are readily available at low cost. For example, the gasket groove would be made with 1/8 [in] end mill and the vacuum channels sandwiched between top and bottom sections are created with 1/2 [in] ball nose end mills. All inner profiles used in the modeling processes and design calculations were specifically matched to the tool that was intended to be used in the milling processes. More over, the drawings incorporate the required tolerance controls that will allow for the fixture components to be easily manufactured and assembled.

Additionally, the team implemented wooden dowels that sit between sheets of MDF board to help align the vacuum channels on the upper and lower fixture components which are glued together. This is necessary because MDF only comes in 1 [in] thick sheets where as our design will be 2.5 [in] thick in total. An example of this is shown in Figure 27.

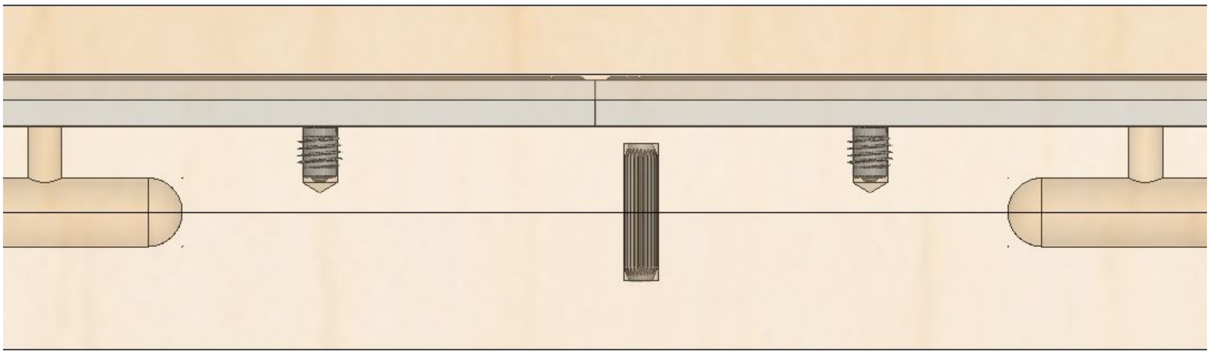


Figure 27: Wood Dowels for Manufacturing

The fixture is designed with the intention that the threaded inserts and tee nuts are permanently glue in place to allow for the fixture frame to handle the perpetual actions of installing and removing the fasteners used in the design. MDF is easily stripped by a process called auguring, so the intention with these components was to make the fixture frame as robust as possible allowing for it to stand the test of time. The only parts in the design that are considered to be consumable are the vacuum gaskets and the modular pads in the event they are damaged by tooling or other external factors.

7 Feasibility Studies

To understand the new process performance associated with the design, the team performed feasibility studies. Three sections outline the feasibility studies: time study, cost analysis, and failure mode and effects analysis (FMEA). The time study analyzed the new cycle time in comparison with the table saw cycle times, and determined whether the functional requirements had been met. The cost analysis calculated all the costs of the materials as well as the manufacturing effort required by the design. The failure mode and effects analysis was performed to identify all the potential causes of the failure in the newly designed process.

7.1 Time Study

This section is intended to analyze whether the new cycle time meets the functional requirement of maintaining or reducing the current cycle time. The cycle time was broken up into two phases: setup time and cutting time. The setup time is the time it takes for the operator to set up the cutting method. For the current process (table saw), it would be the time to set up up the fence to the correct cutting width, and to turn on the table saw. As for the new process, this would include the time to set up the pods and rails, the new fixture, and setting up the tool path on the CNC mill. As for the cutting time, this is strictly the feed rate or speed of the saw. The new process is dependent on the operator while the new process is fully automated. Based on the cutting-process video that the clients provided, we estimated that the triangular piece took 160 seconds to cut a 3-feet long piece. The old cycle time for the table saw process can be found in Table XVII.

TABLE XVII: *TABLE SAW CYCLE TIME*

	Rectangular (120")	**Triangular (120")**
Setup Time (s)	30	90
Cutting Time (s)	30	233.3

The new cycle time cannot be conducted until the prototype is developed but the team made a few assumptions and estimations. The team has expected the new setup time could be much longer than the table saw process because the new process would involve setting up the correct program (g-code), modular pieces, and locating the vacuum pods. In order to analyze the new cycle time, the team assumed the new setup time was about 15 minutes which would be a conservative estimation, as the larger the number of parts produced with a single setup the more this time is dispersed throughout the batch of parts that were processed. As for the cutting time, this process is not estimated. It was discovered that the feed speed for the new process is $10m/min$. The new cycle time can be found in Table XVIII.

