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Product Realization Capstone: Safety Steps for the Willie Price Lab School

Christopher L. Sevigney
University of Mississippi. Sally McDonnell Barksdale Honors College

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PRODUCT REALIZATION CAPSTONE:
SAFETY STEPS FOR THE WILLIE PRICE LAB SCHOOL

by
Christopher Sevigney

A thesis submitted to the faculty of The University of Mississippi in partial fulfillment of the requirements of the Sally McDonnell Barksdale Honors College.

Oxford
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Approved by

Advisor: Dr. Jack McClurg

Reader: Dr. Jim Vaughan

Reader: Dr. Jeremy Griffin

ABSTRACT

The purpose of this document is to outline the engineering design and production development process for a safety step to be used in pre-schools. The team began by establishing customer need and moved through the design and prototyping phases. Once a design was selected, the team focused on developing a production process for the product. The project culminated in two one-hour long production runs in which the team carried out the production process to fill a customer order. The results of the first run indicated that adjustments needed to be made to the process, as the required number of pieces was not produced in the one-hour period. In the second run, the takt time was met with one piece being produced every 4 minutes and 48 seconds.

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I. INTRODUCTION

Capstone Structure

Every student at the Center for Manufacturing Excellence participates in a manufacturing capstone project before graduation. Interdisciplinary teams of students are assembled from business, accounting, and engineering backgrounds, and the team is assigned to a product development project. The team forms a business structure, headed by a CEO, to delegate responsibilities and guide their efforts. In the fall semester, the team designs and prototypes their product and in the spring, the team develops a manufacturing process. The project culminates at the end of the spring semester when the team conducts two production runs to fill a ‘customer order’.

Description of Problem

Ergonomics and human interface are significant considerations in the design of most products today. However, there is a large group of the population for whom these are largely ignored: children. For the vertically impaired, every day activities can require special attention.

The University of Mississippi is home to a pre-school, the Willie Price Lab School, whose facilities are designed for children. The hallways feature shortened water fountains, the tables and chairs are height adjusted, and even the sinks in the facility have lowered counters. Yet despite these special accommodations, some of the children still require help reaching the bathroom facilities. To help these children, the lab school employed plastic step stools and stackable aerobics steps. However, these solutions fail on multiple fronts: stability and safety, ease of cleaning, and platform height.

To improve the environment for their students, the lab school approached the Center for Manufacturing Excellence for an improved step to use in the bathroom facilities. This paper outlines the design and production of improved utility steps (Step Buddies) for students of the Willie Price Lab School to use at sinks, commodes, and water fountains. The organization chart for the team can be found below in Figure 1.

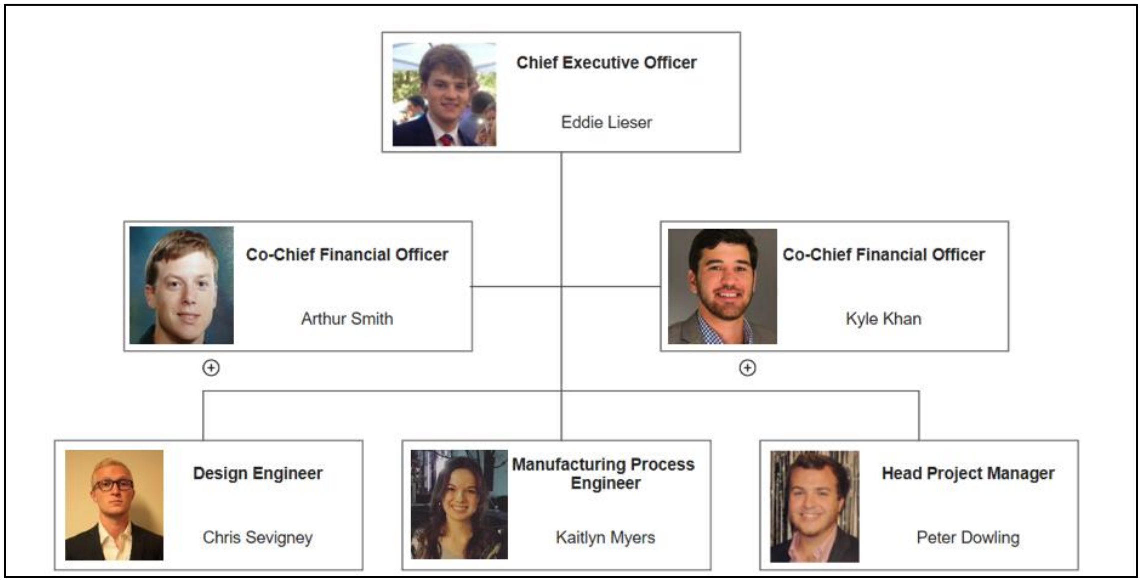


Figure 1: Organization Chart for StepBuddy Team

II. DESIGN

Customer Need

A visit to the lab school marked the beginning of the design process. The project group was led to the bathrooms, the hallway & classroom sinks, and the water fountains where the improved steps would be used. These venues could be divided into three categories: low counters, medium counters, and high counters.

At the lowest counters, children stood on their toes and leaned against the edge of the counter to reach the sinks. This worked for most students; however, it resulted in water on the countertops, which wetted the children’s shirtfronts and dripped on to the floor.

At medium counters, plastic aerobics steps, shown in Figure 2, were used to give the children a four-inch elevation. The aerobics steps had desirable platform dimensions, but the grooved rubber coating on the top was difficult to clean. Also, the height of the platform was insufficient for smaller students to reach sinks without leaning against counter tops’ edges. The floor-contacting surface of the aerobics step was plastic and did not grip well in wet conditions.

At the tallest counters, plastic step stools, also shown in Figure 2, were used for eight and one-half inch elevations. The height of the plastic step stools was well suited for the students. However, the standing area of the platform was smaller than desired, and the plastic floor-contacting surface of the step stool did not grip the floor in wet conditions.

Following the tour, the team spoke with employees of the lab school to determine what they liked and disliked about the current steps. The height of the taller platform accommodated a larger number of the students and allowed them to access the sinks without standing on their toes or leaning against the counter. However, the larger standing area of the aerobics step was preferred, since the positioning of soap and paper towel dispensers often required students to adjust their feet while washing their hands. Finally, both devices being used were prone to slipping on wet floors, and a solution to this problem was requested.

Based on these findings step height, platform size, and user safety were established as key objectives for the StepBuddy. Additionally, the customer had a budget constraint of $75 to $110 per step, and this would need to be considered as the team began the research phase.

Figure 2: Aerobics Step and Plastic Step Stool [1, 2]

Existing Products

To research existing products, the team relied on the Internet. Through image search engines and youth-product retailers, three predominate styles of steps were discovered: stools, boxes, and platforms.

The stool-type step was similar to the tall step being used at the lab school. Commonly injection molded from plastic, the stools had a solid standing platform elevated by four slender legs. The stools were the cheaper options on the market, and the level of safety and stability that these steps provided were in line with their price point.

The box-type step constituted most of the existing products. These steps were predominately built from plywood and consisted of a solid standing area supported by four solid walls. Some designs included gripping feet for floor contact or grip-tape lined standing surfaces, but these were exclusive to the high-end products.

The platform-type step was found by Internet image search. These had a completely wooden construction and were composed of a platform supported by solid walls on the left and right. The platform-type step exhibited the most easily enlarged platform size of any of the steps. An example for each of the three styles is shown is shown in Figure 3.

Research of existing products yielded several observations. First, it was determined that wood was an acceptable step material due to its appearance and durability; however, it would need to be coated or treated to withstand use in wet environments. Second, the base of the step would need to grip the floor in both wet and dry conditions. Third, the top of the step should be made from a material on which the students' feet would not slip and whose surface could be easily cleaned.

Figure 3: Stool, Box, and Platform Style Steps [2, 3, 4]

Brainstorming

After defining the problem, the team came together for several brainstorming sessions. During these sessions, the team distilled many loose ideas into a few practical considerations that will be discussed below.

The first matter of discussion arose while determining dimensions for the step. While comparing the heights of the aerobics step and the step stool, the option of an adjustable height step was investigated. Including an adjustable height feature would allow the lab school's teachers to fine-tune the height of the step according to the height of the counter at which it would be used. However, adding height variability would add to the cost of production significantly, and the durability of a single piece design outweighed the convenience of the small height variations to be offered.

Step construction was the next matter of investigation. The box and platform style steps were the best options that we had seen from retailers. The box style-step would be strong and stable, while being capable of manufacture with the machines currently in the CME. However, the platform-type step also provided these features, in addition to allowing for ventilation below the step.

The final consideration that was discussed was how a non-slip surface could be attached to the standing surface of the step. The team had found a non-slip rubber mat material with a diamond tread pattern, and all agreed that it would be an ideal material choice. The material was manufactured in 1/8” inch thick rolls, which led the team to consider two manners for attachment: wrap or inlay. Wrapping the material around the top edges of the step would provide a padded edge to cushion any kicks or falls against it, and extensive machining would not be necessary to prepare the wooden components for the rubber to be applied. However, covering corners with rubber would involve complex cuts on the rubber sheet, and the procedure for wrapping the rubber around the step could grow time consuming. Inlaying the rubber would make assembly of the parts simpler; rather than pulling, flipping, and clamping, inlaying would require the worker only to adhere the rubber piece in the appropriate recession. On the other hand, a recession would need to be cut into the wooden platform to prepare for the rubber application, which could become a labor and tool intensive feature to add.

From these considerations, two concepts emerged: a box type step with an inlayed rubber standing area and a platform type step with a wrapped rubber standing area. From these, the platform step was selected as the better design for the following reasons. First, the platform step required fewer unique parts. Second, the rubber wrapping process on the platform would provide equal aesthetic merit to the inlayed rubber on the box, while being easier to manufacture. Finally, the airflow allowed by the platform would provide superior performance in wet conditions. With a concept selected, the team was ready to begin prototyping.

Initial Design

The initial design, or Step Buddy Alpha, was a platform-style step. It was constructed of two legs cut from 2” x 8” pine lumber, a top platform cut from ¾” plywood sheet, and a rubber cover for the top which was wrapped around and under the front and back of the standing platform. The Alpha step provided a seven-inch elevation from the floor with a 11” x 18” standing surface. The components were assembled with wood glue, and a nail gun was used to fasten the pieces together as the glue dried. The legs were coated with a spray-on water resistant clear coat. The rubber top was attached with wood glue and clamped between flat boards for curing.

After producing the first prototype, it was quickly realized that some modifications would be required. An adult standing on the step with their feet together caused minor bending of the platform. To fix this, a 2” x 2” pine cross-member was added on the underside of the platform, increasing its rigidity. The initial design can be seen in Figure 4.

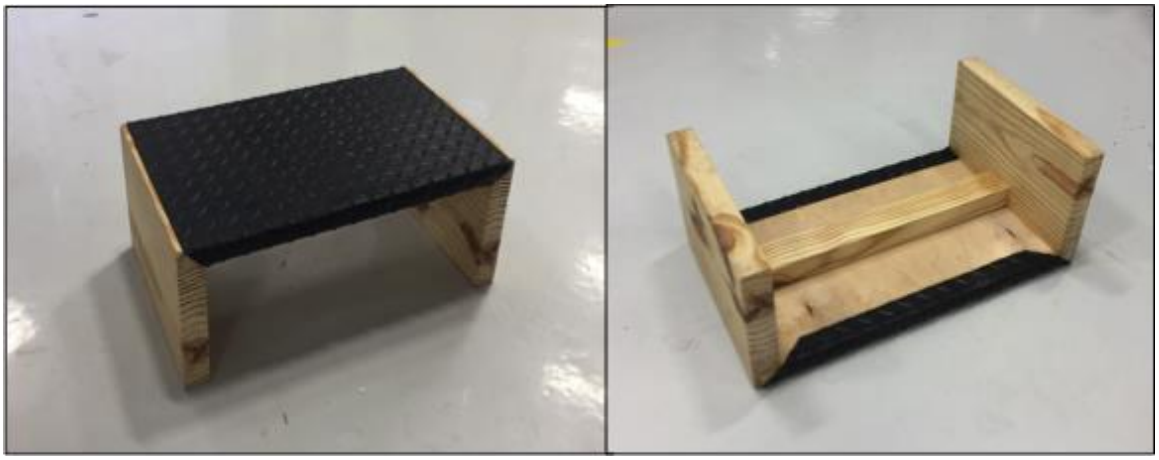


Figure 4: Initial Design with Cross-member Modification

Customer Feedback

There were several aspects of the initial design that the customer was pleased with. The materials were in line with their expectation, and they had the sense that the step was sufficiently strong and durable for their applications. The appearance of the step, while minimalistic and industrial, was pleasing to the customer; the estimated price of the step was well within the customer's budget.

The customer provided a few desired improvements with their feedback. Firstly, an improved floor-contacting surface was requested. The alpha prototype did not include any feet, resulting in a mild rocking motion of the step when placed on hard, uneven surfaces. Second, a larger standing surface was requested. The alpha prototype's platform dimensions were a compromise between the lab school's existing solutions. This meant that the user could not move their feet or turn easily while on the step. A larger platform would allow the user to reach, turn, and shuffle as needed while using the hand washing facilities. Third, the edges and corners on the Alpha prototype were square and sharp. To increase the safety of the product, the customer wanted the edges rounded and the corners softened. These suggestions were implemented in the final design.

Final Design

Success of the final design was determined by three key criteria. The first requirement was strength and stability. The step would need to safely accommodate every student of the lab school, regardless of size or weight. The second requirement was safety. Small children are often still developing their sense of coordination, and this must be considered when designing products for them. The step was designed to be forgiving to the unbalanced user with a rubber front edge to cushion blows to the shin and sufficient platform space for turning and moving about the step. The third requirement was ease of cleaning. As the customer conveyed, children can be very messy and often leave their surroundings dirty. Certain materials and finishes make spot cleaning or disinfecting difficult, so the product would need to accommodate regular cleaning by the limited Lab School staff. The goal of this team was to provide a product that fit these criteria while maintaining an attractive appearance.