TABLE XVIII: *NEW CYCLE TIME*

	Rectangular (120")	**Triangular (120")**
Setup Time (s)	900	900
Cutting Time (s)	18.3	36.6

The cycle time for cutting just one piece of material would be longer than the table saw process. However, the client's expectation of peak production per day is 60 pieces per rectangular and triangular part. Table

XIX shows the comparison of the total time for manufacturing 60 pieces for each shape of the parts. Note that the setup times would be considered a one-time application when calculating the total.

TABLE XIX: *TOTAL TIME COMPARISON*

	Rectangular (120")	**Triangular (120")**
Table Saw Total Time (s)	1830	14090
New Process Total Time (s)	1998	3096

Based on the results, the new total time for cutting 60 pieces of rectangular shape is slightly greater than the table saw process. However, the new process for cutting triangular pieces had significantly increased the production efficiency, from 14090 seconds to 3096 seconds. The total time reduced for cutting the 120 pieces was about 2.76 hours. After calculation, it was found that the minimum amount of pieces to be cut that would make the old and new process equivalent in time is 75(74.354) and 5(4.118) for rectangular and triangular parts respectively. The increased efficiency of the production can be calculated as the following formula which is rounded to largest integer value:

$$Time\ Decreased(\%) = \frac{Time\ Difference}{Original\ Time} \times 100\% \tag{29}$$

In conclusion, the new process of manufacturing had met peak production cycle times. The new process for cutting rectangular pieces starts saving time after the 75^{th} piece being cut. Meanwhile, the triangular piece saves approximately 3.05 hours for peak production. The increase in efficiency for the peak production was about 74%. It is highly recommended to revisit the new cycle time once the prototype can be made so that a true time study can be compared against these theoretical values.

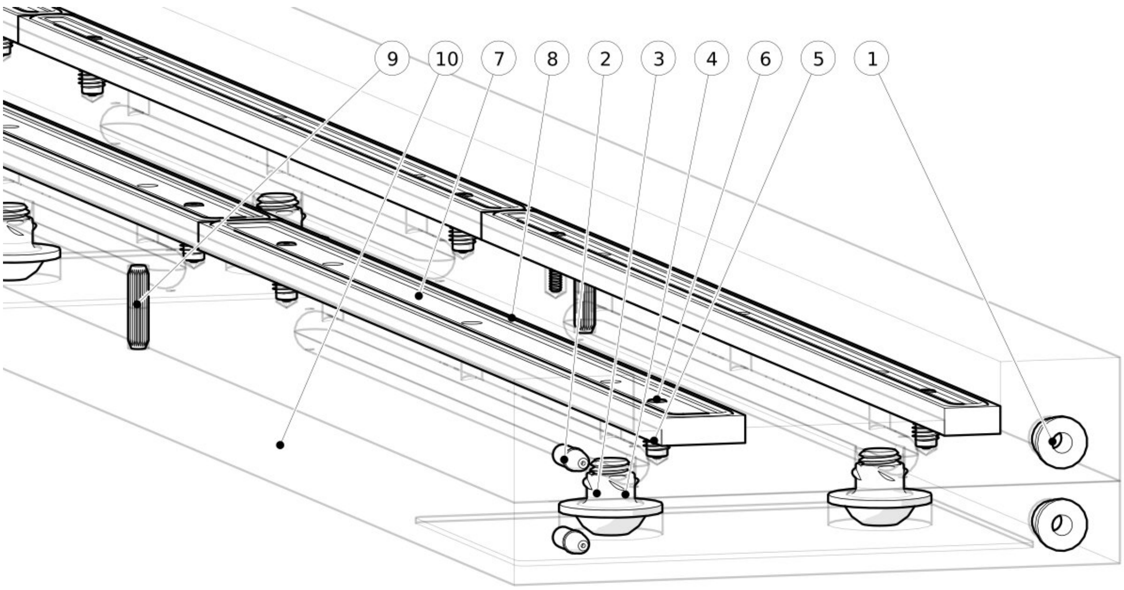
7.2 Cost Analysis

A cost analysis was done on the design to determine if it is feasible and whether adjustments needed to be made. The total cost of the design includes the bill of materials (BOM) and the cost of production. Note that general costs such as training or labour are not included because it is under the assumption that the implementation of the new design is no different from Decor's current CNC mill operations. The design acts strictly as another tool or method for the experienced operator to use. After some initial procurement research, the team developed the following bill of materials listed in Table XX. It was identified by the customer that the estimated shop rate (operator, machine, utilities,etc) is $150/hour. The team estimates that the time to build the fixture in house would be approximately 8 hours. Therefore, the total cost to build the fixture, including the BOM, is about $1580.29 in comparison to the allotted $3,000.

TABLE XX: *BILL OF MATERIALS*

Material		Unit	Quantity	Cost
MDF Panel Sheet - 1" t x 49" w x 97" l	[15]	$64.99 / sheet	1	$ 64.99
HDPE Bar - 3/8" t x 1" w x 4" l	[16]	$5.08 / 4 ft	6	$ 30.48
SS Socket Head Screw for Modular Part	[17]	$10.42 / 25 Pack	24	$ 10.42
SS Tapping Insert for Modular Part	[18]	$2.73 / each	24	$ 65.52
Round Gasket for Vacuum Work holding Modular Part	[19]	$26.05 / 15 ft	3	$ 78.15
SS Button Head Hex Drive Screw for Vacuum Pods	[20]	$7.92 / 5 pack	12	$ 23.76
Tee Nut Inserts for Vacuum Pods	[21]	$9.44 / 5 pack	12	$ 28.32
Wood Dowels for joining MDF together	[22]	$4.02 / 100 pack	8	$ 4.02
Mating Locating Pin	[23]	$4.66 / each	2	$ 9.32
Hole Liner/Insert for Locating Pin	[24]	$6.59 / each	2	$ 13.18
Wood Glue for joining MDF together	[25]	$15.50 / 16 fl oz	1	$ 15.50
Draw Latch for combining two sections together	[26]	$10.41 / 5 pack	4	$ 10.41
Screws for fixing Draw Latch	[27]	$13.11 / 100 pack	1	$ 13.11
			Total:	**$380.29**

To give a better understanding of the BOM, a visual was developed as seen in Figure 28. The main material, MDF, is shown with some transparency so that the materials below or incorporated into the center portion of the fixture can be identified.



Material	BOM ID
Hole Liner/Insert for Mating Locating Pin	1
Mating Locating Pin	2
Tee Nut Insert	3
SS Button Head Hex Drive Screw	4
SS Tapping Insert	5
SS Socket Head Screw	6

Material	BOM ID
HDPE Bar	7
Gasket Triangle	8
Wood Dowel	9
MDF Panel Sheet	10

Figure 28: Detailed view of BOM

The design costs was considered satisfactory in the event they were less than the specified $3000 budget and improved operator safety. So to calculate the payback period, the time savings from the time study will be used in comparison to the material and labour costs associated with the design. The payback period is calculated via Equation 30. The cost of the project is the total aforementioned value of $1580.29, while the time savings would be the time saved in hours of 2.76 [hrs] multiplied by the labor cost of $150/hr. This resulted in a payback period within 4 days.

$$Payback\ Period = \frac{Cost\ of\ Project}{Time\ Saved * Labour\ Cost} \tag{30}$$

Another cost to consider is the intangible cost associated with work place injuries. Although these cannot be calculated directly, they are important points to consider for the team and the company. Examples of these costs include the following points:

- Medical cost - costs that the company may incur to help the employee recover from an incident.
- Opportunity cost - the company could lose out on opportunities. By having an absent worker due to injury, production and productivity would be reduced.
- Labour cost - injuries could cause turnover which is costly for the company to find a replacement and train them.

To summarize, the overall cost of the project is $1580.29 with a payback period of 4 days and a significant improvement in intangible safety costs.

7.3 Failure Mode and Effects Analysis

Failure modes and effects analysis (FMEA) was conducted to identify any potential causes for failure in the process. This allows the team to develop any potential action recommendations to reduce or eliminate the failures identified. Table XXIV lists out all the potential failure modes, the potential effect it has on the process, the potential root cause of the problem, the current control prevention and the current detection method. Along with all that, a score is given for severity, frequency and detection to obtain a risk priority number (RPN). The scale for determining the severity number, frequency and detection were adopted from Vern Campbell's lecture [28]. The scales are explained in Tables XXI, XXII, and XXIII. Furthermore, the risk priority numbers shown in table XXIV are calculated via Equation 31.

TABLE XXI: *SEVERITY RATING SCALE*

Severity of Effect		Ranking
Minor	Unreasonable to expect that the minor nature of this failure would cause any substantial effect on the system performance or on a subsequent process or service operation. Customer unlikely to either notice or care about the failure.	1
Low	Low severity ranking due to nature of failure causing only a slight customer annoyance. Customer will probably notice only a minor degradation of the service, performance, or a slight impact on a subsequent; i.e., some quick, minor rework.	2
Moderate	Failure causes some customer dissatisfaction. Customer is made uncomfortable or is annoyed by the failure. Customer will experience some very noticeable inconvenience or performance degradation. May cause either delay due to rework or irreversible damage.	4,5,6
High	High degree of customer dissatisfaction due to the negative impact of the failure such as an inaccurate payroll run, loss of vital data or an inoperable convenience system (i.e., computer crashes). Does not involve safety or noncompliance to government regulations. May cause serious disruption to subsequent processing; may require major rework or loss to customer and/or create significant financial hardship.	7,8
Very High	Failure mode involves serious personal safety hazards, potential for civil litigation or noncompliance with government regulations.	9,10