To deliver on these goals, the team adopted the following construction. The step is built from two sides (legs), a top platform (the standing surface), a rubber mat to cover the standing surface, a cross-member, and slip-proof feet. The step is designed to provide seven inches of elevation, with a substantial platform of twenty-six inches in width and sixteen inches in depth.

The legs are constructed from pine and are designed with considerable thickness to bear the load of any student. The outer edges and corners are rounded to reduce the risk of injury, improve the feel of the product, and provide a “finished” appearance to the product. The outer faces of the legs feature a natural wood appearance and are coated with a waterproof sealant to improve performance in wet environments and facilitate greater ease of cleaning.

The top platform is constructed of ¾” inch plywood to sufficiently support the weight of any child. High quality plywood is used to ensure lasting performance and minimal wear for many years. As a safety feature for the students at Willie Price, a rubber mat lines the standing platform. This mat features a non-slip, easy-to-clean diamond pattern, and is wrapped around the top, front, and back faces of the top platform component to be fastened on the underside. Wrapping the rubber improves the appearance of the step while providing a cushioned surface to protect the user’s shins from any potential mis-steps. Additionally, the rubber’s top facing standing surface is recessed (making it flush with the bordering wood) to facilitate easier cleaning, to provide a visual indication of the portion of the step on which to stand, and to improve the step’s overall appearance.

Under the platform, a cross-member bridges the span between the legs. This provides a factor of safety to the load bearing capabilities of the plywood top platform and improves the lateral stability of the step. The load bearing capability of the step is enhanced by increasing the cross section of the platform, which reduces the bending moment resulting from a child’s weight. Drawings and dimensions for all components can be found in the Appendix, Figures A1 – A5.

To finish the step, four non-slip feet (manufactured by 3M) are added to prevent the step from sliding on wet or slick surfaces. This greatly improves the user's level of confidence when mounting, using, and dismounting the step and further ensures the safety of the preschoolers.

The customer's feedback was positive on this design, and the design was approved by the CME faculty. Accordingly, the design was deemed final and the StepBuddy team's attention shifted towards production. The product of this final design can be seen in Figure 5.

Figure 5: Initial (left) and Final (right) Designs

Design Calculations

The lab school has children of age three to five years old. According to the CDC, the heaviest ten percent of five-year-old children in the U.S. weighs approximately fifty pounds. In designing for this application, calculations were made for a three-hundred-pound load, which gives the step an approximate factor of safety of six. Figure 6, below, illustrates the free body, shear, and bending moment diagram for the loading situation that the step was designed for.

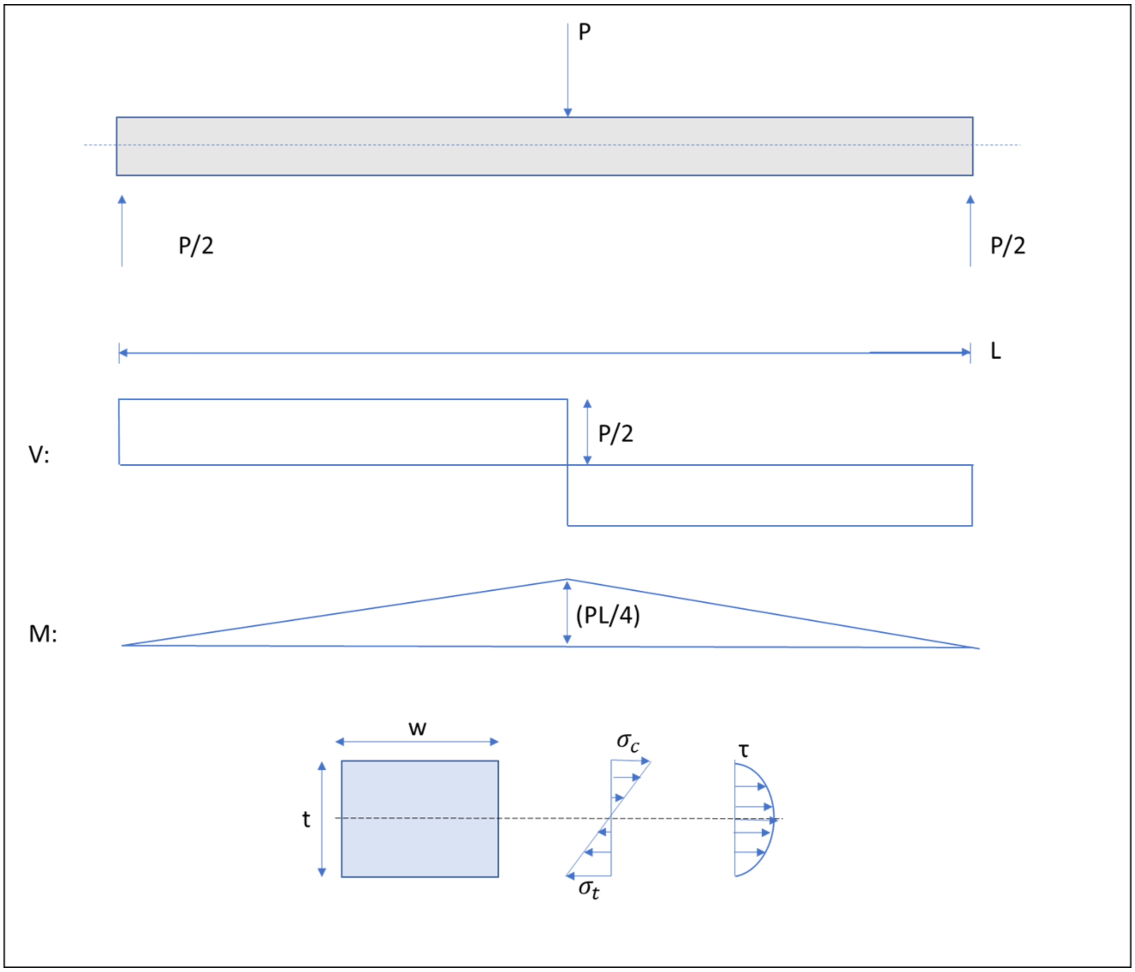


Figure 6: Free Body Diagram, Shear & Bending Moment Diagram

$$\sigma_{max} = \frac{M_{max} y}{I} = \frac{(PL/4)*(t/2)}{(\frac{wt^3}{12})} = \frac{(300lb*26in/4\ )*(0.75in/2)}{(16in*(0.75in)^3)/12} = 1300\ PSI \tag{2-1}$$

Equation 2-1: Equal Tensile and Compressive Bending Stresses on Plywood Top Platform with no Crossmember

$$\tau_{max} = \frac{QV_{max}}{Iw} = \frac{(wt^2/2)*(P/2)}{\left(\frac{wt^3}{12}\right)*(w)} = \frac{(16in*0.75in^2/2)*(300lb/2)}{\left(\frac{16in*0.75in^3}{12}\right)*(16\ in)} = 75\ psi \tag{2-2}$$

Equation 2-2: Shear Stress on Plywood Top Platform with no Crossmember

Equation 2-1 uses the results of Figure 6 to calculate the maximum tensile and compressive stresses on the plywood due to bending from the applied load. As the board is bent, tensile stress occurs on the bottom face of the platform, and compressive stress occurs on the top face of the platform. The tensile and compressive loads are equal for the vertically symmetrical beam, with magnitudes of 1300 psi. Equation 2-2 calculates the maximum shear stress at the vertical centerline of the platform, which was found to be 75 psi. Plywood has compressive strength of 4500psi, tensile strength of 4000psi, and shear strength of 250psi [6]. Based on this, the platform would be sufficient to support the 300 lb load without a crossmember. However, the prototyping process revealed the need for a crossmember to increase the lateral stability of the step and to compensate for deviations in the plywood's quality.

The tensile, compressive, and shear stresses exerted by the same 300lb load are calculated with the inclusion of the crossmember in Equations 2-3, 2-4, and 2-5. In the calculations, the platform and crossmember components are considered as a single T-shaped beam, and the combined moment of inertia is derived from the parallel axis theorem. The results show that there is a maximum tensile stress exerted on the bottom face of the pine crossmember of 708psi, a maximum compressive stress exerted on the top surface of the plywood platform of 238psi, and a maximum shear stress of 51psi at the centerline of the complex geometry, which lies inside of the plywood's cross section. Again, the compressive and shear stresses exerted on the plywood were less than the materials compressive and shear strengths. The pine lumber has a tensile strength of 11300 psi, meaning that the applied stress should be within the material's limits [7]. This analysis is completed more fully in the Appendix [8, 9, 10].

$$\sigma_{max,tension} = \frac{M_{max}y}{I} = \frac{(1950\ lb.in\ )*(1.87\ in)}{5.15in^4} = 708\ PSI \qquad (2\text{-}3)$$

Equation 2-3: Tensile Bending Stress on Plywood Top Platform with Crossmember (at Bottom Surface of Pine Crossmember)

$$\sigma_{max,compression} = \frac{M_{max}y}{I} = \frac{(1950\ lb.in)*(0.63\ in)}{5.15\ in^4} = 238\ PSI \qquad (2\text{-}4)$$

Equation 2-4: Compressive Bending Stress on Plywood Top Platform with Crossmember (at Top Surface of Plywood)

$$\tau_{max} = \frac{QV_{max}}{Iw} = \frac{(16in*0.75in^2/2)*(300lb/2)}{\left(\frac{16in*0.75in^3}{12}\right)*(16\ in)} = 51.3\ PSI \qquad (2\text{-}5)$$

Equation 2-5: Shear Stress on Plywood Top Platform with Crossmember (at neutral axis in plywood)

III. PRODUCTION

Prototype Process: Single Piece

Production of the legs is shown graphically in Figure 7. The raw material that was used is 2” x 8” x 8’ pine lumber, shown in panel (a). Using a compound miter saw, one 33” piece was measured and cut from the long board, shown in panel (b). This short board was taken to the planer. Using the planer, the thickness of the board was reduced to 1 ¼” using approximately 1/32” increments, shown in panel (c). The final thickness of the planed board was within one thousandth of an inch of the 1 ¼” nominal dimension. A total of six passes were used to bring the board to the appropriate thickness. The 33” x 8” board was then ripped to 7 ¼” inches in width on a table saw. A second rip cut was made to remove the raw edge of the board, bringing the width to 7”, shown in panel (d). Next, the table saw was used with a miter gauge to crosscut two sixteen-inch sections from the board, shown in panel (d).

The two squared 16”x7”x1 ¼” boards were then taken to a second table saw with a dado-blade attachment. The height of the dado blade was set to three quarters of an inch, and the table saw’s fence was set to create a 7/8” wide notch. Using the dado blade, a notch was cut into one of the long edges of each of the boards. However, because the width of the desired notch was greater than the width of the dado blade, a second pass had to be made to extend the notch past the edge of the board. The notched board is shown in panel (e). Once the notch was cut into both leg pieces, a table-mounted router was used to round the non-floor facing outside edges of the board. To avoid chipping and damaging the parts, the cross-grain edges were routed before routing the long edge going with the grain. This is shown in panel (f). Finally, the legs were taken to a belt sander to smooth the outside faces and round the sharp upward facing corners of each leg.

Figure 8 demonstrates the initial steps of production for the plywood platform component of the StepBuddy. A table saw was used to cut the plywood platform from an 8’x4’ sheet of three-quarter inch plywood sheathing, shown in panel (a). The fence was set to cut a 48” by 26” strip from the plywood sheet. The resulting strip is shown in panel (b) The fence was then adjusted to cut a 16” by 26” rectangle from the plywood strip, shown in panel (c). With this, the plywood platform was complete.

Figure 9 demonstrates the initial production steps for the cross-member component. To create the cross beam, a 2” x 2” x 8’ pine furring strip was used, shown in panel (a). With a compound miter saw, several inches were trimmed off the end of the strip. This was done to remove the staple which held the price tag to the end of the strip and to ensure that the end of the part was square. A 24 ½” section was then cut from the strip, shown in panel (b). With this, the cross-member was complete.

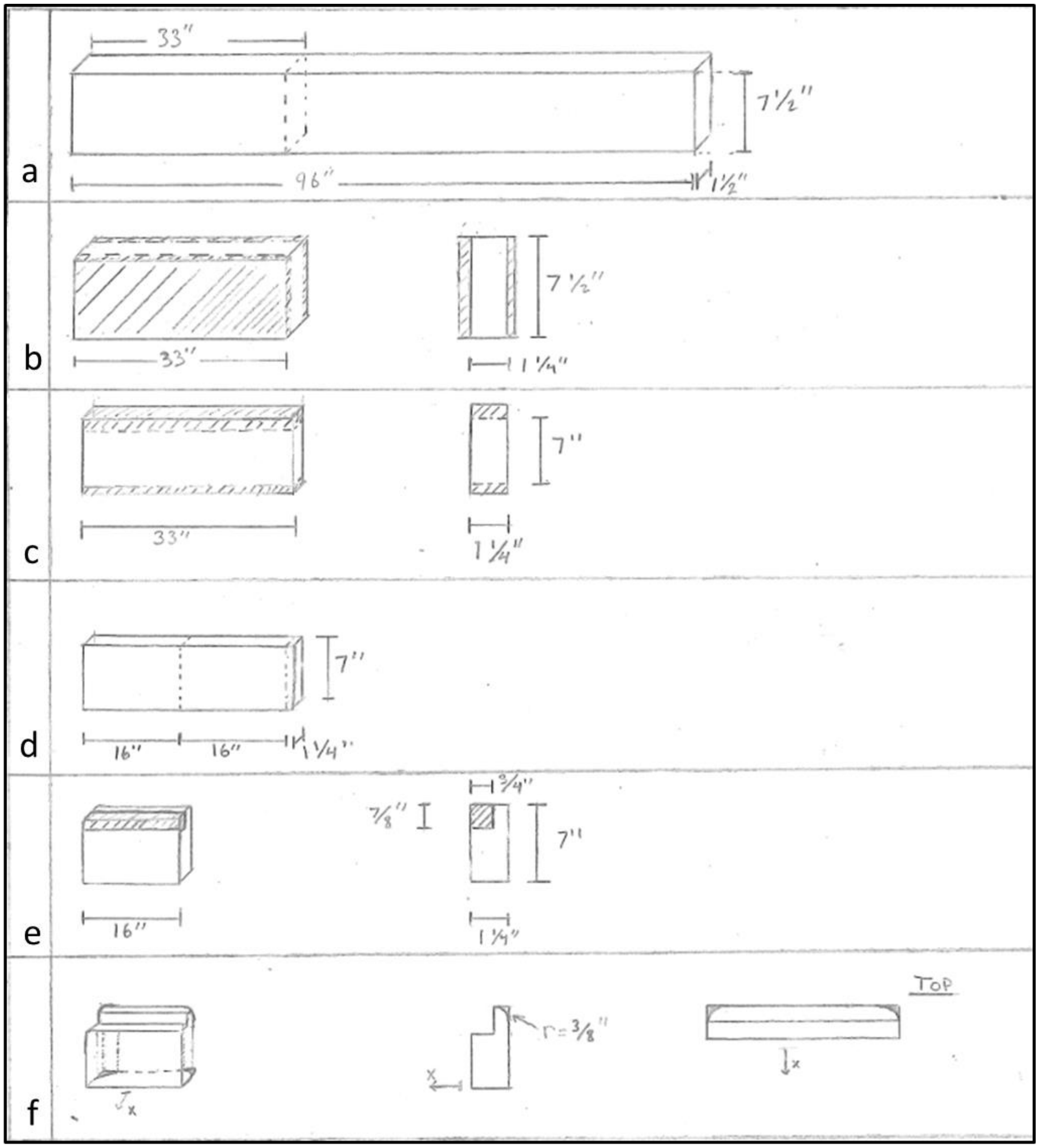


Figure 7: Initial Component Production Process – Leg

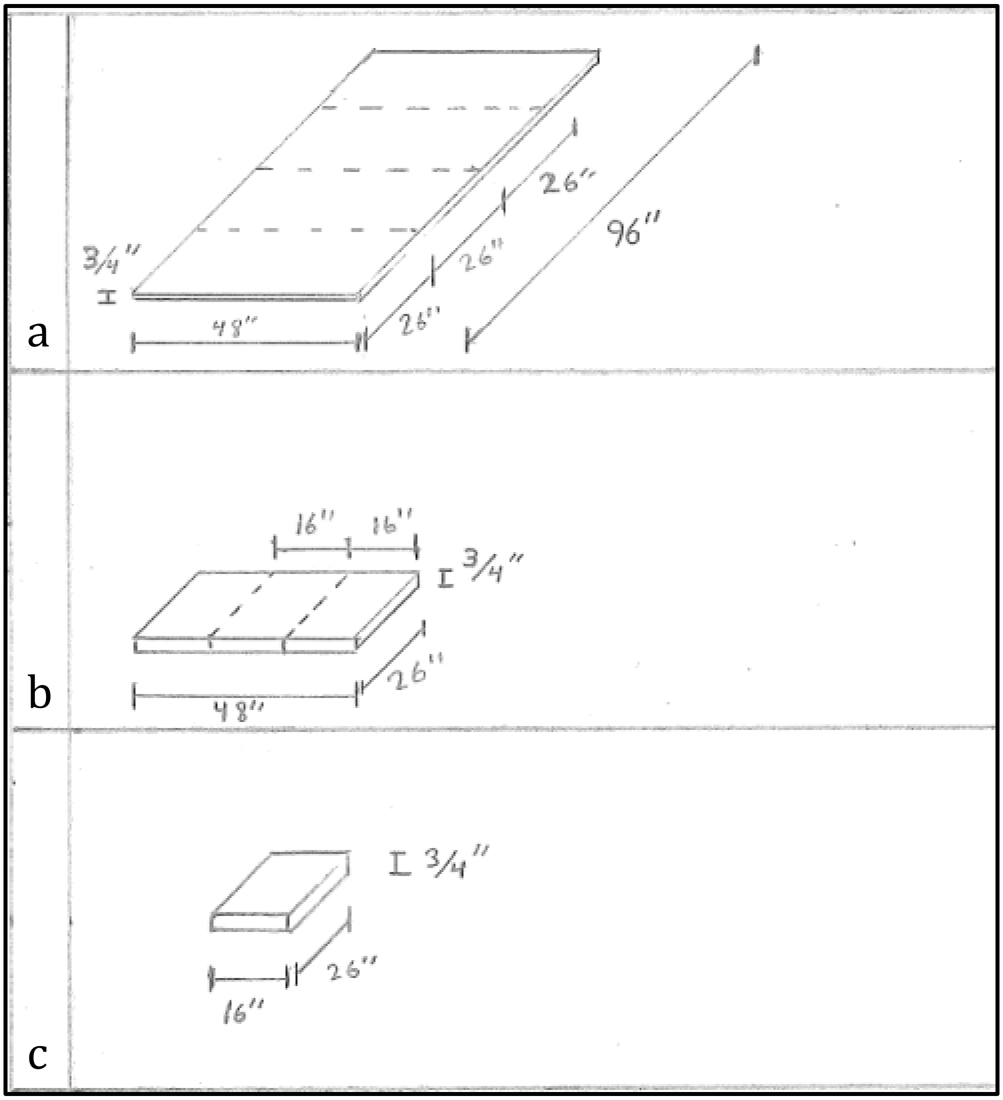


Figure 8: Initial Component Production Process – Platform

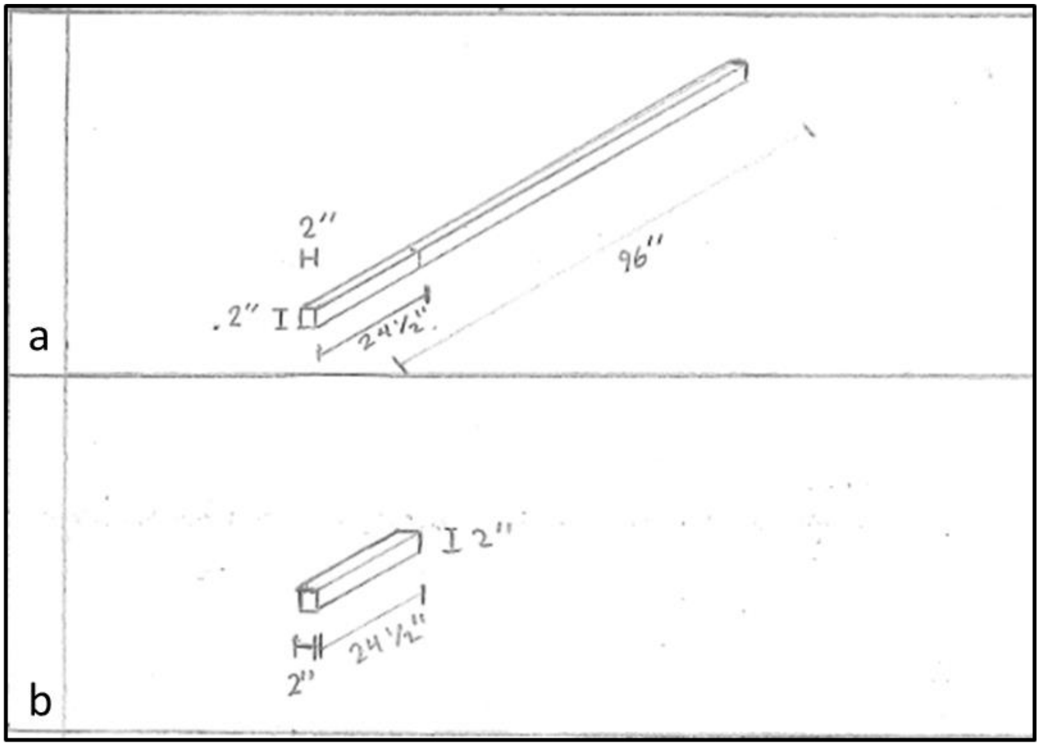


Figure 9: Initial Component Production Process – Crossmember

Figure 10 demonstrates the initial steps of production for the rubber cover piece. Production of the rubber cover piece began with a 48” wide by 108” long roll of rubber, shown in panel (a) and a hydraulic shearing machine. To prepare the hydraulic shearing machine, a working platform had to be improvised with a large piece of sheet metal, which can be seen in Figure 11. Using the tool’s attached ruler and compensating for the blade’s offset, a 26” x 48” strip was cut from the roll of rubber, as shown in panel (b) of Figure 10. The shear was then used to cut two 26” x 22” rubber rectangles out of the 26” x 48” strip. A 26” x 22” rectangle is shown in panel (c). The rubber was then taken to the cutting station where a template was placed on top of the rubber and traced with a utility knife to remove the corners of the material, shown in panel (d). The template would only fit on the long edge of the rectangle, and this minimized mistakes. The completed rubber piece is shown in panel (d).

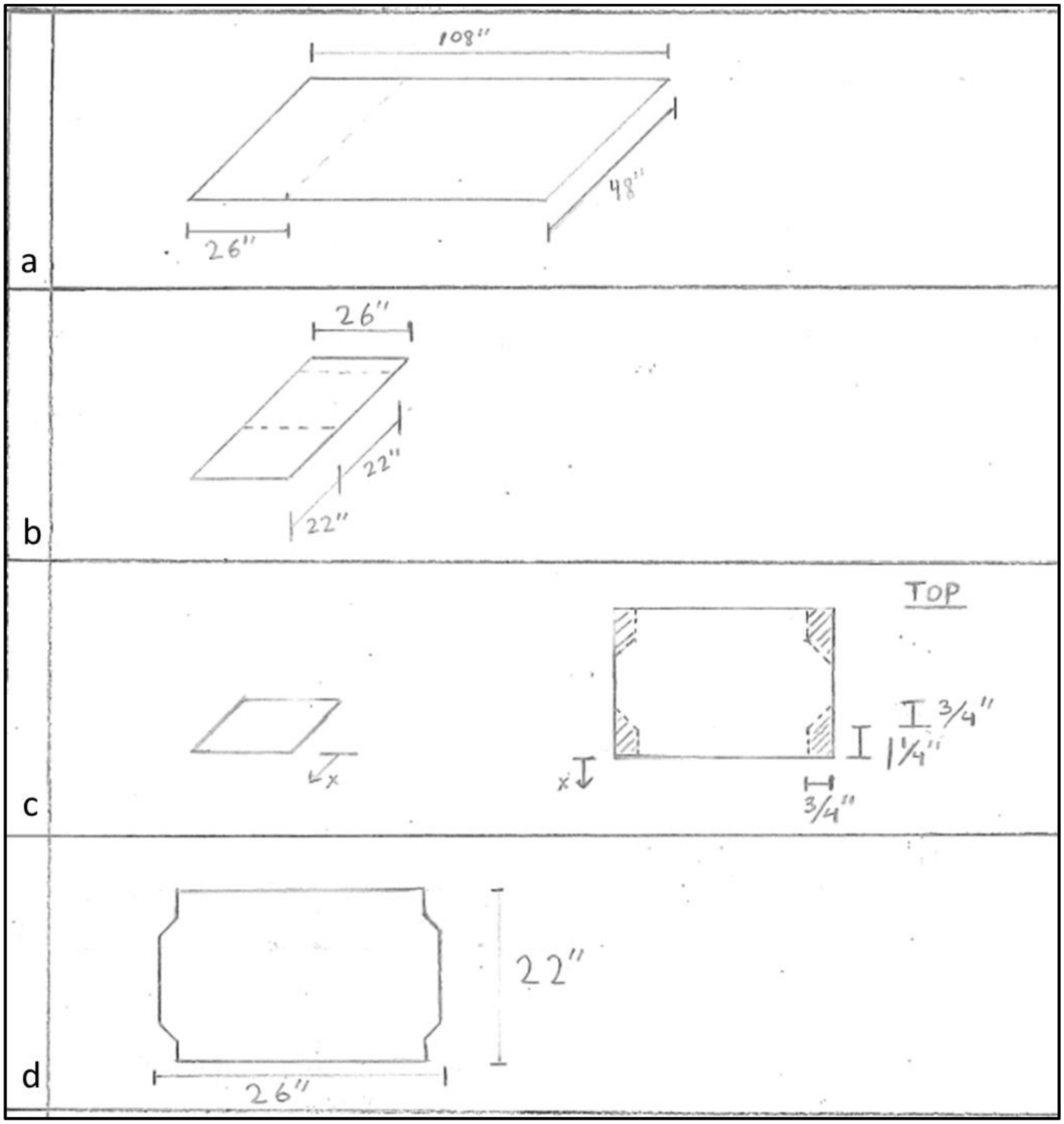


Figure 10: Initial Component Production Process - Rubber Cover

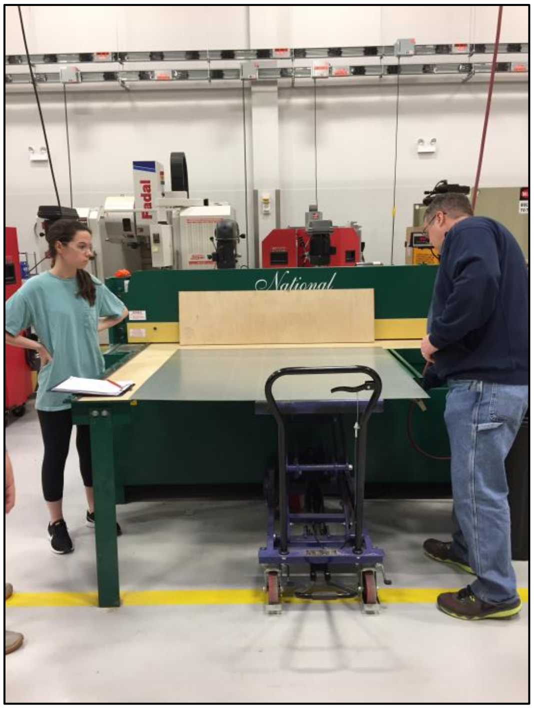


Figure 11: Hydraulic Shear for Cutting Rubber Strips

With the component parts completed, it was time for assembly. First, the legs were balanced upright, and the plywood platform was dry-fitted. The plywood top was then removed, and Titebond II wood glue was applied to the upward facing face of the notch on each leg in one thick line, as shown in panel (a) of Figure 12. The plywood top was then placed into the notch, and the front and back edges were aligned with each leg. A nail gun with 1 ¾” brad nails was used to fasten the plywood top to the legs while the glue cured. This is shown in panel (b). The step was then flipped upside down and placed on the worktable, as shown in panel (c). The midline of the plywood platform was then marked with a pencil on the underside of the step. A line of glue was then applied to the cross member, and the cross member was placed on the pencil-marked midline. The cross member was then nailed into place through the sides of the legs. The attached crossmember is shown in panel (d). The step was then flipped right side up. Nails were driven through the plywood top and into the cross member across the width of the step. With all the wooden components assembled, a weight was placed on top of the platform, and the glue could dry overnight. The next day, the weight was removed, and a palm sander was used to soften the leg’s sharp corners and smooth the outside faces of the legs. Once smoothed, a paper towel was used to clean the wood dust off the part. All visible faces, and the floor contacting faces of the legs, were then coated with Krylon’s spray-can clear coating by spraying multiple light coats and allowing it to dry. With the clear coat applied, the final step was to attach the rubber platform cover. The step at this phase is shown in panel (f).