TABLE XXII: *FREQUENCY RATING SCALE*

Probability of Failure	Ranking	Possible Failure Rates
Remote: Failure is unlikely. No failures ever associated with almost identical processes	1	<1 in 20,000
Very Low: Process is in Statistical Control. Only isolated failures associated with almost identical processes	2	1 in 20,000
Low: Process is in Statistical Control. Isolated failures associated with similar processes	3	1 in 4,000
Moderate: Generally associated with processes similar to previous processes which have experienced occasional failures, but not in major proportions. Process is in Statistical Control	4 5 6	1 in 1,000 1 in 400 1 in 80
High: Generally associated with processes similar to previous processes that have often failed. Process is not in Statistical Control.	7 8	1 in 40 1 in 20
Very High: Failure is almost inevitable.	9 10	1 in 8 1 in 2

TABLE XXIII: *DETECTION RATING SCALE*

Likelihood of Detection		**Ranking**
Very High	Current Control will almost certainly prevent the failure (process automatically prevents most failures).	1,2
High	Current control have a good chance of detecting the failure.	3,4
Moderate	Current controls may detect failure.	5,6
Low	Current controls have a poor chance of detecting the failure.	7,8
Very Low	Current controls probably will not detect the failure.	9
Absolute Certainty of Non-Detection	Current controls will not or cannot detect the failure.	10

$$RPN = (SEV) * (FREQ) * (DET) \tag{31}$$

All of the identified potential failures do not pose a major concern and no immediate action is required. Of the nine listed potential failures, five have listed potential action recommendations if they are to arise. These will be important to consider moving forward into the prototyping and testing phase. The highest risk item would be the first item having a RPN value of 105. This component, the modular piece, runs the risk of having vacuum leaks at the bottom surface where it contacts the MDF. As a result, the work piece could become loose and become problematic. The piece could potentially fall off during processing and cause damage to the Homag machine and/or its operator. To combat this, it would be good to consider not using screws and have the pieces permanently fixed. However, this goes against the functionality of the design and contradicts what the theoretical analysis deems as a safe system. The recommended action should only be considered if absolutely necessary after the problem has been experienced in the process. Again, it will be important to monitor once prototyping and testing phase are in process.

TABLE XXIV: *FMEA*

Component or Process Setup	Potential Failure Mode	Potential Failure Effect	SEV	Potential Cause of Failure	FREQ	Current Process Control Prevention	Current Process Control Detection	DET	RPN	Action Recommendations
Modular piece	Bottom surface leak air	Vacuum holding force decreased, part not held in place and could be hazardous	7	The screw prevent two surface in good contact condition	5	Enough compression force when setting up the screw between two surfaces	Turn vacuum pump on and check if the air is leaking	3	105	Consider not using screws, add glue to the bottom surface of the modular piece
Fixture	Damage fixture by tool	Fixture damage	10	Programming error	2	Monitor the process	Check the CNC programming	2	40	Simulate the CNC cutting process before hand
Modular piece	Top surface gasket leak air	Lose holding force on the cutting material	6	Improper position of the gasket	5	Make sure the gasket is in compression not elongation	Visual Inspection of gaskets	3	90	Consider fully rubber surface rather than just a gasket
Pod	Air leak from pods	Poor vacuum holding force	8	Incorrect alignment when setting up fixture	2	Allowing tolerance on grooved pocket where pod sits	Operator checking vacuum pressure gauge	1	16	No recommended actions
Process	Operator does not feel comfortable using fixture	Fixture not in operation	10	Incorrect fixture design/ lack of design input from operator	1	Obtain input from operator regarding use of fixture	Operator Feedback	1	10	Training session and periodic knowledge review
Process	Incorrect fixture setup	work piece/ fixture damaged/-tolerance not achieved	10	Setup instructions not clear to operator	3	Discuss setup with operator ensuring they understand the process	Visual inspection for damage and tolerance checks	2	60	Training session and periodic knowledge review
Fixture	Vacuum channel leak air	Vacuum holding force decrease	7	Improper top and bottom fixture assembly/gluing	1	Enough glue to make sure good sealing	Check the gauge pressure after all the vacuum holes are blocked	1	7	No recommended actions
Process	Vacuum not engaged	Fixture/ work piece damage	10	Operator forgets to engage vacuum	1	Develop standard process procedures	workpiece moves during processing	1	10	No recommended actions
Modular piece	The proper positioned screws leak air	Leak air inside of modular piece	1	Screws not properly sealed	1	Does not affect functionality of the part	No need	8	8	No recommended actions

8 Conclusion

The project started with the understanding that a design for a fixture was to be comprehensively developed with the key objective of increasing operator safety in the specialty department at Decor Cabinets. An exhaustive FMEA was conducted on the fixture design resulting in objective determination for the fact that the risks require no further action, and the existing residual risks are acceptable to both the team and the client. This also means that the design must meet the existing quality standards of no more than 1/32 (.031) [in] of vertical variation in the cut dimensions over 10' $[ft.]$ and match the processing time currently measured in the specialty department.

The final design exceeds this standard by only allowing for a maximum of (.003) [in] of vertical deflection. The processing time eliminates the need to reset the angle of the blade which yields a total time savings of 2.76 hours for the triangular pieces made during peak production. A budget of $3000.00 was set by the client for one unit, the bill of materials for this unit revealed that the total material input and labour cost combine for a total associated input cost of $1580.29. The team was required to deliver this detailed design report before December 9$^{\text{th}}$ 2020 meaning that this project came in on time as well as successfully meeting the budget expectations set by the client. A render of the final design can be seen below in figure 29

This fixture was designed with serviceability and ergonomics in mind, incorporating elements such as the two-part division allowing for operators to easily manage the fixture loading and unloading independently. The fixture successfully meets all the customer needs that were set out while also providing the added functionality to manufacture other small dimension parts at a variety of lengths on the same fixture. The design team and the client dealt with the barriers provided by COVID-19 and the visitation restrictions by creatively communicating through distanced platforms. Overall the successful results of this design mean that all stakeholders involved in this project have realized added value from the results of the project to date, most importantly the real opportunity to capture increased safety of the table saw operators in the specialty department by manufacturing this fixture as outlined according to this design report.

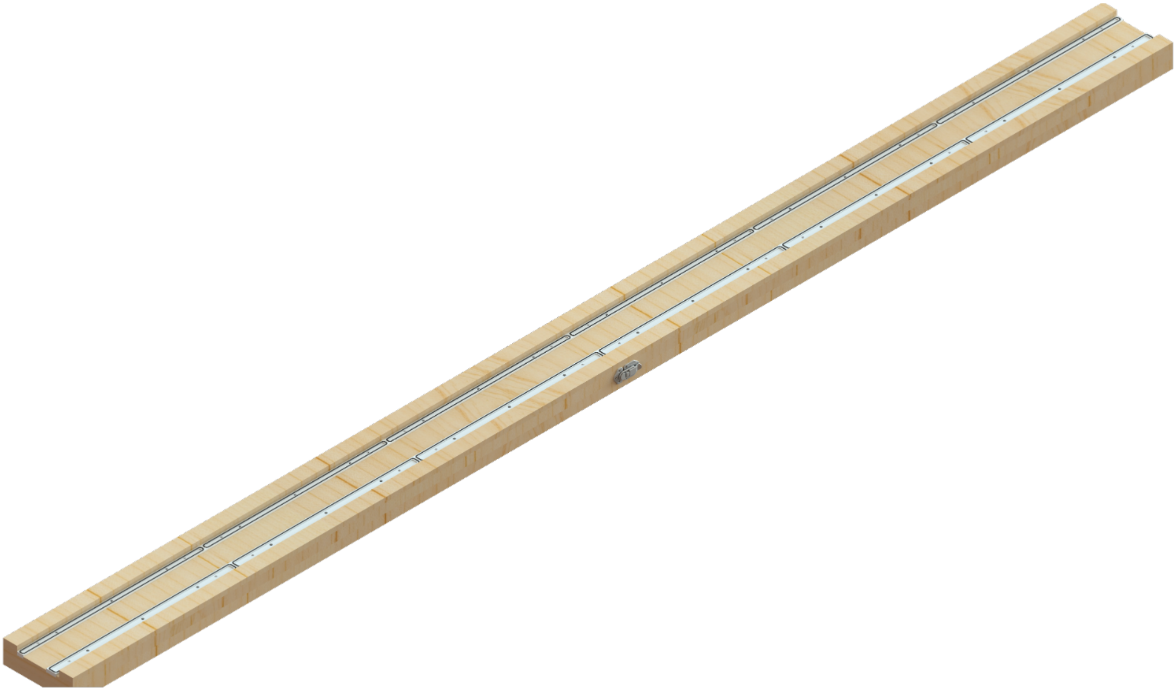


Figure 29: Full Length Design Render

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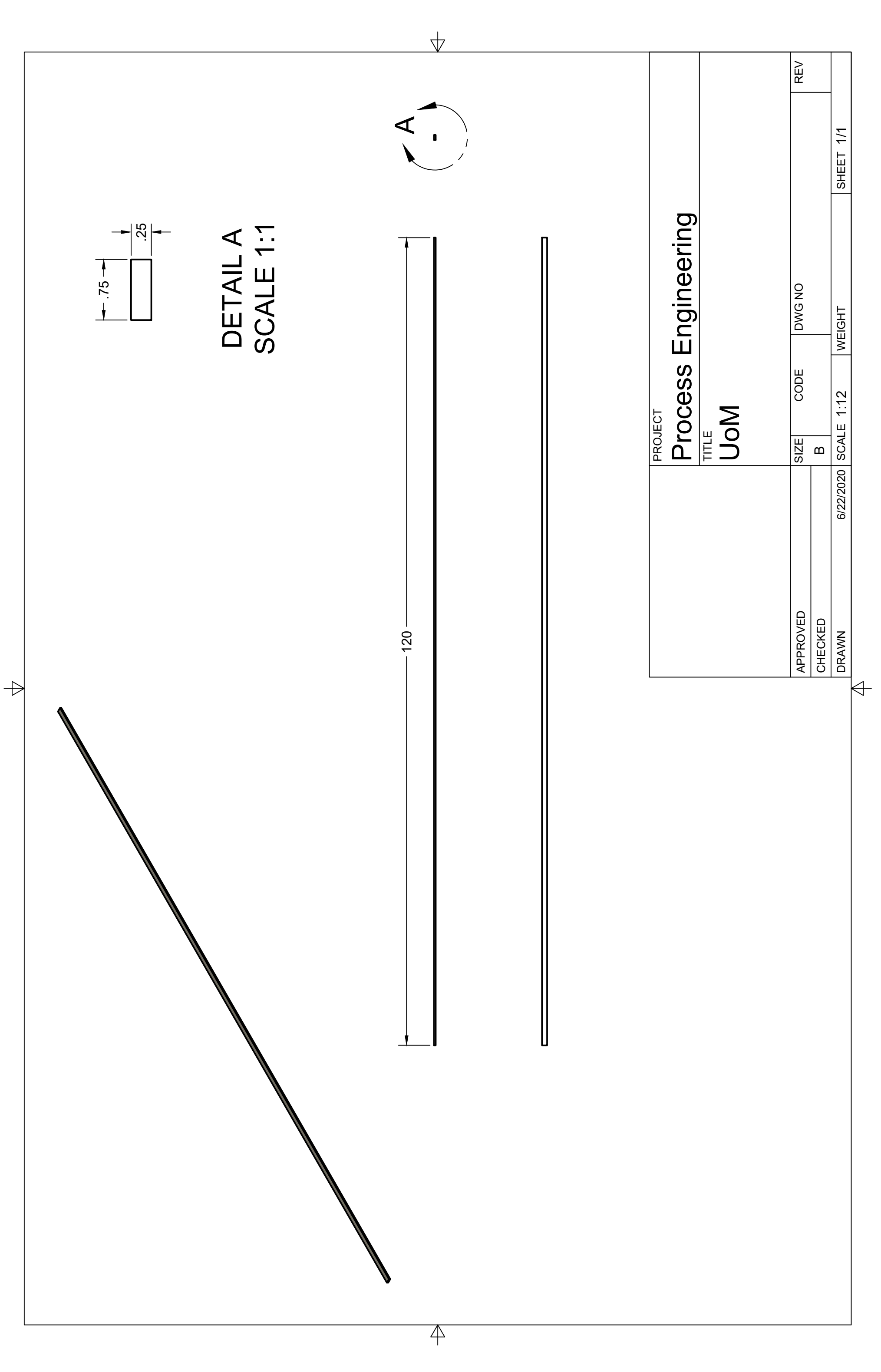
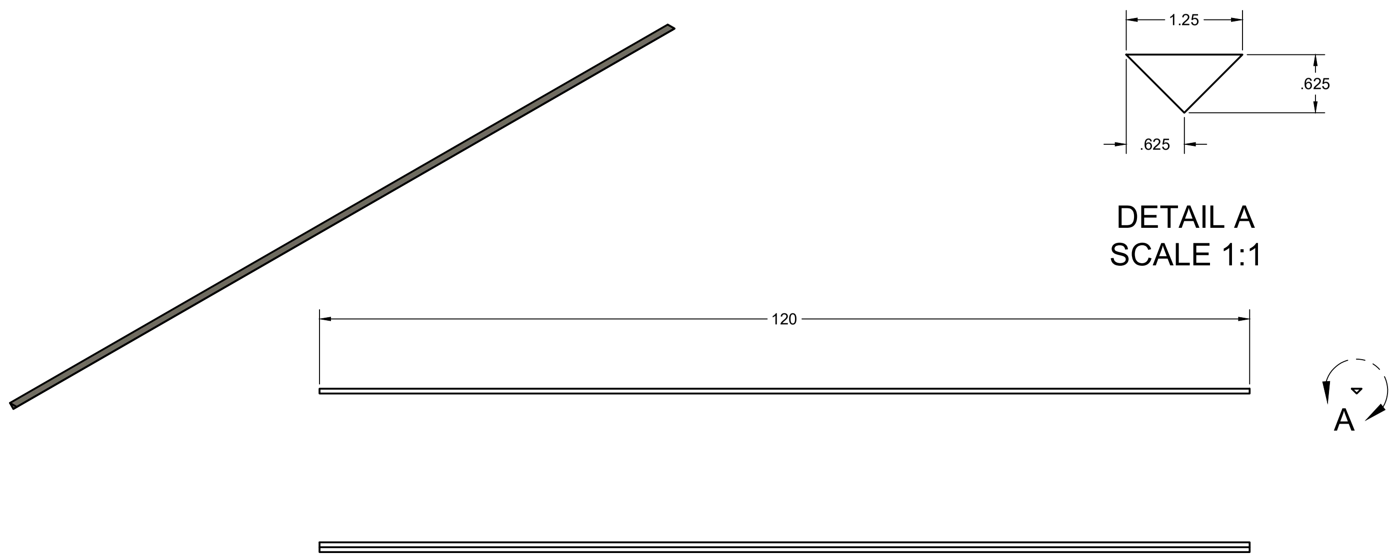
A Technical Drawings