To attach the rubber platform cover, a large amount of wood glue was dispensed from a squirt bottle onto the wooden platform surface. A cardboard rectangle was then used to spread the glue into a thick, even layer covering the plywood surface. The rubber was then placed onto the glue, and a flat board and weight were placed on top of the rubber to flatten it while it cured. Once the glue dried, the weight and board were removed, and the step was flipped upside down. Glue lines were then applied to the underside of the step along the edge where the rubber would wrap around and be stuck to (approx. 2 ¼” band along the edge). Working from one leg to the other, rubber was then pulled tightly around the plywood, and nailed to the underside of the platform with ¼” nails. Once nailed into place, a wooden slat was clamped over the glued section to flatten the rubber against the glue. The wrapping procedure was carried out for the front and backsides of the step. Once the glue dried, the clamps were removed. Four 3M non-slip feet were placed on the bottom of the step (two feet per leg). The completed step is shown in panel (f) of Figure 12.

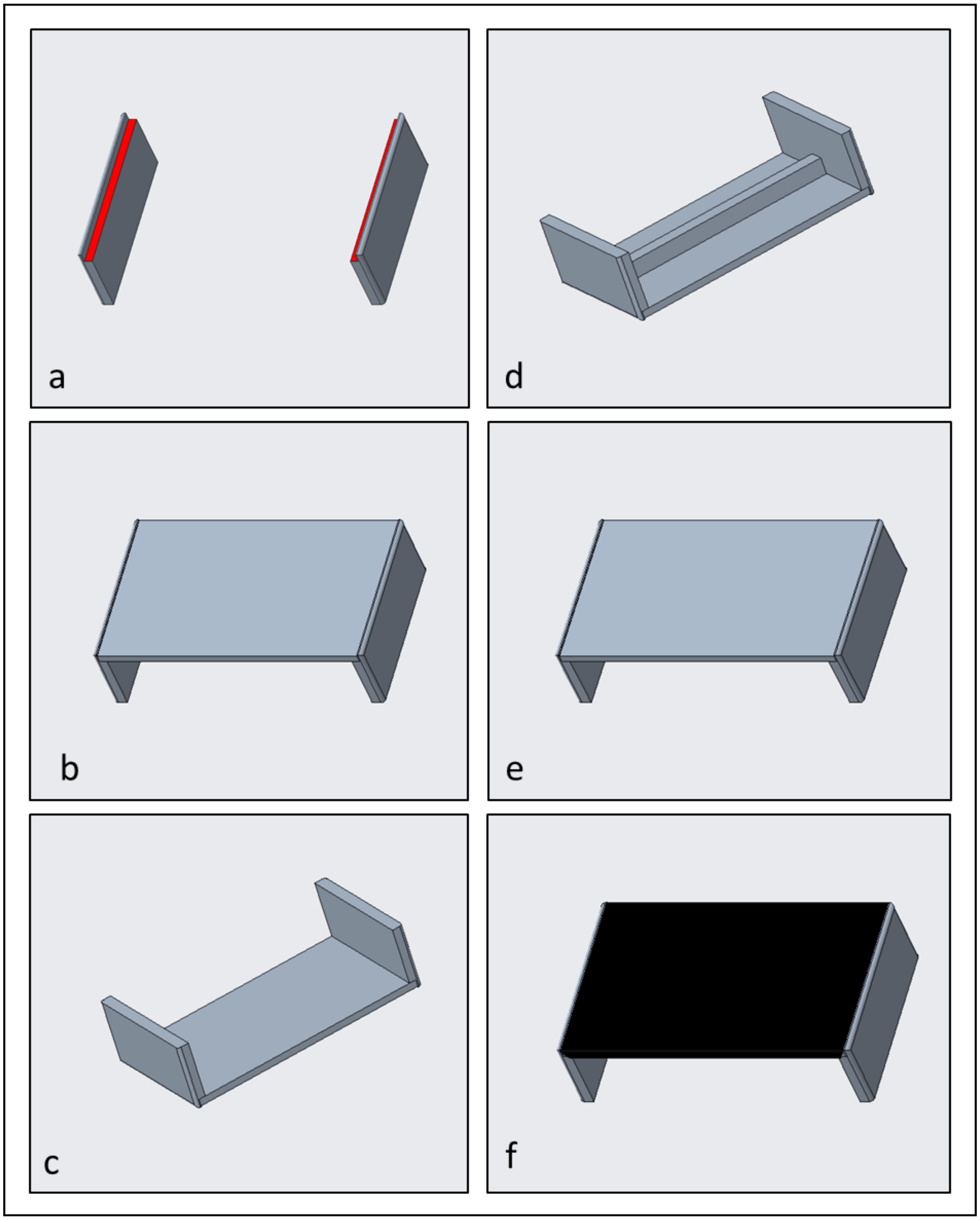


Figure 12: Initial Production Process – Step Assembly

Process Development

The single piece process required several changes to adapt to multiple piece production, and the revised procedure is illustrated in Figure 13. For the legs, the raw 2”x8” boards would be planed as a single board, shown in panel (a). Once planed, the board would immediately go to a compound miter saw, where 16” leg blanks would be made, shown in panel (b). Planing the long board as a single piece would save time over planing multiple small pieces. Also, cutting the boards to 16” immediately would improve the one-piece flow characteristics of the process. Once cut to blanks, the material would only be worked on from one side, rather than attempting to square both sides of the material. The time requirement and noticeable inaccuracy of quick table saw adjustments associated with squaring both long edges of the board outweighed the value added to the product.

The leg blanks would be ripped to their final 7” width by making two passes on the dado-blade saw, instead of cutting it to size on the normal table saw blade. The time to change the blades in the table saw was excessive, and the option of using two separate table saws was not a possibility, as the extra saw was needed to produce the plywood platform pieces. Making multiple passes on one saw was the best solution to the equipment capacity issue. Panel (c) demonstrates the sequence of cuts made with the dado-blade to rip and notch the leg blanks. The remainder of the leg making process was unchanged, as shown in panels (d).

The plywood platform piece would also face process changes. Cutting the full sheets of plywood into workable sizes was a two-person process, and it was determined that the cost of the extra person was unnecessary. Instead, the work of precutting the plywood sheet into 26” x 48” strips would be outsourced, and the 26”x48” strips would be kept as inventory for use in the assembly line. While keeping inventory has a cost associated with it, the benefits of making the process more consistent (only cutting rectangles from strips rather than making both strips and rectangles) and freeing up an extra employee outweighed this cost.

The rubber cover piece would see a simplified production procedure, shown in Figure 14. Rather than using the hydraulic shear, a full template of the rubber cover piece would be placed directly onto the roll of rubber, shown in panels (a) and (b). The outside edges of the template would then be traced with a utility knife to produce the rubber cover piece. The completed component is shown in panel (c).

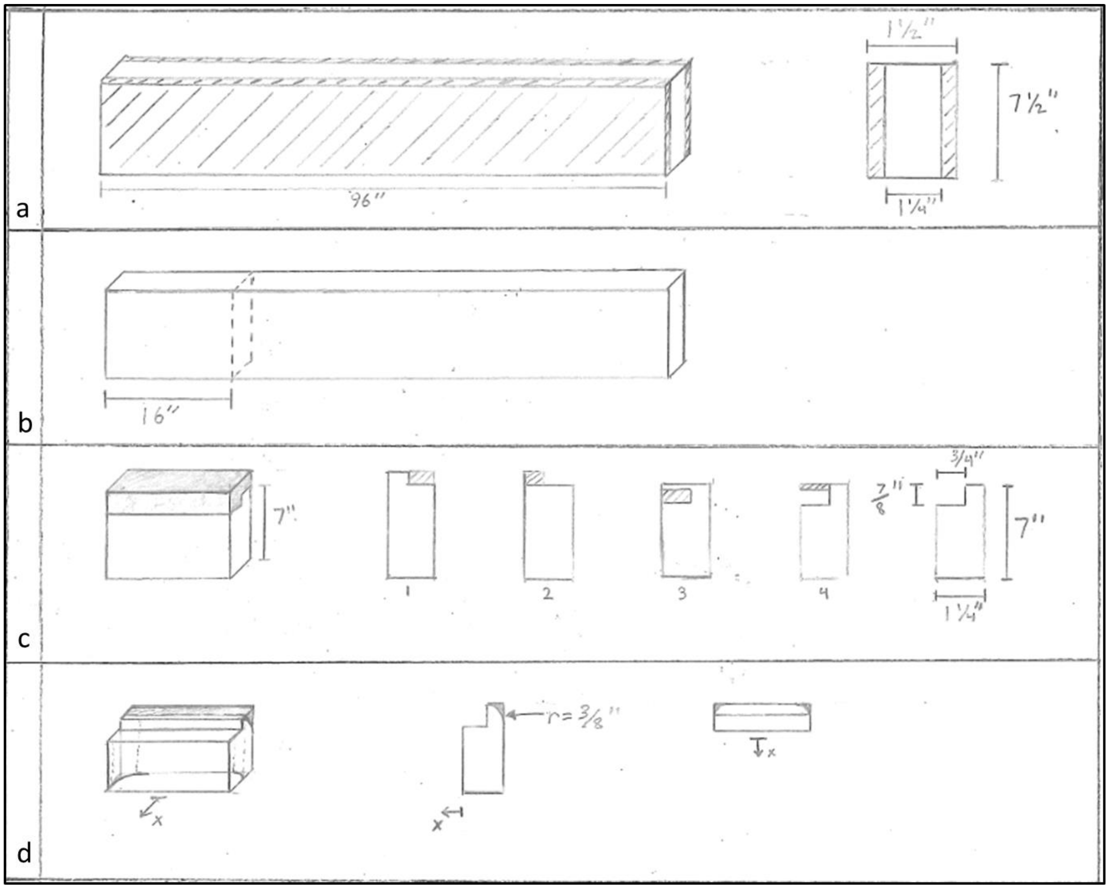


Figure 13: Revised Component Production Process – Leg

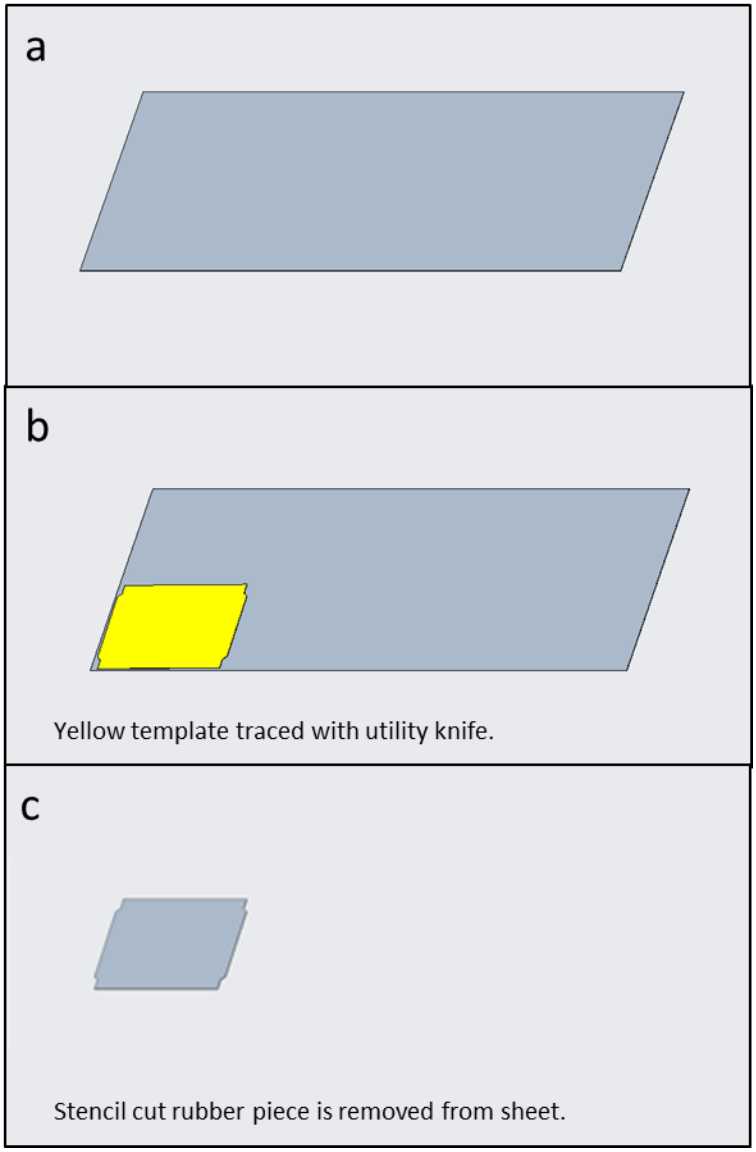


Figure 14: Revised Component Production Process – Rubber Cover

The assembly process for the wooden components would face improvements to adapt to multiple piece production as well. The revised assembly process is shown in Figure 15. A jig was introduced to allow for more stable and simplified assembly, shown in panel (a). During assembly, the legs would be placed on the outsides of the jig, the cross-member would fit into a slot on the top of the jig, and glue could be applied to the cross member and legs simultaneously, as shown in panel (b). The plywood top would then be placed, and a nail gun could be used to fasten the wooden pieces for drying, as shown in panel (c). Inclusion of this assembly jig made the assembly procedure safer by increasing the stability of the component pieces, and it made the procedure easier, as the step would no longer need to be flipped upside down during the wooden component assembly.

Finally, the rubber attachment procedure was modified to complete all gluing and attachment in one station. Rather than attaching the rubber to a single face before drying, the rubber would be completely glued, wrapped, and clamped before being set aside for the glue to cure. The finished step is shown in panel (d).

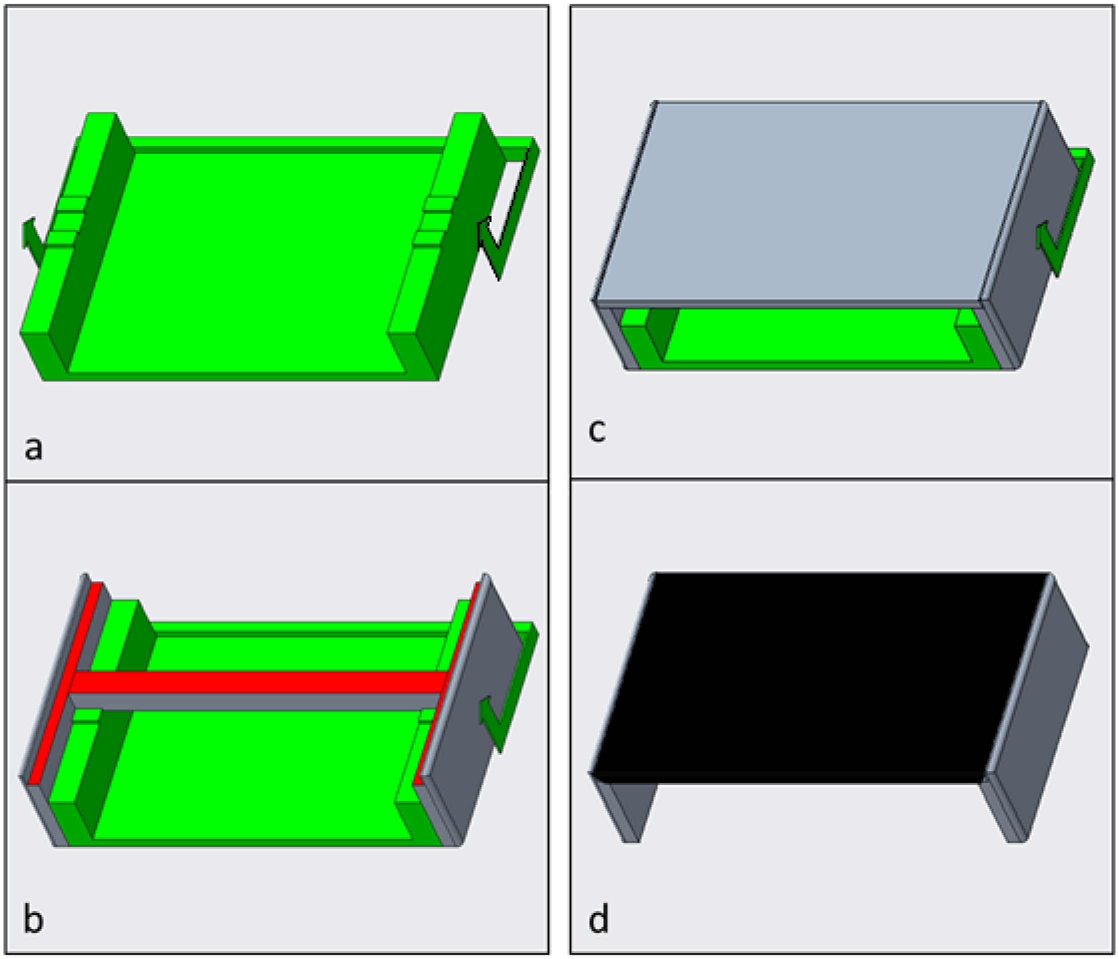


Figure 15: Revised Production Process – Step Assembly

Time Study

When developing a production process with one-piece-flow, timing is paramount to the success of the line. One employee’s work should be completed “just in time” for the employee before them to pass their work on, and the employee after them to take their next work piece. To make this happen, two metrics are considered; takt time and cycle times.

The takt time represents the rate at which finished parts must leave the assembly line. This is determined as a function of the number of pieces scheduled for production and the time allowed for the production shift. Satisfied with the prototype StepBuddy, the staff at the Willie Price school placed an order for twenty-four steps. Based on the framework of the CME's capstone project, these steps would be produced in two one-hour long production runs. Therefore, the team would be required to produce twelve pieces per production run. To produce the twelve pieces in a single hour, the team would need to produce one step every five minutes. This five-minute limit is the takt time for our production schedule.

The cycle time represents the time taken by each step in the production process. To collect the cycle times, the team used a stopwatch to time each step in the manufacture of one finished StepBuddy product. These times can be categorized as manual or automatic, where manual times correspond with processes which require a person to actively be completing the task and automatic times are those which do not require a person to be attending to the task (e.g. drying glue). The summation of the times in each category yields the total manual time and total automatic time. The sum of all these times is the total cycle time.

An estimated labor requirement can be obtained using the takt time and cycle times above. Dividing the manual cycle time (with units man*minutes/part) by the takt time for the production schedule (with units minutes/part) yields a hypothetical labor requirement (with units of man). This is shown in Equation 3-1. This estimate assumes that the total time for each worker to complete his or her assigned tasks will equal exactly the takt time. However, grouping tasks to fit this criterion is not always possible. Because some workers' tasks will require more time than others, and most workers' tasks will require less time than the takt time, the labor requirement will commonly exceed the time estimates.

$$Labor\ (people) = \frac{Manual\ Cycle\ Time\ \left(\frac{person*minutes}{part}\right)}{Takt\ Time\ \left(\frac{minutes}{part}\right)} \tag{3-1}$$

Equation 3-1: Calculation for Labor Requirements

Process 1

With the process adapted to multiple piece production, an initial floor layout was developed. The first layout consisted of four component-specific “islands” that joined at the assembly island, resembling a fork where the component production takes place on the tines and the assembly on the handle of the fork. This layout allowed the work pieces to flow in a single direction and prevented the movement of the parts from “crossing lines”. Tasks were delegated to employees by combining tasks whose cycle times summed to nearly the takt time. Figure 16 demonstrates the initial layout, including each tasks’ cycle times. Following this criterion, 6 laborers would be required for production. In this layout, the first employee would run miter saw 1, table saw with dado blade, and router. The second employee would run the belt sander, miter saw 2, the table saw, and the hydraulic shear. The third employee would work the rubber cover cutting station and the assembly fixture. The fourth employee would work the clear coating station, and the fifth employee would complete the rubber wrapping procedure. The sixth employee would oversee the planer.

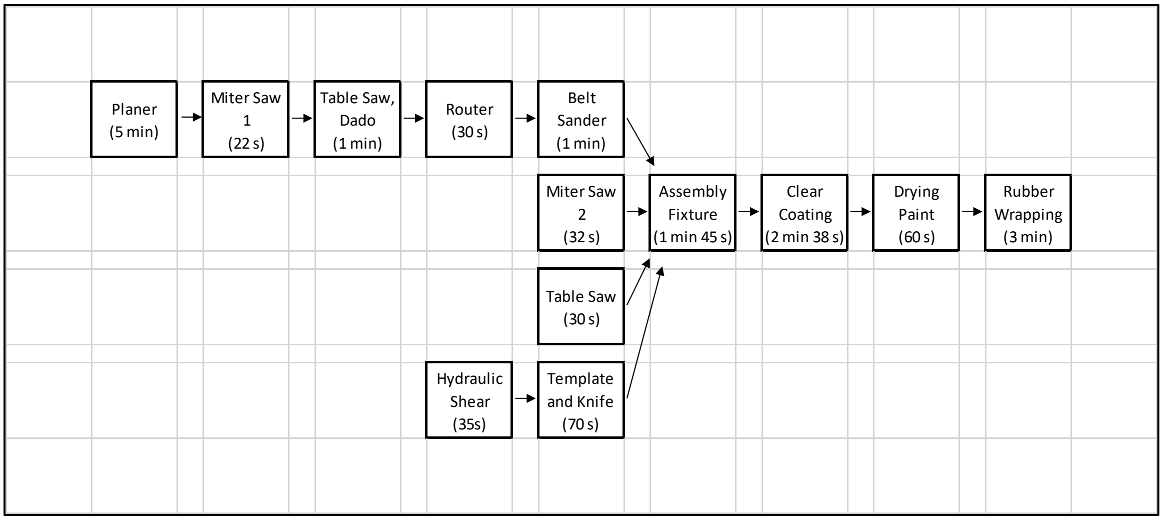


Figure 16: Initial Layout with Cycle Times

Production Trial

To test the process that had been developed, the team conducted a production trial run. In this trial, each employee's group of tasks was conducted as if continuous production was being conducted. Each task set was timed to ensure that they were less than the takt time. The results of the production trial were that the only procedure that exceeded the takt time was the attachment of the rubber cover. Changes would be required to either reduce the cycle time of the rubber attachment procedure, or the task would have to be divided for completion by two employees.

In addition to the time considerations, a quality issue surfaced. It was found producing the rubber cover piece with the hydraulic shearing machine was causing deviations to the critical dimension of the step, the 26" length. When making the 26" strips, the dimensions of the strip varied increasingly as the distance from the ruler edge of the machine increased. This was attributed to the flexibility of the rubber material. Because of the high rate of scrap pieces, the hydraulic shear was abandoned, and alternative procedures for making the rubber cover were investigated.

Questions about the durability of the step were also brought to the team's attention. Advisors to the team began to question the use of wood glue to attach the rubber cover to the plywood platform. Further research led to conflicting reports about the ability of PVA wood glues to bond with rubber materials; however, none of the reports included any information about the composition of the rubber materials being referenced. While the team's prototype experience confirmed the performance of the wood glue in this application, it was hypothesized that the rigidity of the dried wood glue would cause failure of the bond between the wood and rubber to fail in the long term. To maximize the life of the product, alternative adhesives would be considered, including multi-part epoxies, contact adhesives, construction adhesives, and urethane adhesives.

Finally, a manufacturing advisor brought concerns about the floor layout to our attention. The use of individual islands to produce each component necessitated laborers to serve at each island. This made the layout 'inflexible', in that a change in demand could not be easily accommodated. If increased production was required, the three-island approach did not easily facilitate additional workers. Similarly, if lower production was needed, reducing the number of workers could not be accomplished without adding significant wasted motion as the workers moved between lines. The layout would require revision to increase flexibility in the face of varying production schedules.

Process 2

The process was revised to correct the errors that surfaced during the production trial. To adhere the rubber cover to the plywood platform piece, wood glue would no longer be used. In its place, Loctite Pro Line Premium polyurethane construction adhesive would be used. This adhesive is applied with a caulking gun, rather than with a jug or squirt-bottle and would not require spreading. By using the urethane adhesive, the cycle time for the rubber attachment process was reduced to be less than the takt time. Additionally, the flexibility of the polyurethane bond would address the long-term quality concerns that existed with the PVA attachment.

The method for producing the rubber cover piece would no longer use the hydraulic shear machine. Instead, a template would be used to cut the rubber directly from the roll. The rubber roll would be placed on a rack behind the cutting table. The roll would be pulled so that fresh material would rest on a self-healing cutting mat on the table. The template, which was the exact shape of the desired rubber piece, would be placed on top of the unrolled rubber sheet. A utility knife would then be used to cut the rubber around the perimeter of the template. This process simplified the equipment needs while correcting the quality issue of the previous procedure.

The revised process featured an updated floor layout. Rather than considering a separate line for each component that would meet at assembly, the new layout would think of each step as adding value to the product. As legs are sent down the line, they are given a cross member, a top, and a rubber cover before being assembled. This value-added approach manifested itself as a single “island”, where all work would move in a single direction along a single line. The benefit of working with the single island layout is that it allows the number of workers to be changed to accommodate different production requirements; division between lines in the previous layout inhibited this flexibility. The updated floor layout is shown below in Figure 17. The cycle times for each step in the procedure can be seen in Table 1, as well as the takt time and the estimated labor requirement. These calculations determined that four employees would be required. To delegate the process steps among the employees, tasks would be combined into sets whose cycle times summed to nearly the takt time without exceeding the takt time. The proposed division of labor can be seen in Table 1. Employee A would be responsible for using the planer, the miter saw for leg cutting, the table saw with dado blade, and the edge router. Employee B would be responsible for using the belt sander to sand the legs, a miter saw to cut the cross members, and the template to cut out the rubber cover pieces. Employee C would be tasked with producing the top platform with a table saw, assembling the wooden pieces with the assembly fixture, and clear-coating the wooden assemblies at a paint booth. Employee D would be responsible for attaching the rubber cover pieces and moving the completed pieces to a drying area.