Appendix A shows technical drawings for the two different pieces being manufactured for this project. The first is an isosceles triangle with a base of 1.25" and a height of 0.625". The second is a rectangle measuring 0.75"x0.25". Both pieces have a length of 120".





	PROJECT Process Engineering TITLE UoM			
APPROVED	SIZE	CODE	DWG NO	REV
CHECKED	B			
DRAWN 6/22/2020	SCALE 1:12	WEIGHT	SHEET 1/1	

B Cutting Force Analysis Results

This section outlines the calculations used to determine the cutting forces on the stock material with a saw blade of 350mm diameter and a kerf of 3.2mm to 4.4mm.

TABLE B-I: *CUTTING FORCE ANALYSIS*

Saw Blade Specs			
Symbol	**Value**	**Unit**	**Definition**
D	1.15	ft	Diameter
T	72	#	# of teeth
γ	16	degree	Rake angle
b	0.173	in	Width of the cut
a_b	1.18	in	Arbor
C	43.3	in	Circumference
P_i	0.6	in	Pitch

Machine Parameters			
Symbol	**Value**	**Unit**	**Definition**
N	6000	rpm	Rotation speed
FE	32.8	ft/min	Feed speed
P_max	16	HP	Max power

Maple Wood Properties			
Symbol	**Value**	**Unit**	**Definition**
τ_s	1.08	ksi	Shear strength
µ	0.4	N/A	Friction coefficient

	Actual	Recommend		
Symbol	**Value**	**Value**	**Unit**	**Definition**
a	0.02	0.02	in	Chip load

Delivered Load				
	Actual	**Recommend**		
Symbol	**Value**	**Value**	**Unit**	**Definition**
τ	21.80	21.80	degree	Friction Angle
β	39.20	39.20	degree	Shear Angle
F_s	0.27	5.92	lbf	Shear Force
F_r	0.38	8.37	lbf	Resultant Force
F_c	0.38	8.33	lbf	Horizontal Cutting Force
F_T	0.04	0.85	lbf	Vertical Cutting Force

Machine Load			
Symbol	**Value**	**Unit**	**Definition**
T	14.1	lbft	Torque
F_max	109.13	lbf	Max Cutting force

C Work holding Analysis Results

This section provides the detailed calculations of the vacuum forces used in the fixture design.