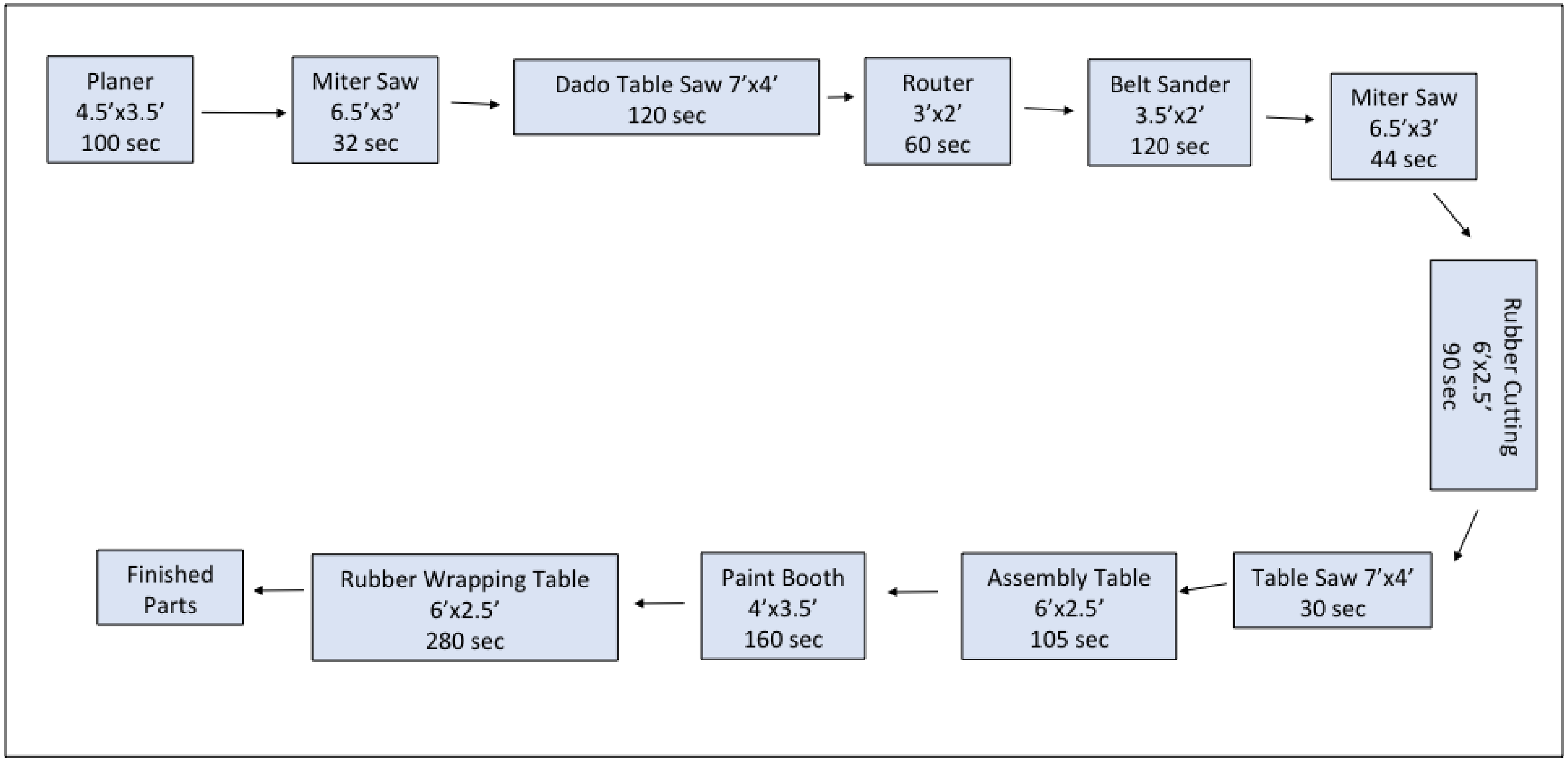
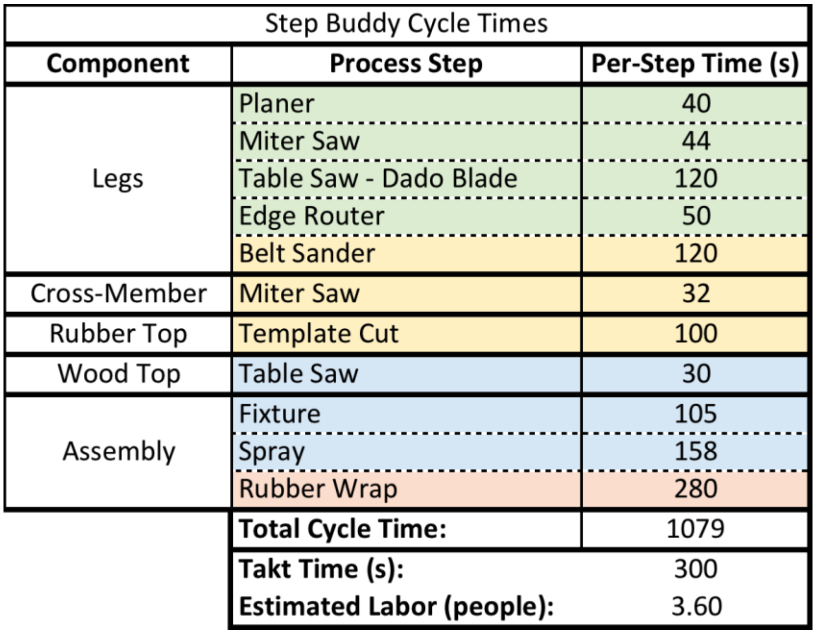


Figure 17: Final Layout with cycle times

Table 1: Cycle Times for Updated Procedure, Colors indicate Each Worker's Tasks



Step Buddy Cycle Times

Component	**Process Step**	**Per-Step Time (s)**
Legs	Planer	40
	Miter Saw	44
	Table Saw - Dado Blade	120
	Edge Router	50
	Belt Sander	120
Cross-Member	Miter Saw	32
Rubber Top	Template Cut	100
Wood Top	Table Saw	30
Assembly	Fixture	105
	Spray	158
	Rubber Wrap	280
	Total Cycle Time:	1079
	Takt Time (s):	300
	Estimated Labor (people):	3.60

<u>Production Runs</u>

The customer order of 24 steps was to be completed in two one-hour production runs. During each one-hour run, twelve steps were to be produced.

In preparation for these production runs, a program was written in MatLab to simulate a one-hour production run. Based on the worker cycle times (sum of individual cycle times for each worker's task set), the program would be told how many pieces of work in progress (WIP) each worker had at the beginning of the run and determine how many pieces would be produced in the one-hour run. If all twelve pieces could be produced within the one-hour time frame, the software would communicate the time it took to produce all the 12 steps. The software determined that the production schedule could only be achieved if workers b, c, and d started the shift with WIP. With one piece of WIP each, the 12-step order would be completed in 59 minutes. By increasing the WIP for Employee D, the 12-step order would be completed in 56 minutes. Based on these determinations, the team decided that Employees B, C, and D would each start with one piece of WIP. Code for the MatLab program can be found in the Appendix.

In the first run, the roles of Employees A, B, C, and D were filled by Eddie, Chris, Kyle, and Peter respectively. In 60 minutes: five steps were completed, two steps were scrapped due to defects, and five steps were still work in progress at the end of the shift. This was due to several reasons. Firstly, the tools were set up on the day before the trial run, and the tool settings were not confirmed at the beginning of the shift. After starting the production run, it was discovered that an individual outside of our team had moved the fence on the table saw. This caused Employee C to mis-cut a plywood platform piece, before pulling a more experienced person over to re-set the table saw. Secondly, a bottleneck was discovered. While Employees B and D performed their work at a rate very close to the anticipated cycle time, Employee A had a shorter cycle time than anticipated, and Employee C had a much longer cycle time than anticipated.

During the day between the trial runs, the cause of the bottleneck was investigated. It was discovered that the cycle time obtained from the time study was a good approximation for the actual time needed by an experienced operator, but underestimated the time required by an inexperienced operator. The team re-evaluated the experience requirements for each of the operator roles and assigned responsibilities accordingly. The most experienced operators were moved to employee stations C and D, while the least experienced operator was assigned to station A. Each operator was timed at his new station to ensure that the bottlenecking issue would be resolved. The operator's cycle times were confirmed to be under the takt time requirement, and additional time was spent training each operator in the new assignments.

In the second run, the roles of Employees A, B, C and D were filled by Kyle, Chris, Peter, and Eddie. The tools settings were all inspected before the shift began, and test pieces were cut to check the fit in the assembly jig. The line produced ten steps in forty-seven minutes, before running out of cross-member material. The team, when making the material purchase for the second production run, did not predict the amount of scrap that would be created when unusable test pieces were made at the beginning of the run. While this oversight led the team to produce two fewer pieces than was scheduled, the rate of part completion (4 minutes and 42 seconds per finished part) was less than the takt time requirement, which indicated that the line was on track to fulfilling the full order in the one-hour shift.

Financials

Based on the team's market research and the customer's budget, the price of the StepBuddy was set at $110 per unit. Using the five-minute takt time from the production runs and an 1800-hour work year, the annual sales volume was 21,600 parts and the projected annual revenue was $2,376,000. Variable cost considerations include direct labor costs for four full-time operators, outsourced labor costs for pre-cutting of the plywood sheets (charged at 2.5 times the cost of producing in-house), manufacturing overhead (charged as 70% of direct material costs plus R&D expenses), and the direct material costs (considered separately for the cases of purchased and rented equipment). Material costs are shown in the BOM of Table 2, and the equipment rental rates are shown in Table 3. Summarized revenue and variable cost values can be found in Table 4. The annual variable cost total with rented equipment was $1,421,576.40, and the annual variable cost total with purchased equipment was $1,296,776.40.

Fixed cost considerations include fixed labor (salaried employees) and fixed manufacturing overhead (billed as 80% of non-labor fixed costs) for the case of rented equipment. Fixed labor positions and expenses can be found in Table 5. For the case of purchased equipment, the fixed costs also included machine depreciation (assumed straight-line depreciation over 7 years). The purchase costs for the equipment are shown in Table 6. The annual fixed costs with machine rental was $677,950.78 and the annual fixed costs with machine purchase was $681,622.38.

Profit was determined on an annual and per-part basis by deducting total fixed and variable costs from annual revenue. With rented equipment, the profit was $12.80 per part or $276,472.82 annually. With purchased equipment, the profit was $18.41 per part or $397,601.22 annually. Considering the up-front investment to be the sum of the machine purchase costs and annual fixed costs for the case where equipment is purchased, the break-even period was determined to be 33,890 parts, or approximately 1.6 years. Summarized fixed cost, profit, and investment values for this analysis can be found in Table 7, and the break-even period is shown graphically in Figure 18.

Table 2: Bill of Materials

Part No.	Qty	Description	Comments	Size	Unit Cost	Total Cost	Per Unit Cost	Comments
1	10	pine board	Material for the side boards	2” x 8” x 8’	$5.79	$57.86	$2.41	5 legs out of 1 board, 2 legs for one step
2	8	pine board	Material for crossmember	2" x 2" x 8'	$1.96	$15.68	$0.65	3 crossmembers out of 1 board
3	4	plywood project panel	Material for the top board	¾” x 4’ x 8’	$46.88	$187.52	$7.81	6 tops per plywood sheet
4	3	Rubber Mat Roll	Non-slip covering on top	1/8"x 4' x 9'	$53.82	$161.46	$6.73	8 rubber tops per roll, 3 rolls total. 1 unit uses 1/8 of one roll
5	3	Scotch Grip Pads	Non-slip feet for bottom	3/4" - 1"	$6.27	$18.81	$0.78	32 usable grip pads per pack, 4 used per step
6	4	Construction Adhesive	Adhesive to attach rubber	28oz	$6.97	$27.88	$1.16	1 tube per 6 steps
7	1	Wood Glue	Supports the wooden joints in the product	1 gal	$15.97	$15.97	$0.67	Estimate
8	6	Kyrlon Aersol Poly	Seal to prevent splintering and damage to wood	12 oz	$3.86	$23.16	$0.97	6 total cans for 24 steps, 4 steps per can
9	1	1250 Staples	Extra support for the rubber attachement	3/8"	$3.22	$3.22	$0.13	Estimate
10	1	2000 Nails	Connects the wooden joints in the product	2"	$4.95	$4.95	$0.21	Estimate
			Total			$516.51	$21.52	*Includes cost for scrap
								**Strictly production materals, not other production related costs from cost sheet

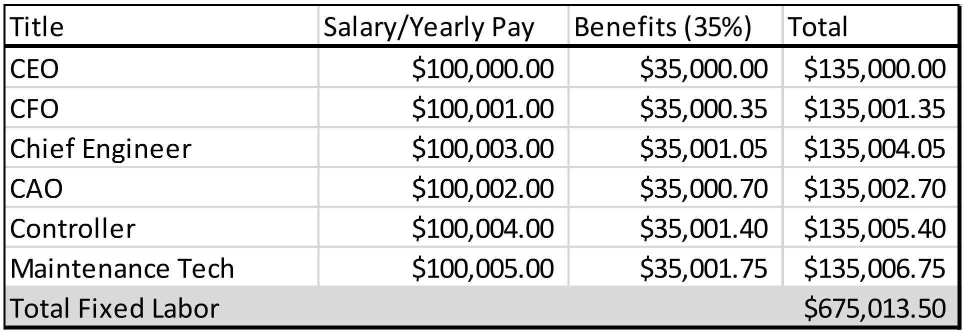
Table 3: Machine Rental Rates

Machine	Hourly Cost
Table Saw	10
Miter Saw (Crossmember)	10
Table Saw/Dado	10
Miter Saw (Legs)	10
Router	10
Planer	10
Hours per Year	2080
Total Yearly Rental cost	$ 124,800.00
Total Machine Rental Cost Per Unit	$ 5.78