TABLE C-I: WORK HOLDING ANALYSIS DATA

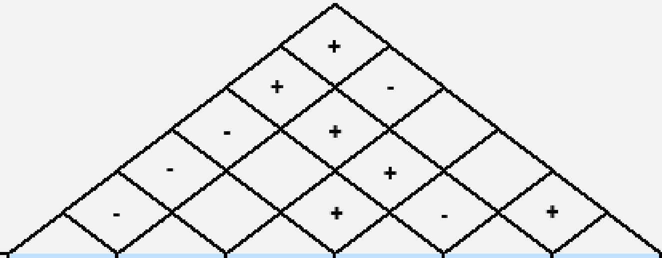
Analytical Work Holding Data					
Shape	**Moment of Inertia in^4**	**Label**	**Value**	**Unit**	
Rec Blank	1.63e-03	b	1.25	in	
		h	0.25	in	
Tri Blank	3.56e-02	b	1.75	in	
		h	0.625	in	
Vacuum Pad	N/A	L_v	19.13	in	
		w_v	0.54	in	
μ	0.7				
F_f	43.6				
F_s	4.0				
Cutting Forces (lbf)					
F_x	24.4				
F_y	2.5				
Force Analysis (Triangle)					
Force	**Value (lbf)**	**Area in^2**		**Pressure**	**Psi**
F_v	0.7	A_v	10.3	P_v	0.07
F_a	151.8	A_p	10.3	P_a	14.7
F_{eq}	148.6				
Bending Force (lbf)					
δ	1				
F_y	0.5				
Holding Forces (lbf)					
F_x	201.9				
F_y	1221.8				
Force Analysis (Rectangle)					
Force	**Value (lbf)**	**Area in^2**		**Pressure**	**Psi**
F_v	0.3	A_v	4.4	P_v	0.07
F_a	65.1	A_p	4.4	P_a	14.7
F_{eq}	62.3				
Bending Force (lbf)					
δ	1				
F_y	0.023				
Holding Forces (lbf)					
F_x	324				
F_y	535				

TABLE C-II: SUPPORT SPAN DISTANCE DATA

Rectangular Part					Fixture Beam Analysis		
Shape	**Moment of Inertia in^4**	**Callout**	**Dim**	**Unit**	**Property**	**Value**	**Unit**
Vacuum Pad	N/A	L_v	19.25	in	Modulus (MDF)	507632	PSI
		w_v	0.23	in		3.5	Gpa
		Quantity:		6	Neutral Axis	1.055	in
Fixture	12.35	b_t	7.6	in	Density	0.029	lb/in^3
		h_t	2.04	in	Distributed Mass	0.450	lb/in
		A_t	15.51	in^2	Distributed Load	14.5	lbf/in
A_1	4.19E+00	b_1	3	in	Gravity	32.17	ft/s^2
		h_1	2.5	in	Support Distance	2	ft
		A_1	7.5	in^2		26	in
A_2	5.63	b_2	2.85	in	Force	376.26	lbf
		h_2	1.81	in	y_{allow}	0.031	in
		A_2	5.16	in^2	y_{Tot}	0.003	in
A_3	2.53	b_3	1.75	in	Fs	11	
		h_3	1.63	in			
		A_3	2.85	in^2			

D House of Quality

House of Quality



Customer Importance 1: low - 3: high	Functional Requirements / Customer Requirements	Tolerance	Materials	Easy to Use	Cycle Time	Cost	Tool Protection	1. T-slot Spoil Board	2.Routed Vacuum T-Slot	3.Elevated Fingers	4.Routed Vacuum	5.Combination
								Design Concepts Competitive Evaluation				
3	*Operator Safety*	0	1	3	2	2	0	3	2	1	5	5
2	*Production Capacity*	3	1	3	3	1	5	2	3	5	4	5
3	*Quality*	3	2	2	2	1	1	2	1	2	4	5
3	*Interchangeable Feed Materials*	2	1	2	3	0	1	4	5	1	5	5
3	*Ergonomics*	0	1	1	1	1	0	1	1	4	2	3
2	*Cutting Loads*	3	2	0	0	2	1	2	2	1	4	4
2	*Tool Life*	1	2	0	0	0	3	2	4	4	2	3
1	*Part Protection*	3	2	3	0	3	1	2	3	5	4	5
1	*Tool Protection*	1	0	0	2	1	3	3	4	5	4	4
2	*Cost Reduction*	3	2	2	3	3	2	2	2	3	3	2
	Technical Importance Score	*39*	*31*	*37*	*38*	*28*	*32*	*51*	*56*	*60*	*82*	*91*
	Importance %	**19%**	**15%**	**18%**	**19%**	**14%**	**16%**	**15%**	**16%**	**18%**	**24%**	**27%**
	Priority Rank	1	5	3	2	6	4	5	4	3	2	1

		Tolerance	Materials	Easy to Use	Cycle Time	Cost	Tool Protection
Concept Evaluation(3: Best, 1: Worst)	1	1	2	1	1	2	1
	2	3	3	1	1	2	2
	3	2	1	3	2	2	3
	4	3	2	2	2	3	2
	5	3	2	3	3	1	3
Target Value/ Specification Value		+/- 1/64"	Maple and Melamine	No human interation	<=160s	<3000	No Tool Interference
Technical Difficulty (1:low,5:high)		5	3	1	5	2	3

E Drawing Package