Table 4: Summary of Income and Variable Costs

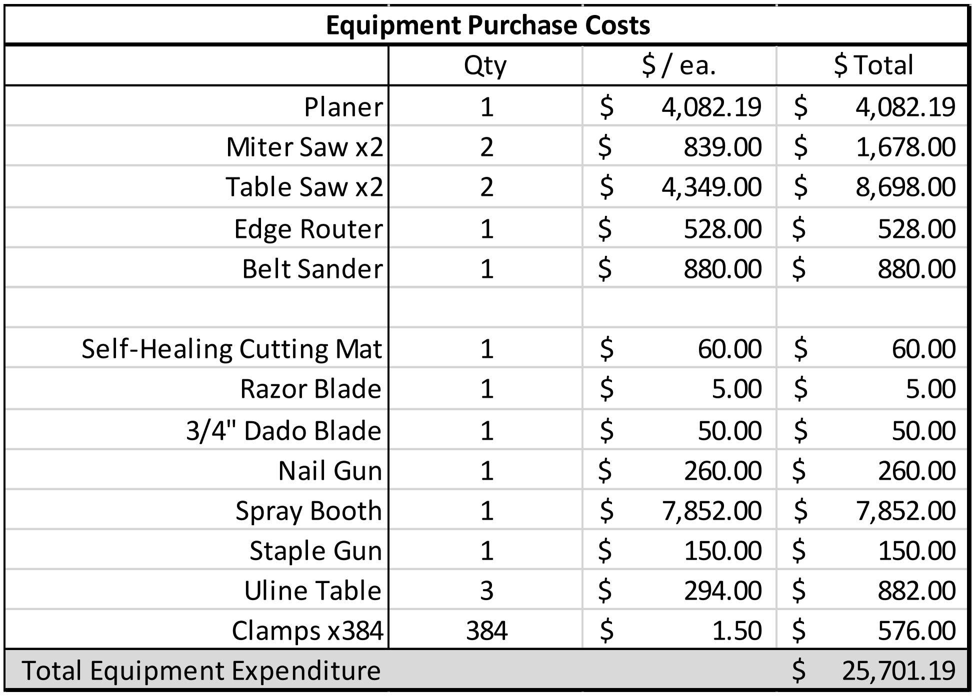
Income			
	Sales Price	$/part	$ 110.00
	Takt Time	hrs/part	0.083
	Hours per Work Year	hrs/year	1800
	Annual Sales Volume	parts/year	21600
	Annual Revenue	$/year	$ 2,376,000.00
Variable Costs			
	Labor Wage	$/man.hour	15
	# of Workers*	man	4
	Takt Time	hrs/part	0.083
	Direct Labor	$/part	$ 5.00
	Outsourced Labor	$/part	$ 6.25
	Total Direct Labor	$/part	**$ 11.25**
	Direct Material	$/part	**$ 21.52**
	Machine Rental Costs	$/year	$ 124,800.00
	Machine Rental Costs	$/part	$5.78
	Direct Material with Equipment Rental	$/part	**$ 27.30**
	Variable Manf. Overhead Rate	% Dir. Matl.	70%
	Variable Manf. Overhead	$/part	$ 19.11
	R&D Costs per 24 Part		$195.78
	R&D Costs per Part	$/part	$8.16
	Manf. Overhead	$/part	**$ 27.27**
	Total Variable Costs, Purchased Equip.	$/part	$ 60.04
	Total Variable Costs, Rented Equip.	$/part	$ 65.81
	Total Variable Costs, Purchased Equip.	$/year	$ 1,296,776.40
	Total Variable Costs, Rented Equip.	$/year	$ 1,421,576.40

Table 5: Fixed Labor Positions and Cost



Title	Salary/Yearly Pay	Benefits (35%)	Total
CEO	$100,000.00	$35,000.00	$135,000.00
CFO	$100,001.00	$35,000.35	$135,001.35
Chief Engineer	$100,003.00	$35,001.05	$135,004.05
CAO	$100,002.00	$35,000.70	$135,002.70
Controller	$100,004.00	$35,001.40	$135,005.40
Maintenance Tech	$100,005.00	$35,001.75	$135,006.75
Total Fixed Labor			$675,013.50

Table 6: Equipment Purchase Costs



Equipment Purchase Costs			
	Qty	$ / ea.	$ Total
Planer	1	$ 4,082.19	$ 4,082.19
Miter Saw x2	2	$ 839.00	$ 1,678.00
Table Saw x2	2	$ 4,349.00	$ 8,698.00
Edge Router	1	$ 528.00	$ 528.00
Belt Sander	1	$ 880.00	$ 880.00
Self-Healing Cutting Mat	1	$ 60.00	$ 60.00
Razor Blade	1	$ 5.00	$ 5.00
3/4" Dado Blade	1	$ 50.00	$ 50.00
Nail Gun	1	$ 260.00	$ 260.00
Spray Booth	1	$ 7,852.00	$ 7,852.00
Staple Gun	1	$ 150.00	$ 150.00
Uline Table	3	$ 294.00	$ 882.00
Clamps x384	384	$ 1.50	$ 576.00
Total Equipment Expenditure			$ 25,701.19

Table 7: Summary of Fixed Costs, Profit, and Investment

Fixed Costs			
	Fixed Labor	$/year	$675,013.50
	Machine Purchase Costs	$	$ 25,701.19
	Machine Depreciation Costs	$/year	$ 3,671.60
	Fixed Cost Overhead Rate	% Non Labor FC	80%
	Fixed Overhead	$/year	$ 2,937.28
	Total Fixed Costs, Purchased Equip	$/year	$681,622.38
	Total Fixed Costs, Rented Equip	$/year	$677,950.78
Profit			
	Annual Revenue, Rented Equip.	$/year	$ 2,376,000.00
	Total Variable Costs, Rented Equip.	$/year	$ 1,421,576.40
	Total Fixed Costs, Rented Equip	$/year	$677,950.78
	Annual Profit, Rented Equip	$/year	$ 276,472.82
		$/part	$ 12.80
	Total Variable Costs, Purchased Equip.	$/year	$ 1,296,776.40
	Total Fixed Costs, Purchased Equip	$/year	$681,622.38
	Annual Profit, Purchased Equip	$/year	$ 397,601.22
		$/part	$ 18.41
Investment			
	Machine Purchase Costs	$	$ 25,701.19
	Total Fixed Costs, Purchased Equip	$/year	$707,341.97
	Total Investment	$	$ 733,043.16
	Parts to Break Even	parts	57271

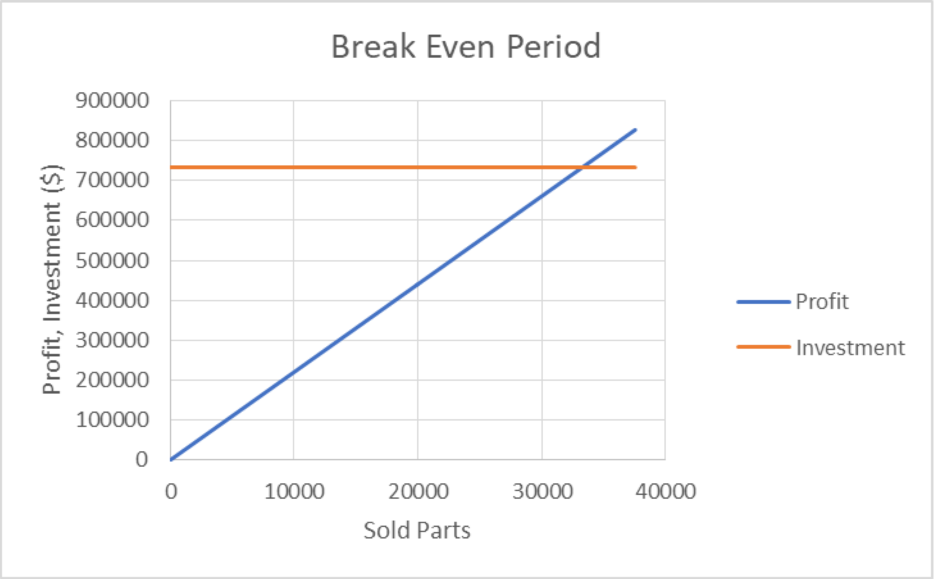


Figure 18: Break Even Period by Number of Parts Sold

IV. CONCLUSIONS

The team performed well at identifying customer needs and translating that into design features. The final design met the customer's expectations and fit within their budget requirements. Additionally, the team succeeded in creating a production line that incorporated flexibility to change the number of workers based on production schedule changes and one-piece-flow characteristics. However, both the design and production of the StepBuddy has room to be improved.

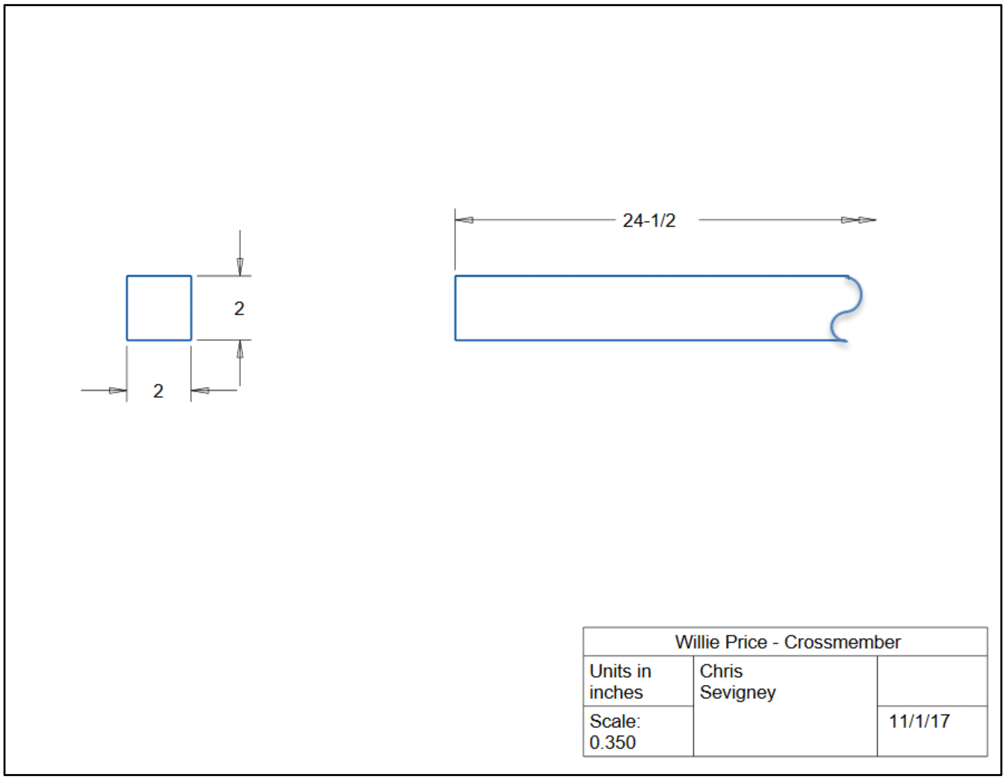
The greatest shortcoming of the StepBuddy's design was the amount of plywood material that had to be scrapped when producing the plywood platform component. The dimensions of the StepBuddy's platform led 46% of each plywood sheet to be scrap material. To resolve this, two projects could be investigated. The first would consider re-sizing the step to have a slightly smaller platform, which would allow more of the platforms to be cut from one sheet of plywood. The second would investigate using the scrap plywood materials to replace the furring strip as the cross-member material.

The production of the StepBuddy would benefit most greatly from improvements to the pre-shift start-up procedures. Although the team learned to check tool settings before working in the first production run, more needs to be done to address this set-up phase. Pre-shift operator checklists could be created to include material checks, tool setup, and safety precautions. Creating this standard work for the start-up phase of the shifts would ensure that mistakes, such as the material inventory issues experienced in the second production run, would not appear in the middle of the shift again. Further, tool calibration pieces could be introduced to negate the need for the test cutting and dry-fitment of parts before a shift. Improvements of this kind increase the reliability and capabilities of the production operations.

The StepBuddy project was a fulfilling and educational experience. Each member of the team communicated effectively and was reliable and responsible in his or her role. The successes of the StepBuddy project are a product of the team's professional attitudes and hard work.

VI. APPENDIX

Engineering Drawings



Willie Price - Crossmember		
Units in inches	Chris Sevigney	
Scale: 0.350		11/1/17

Figure A1: Engineering Drawing for Crossmember

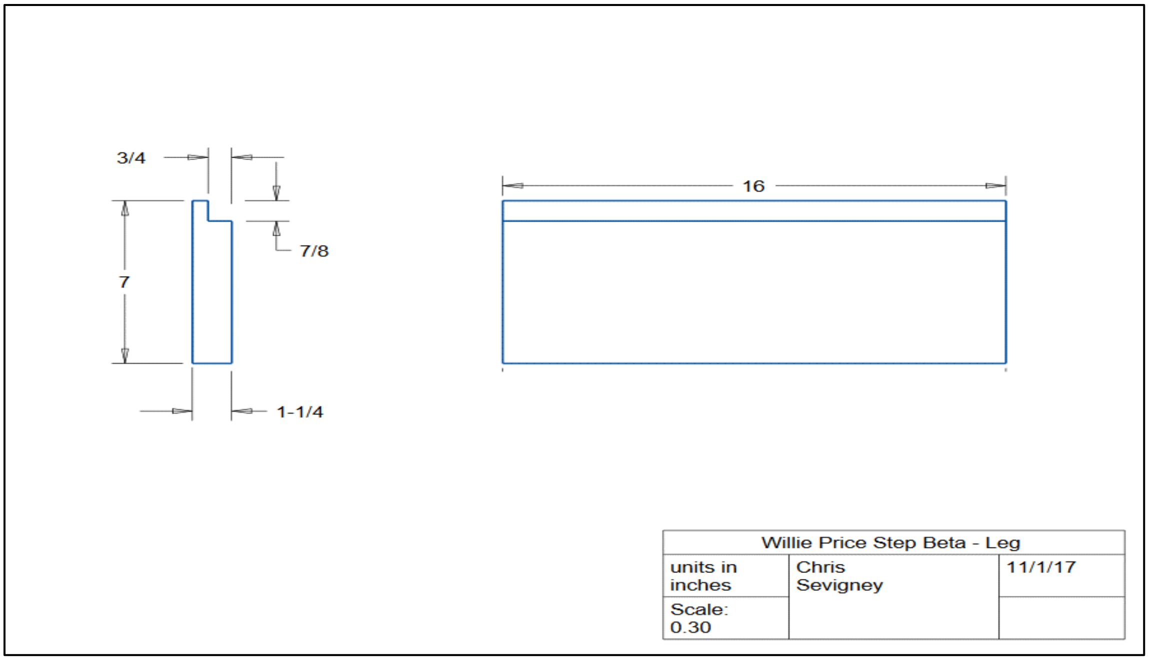


Figure A2: Engineering Drawing for Leg

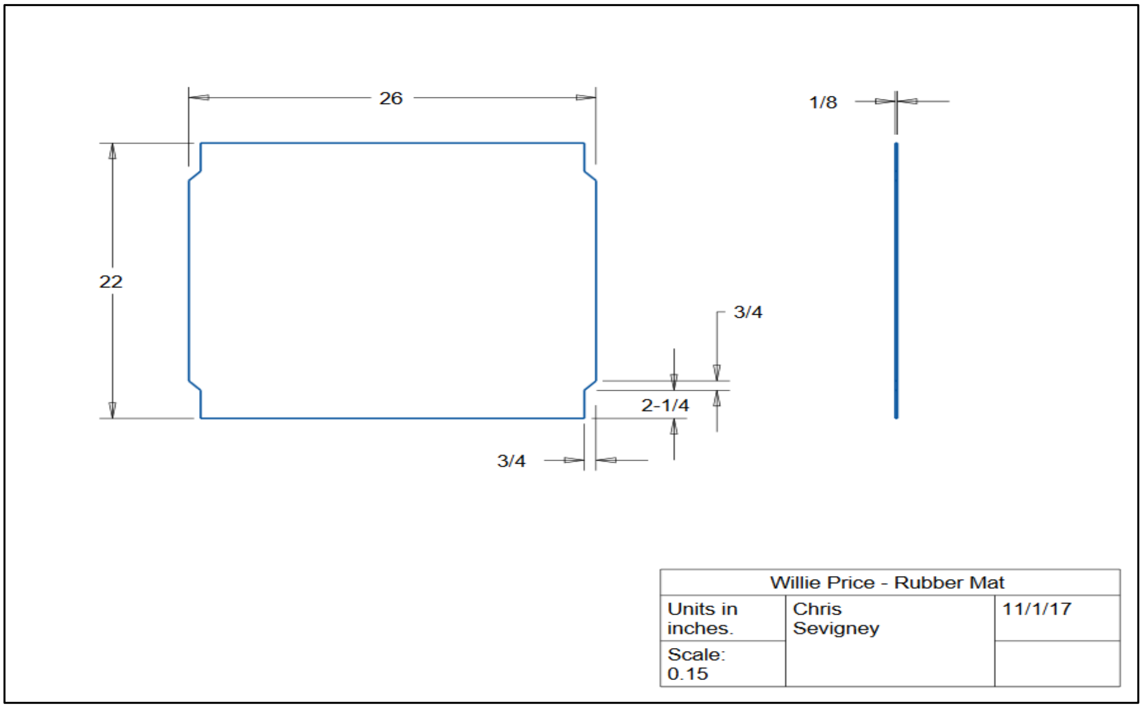
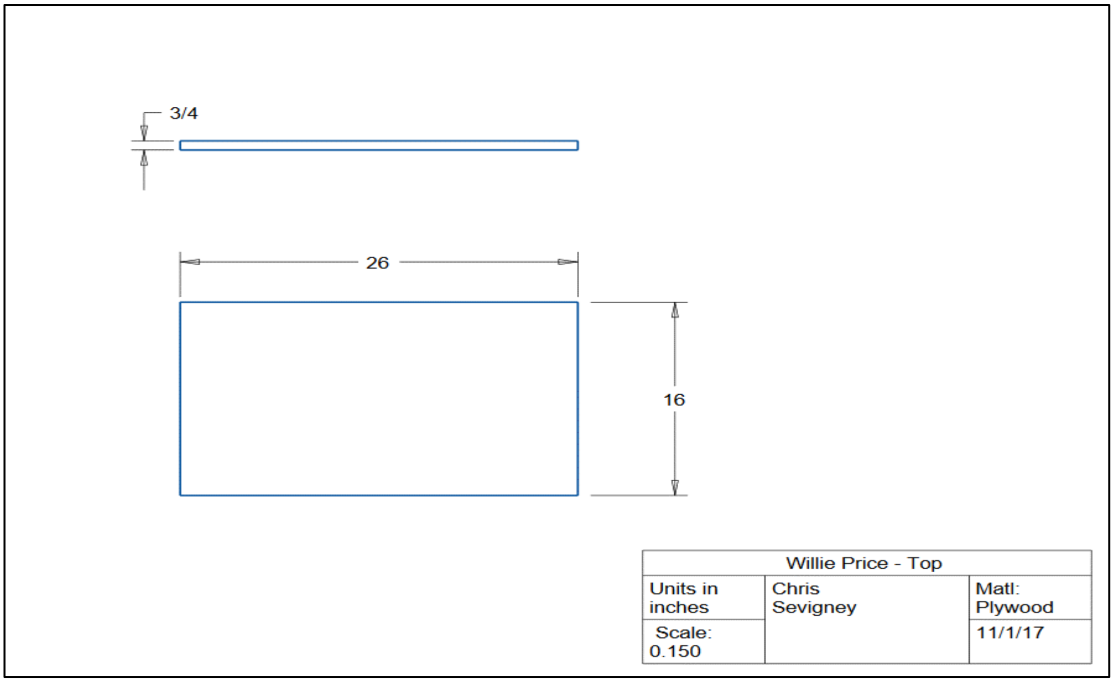
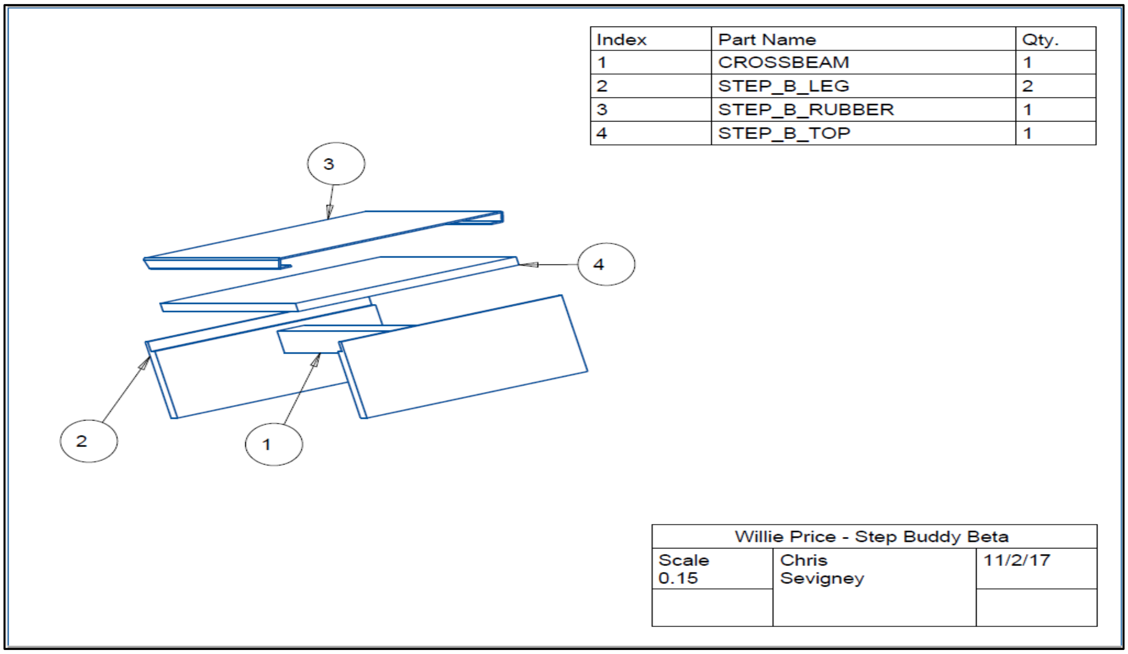


Figure A3: Engineering Drawing for Un-Wrapped Rubber Mat



Willie Price - Top		
Units in inches	Chris Sevigney	Matl: Plywood
Scale: 0.150		11/1/17

Figure A4: Engineering Drawing for Top Platform



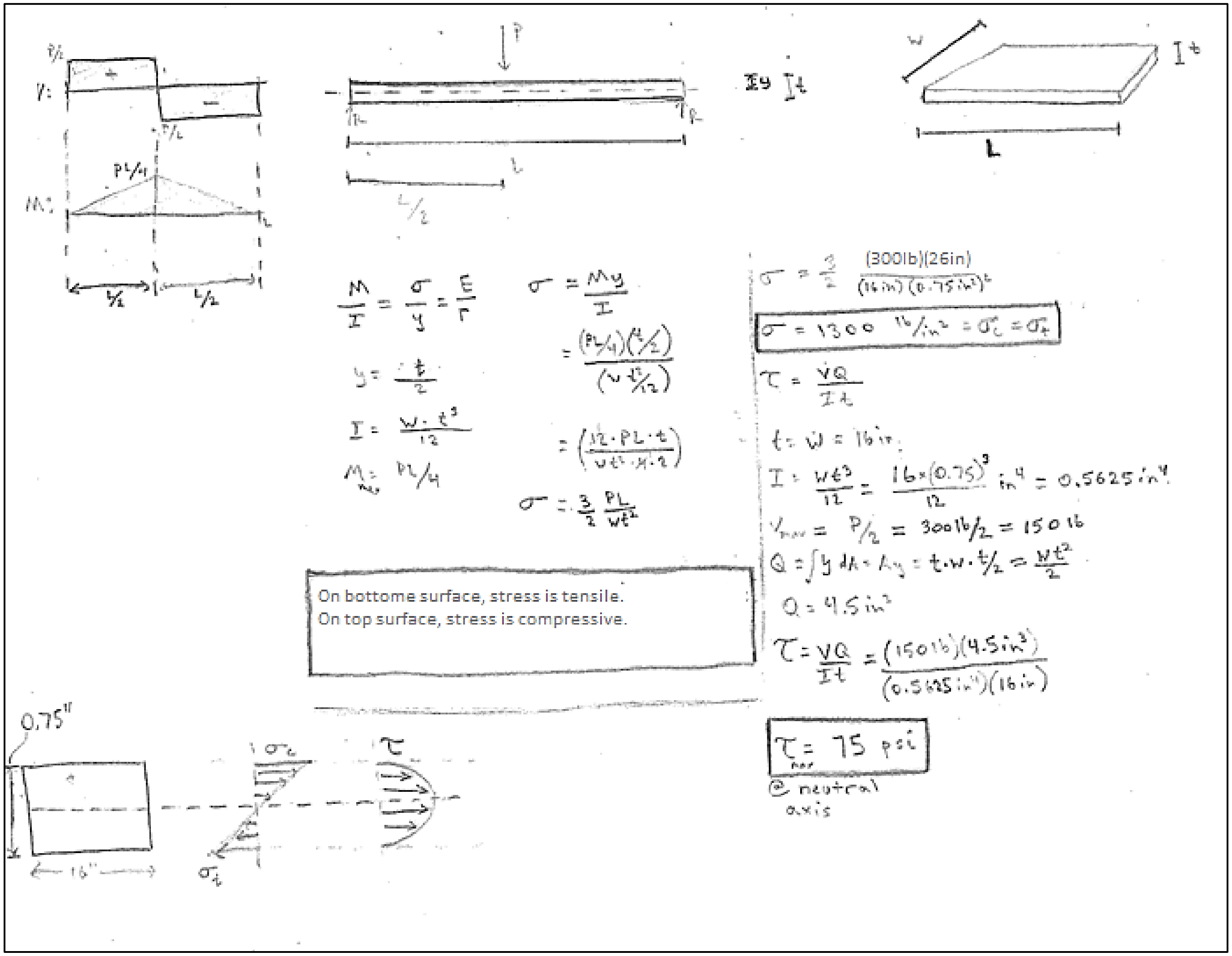
Index	Part Name	Qty.
1	CROSSBEAM	1
2	STEP_B_LEG	2
3	STEP_B_RUBBER	1
4	STEP_B_TOP	1

Willie Price - Step Buddy Beta		
Scale 0.15	Chris Sevigney	11/2/17

Figure A5: Assembly Drawing

Beam Analysis

Platform without Crossmember:



$$\frac{M}{I} = \frac{\sigma}{y} = \frac{E}{r}$$

$$y = \frac{t}{2}$$

$$I = \frac{w \cdot t^3}{12}$$

$$M_{max} = PL/4$$

$$\sigma = \frac{My}{I} = \frac{(PL/4)(t/2)}{(wt^3/12)} = \left(\frac{12 \cdot PL \cdot t}{wt^3 \cdot 4 \cdot 2}\right)$$

$$\sigma = \frac{3}{2}\frac{PL}{wt^2}$$

On bottome surface, stress is tensile.
On top surface, stress is compressive.

$$\sigma = \frac{3}{2}\frac{(300lb)(26in)}{(16in)(0.75in)^2}$$

$$\boxed{\sigma = 1300\ lb/in^2 = \sigma_c = \sigma_t}$$

$$\tau = \frac{VQ}{It}$$

$$t = w = 16in.$$

$$I = \frac{wt^3}{12} = \frac{16 \times (0.75)^3}{12}\ in^4 = 0.5625in^4$$

$$V_{max} = P/2 = 300lb/2 = 150lb$$

$$Q = \int y\,dA = Ay = t \cdot w \cdot t/2 = \frac{wt^2}{2}$$

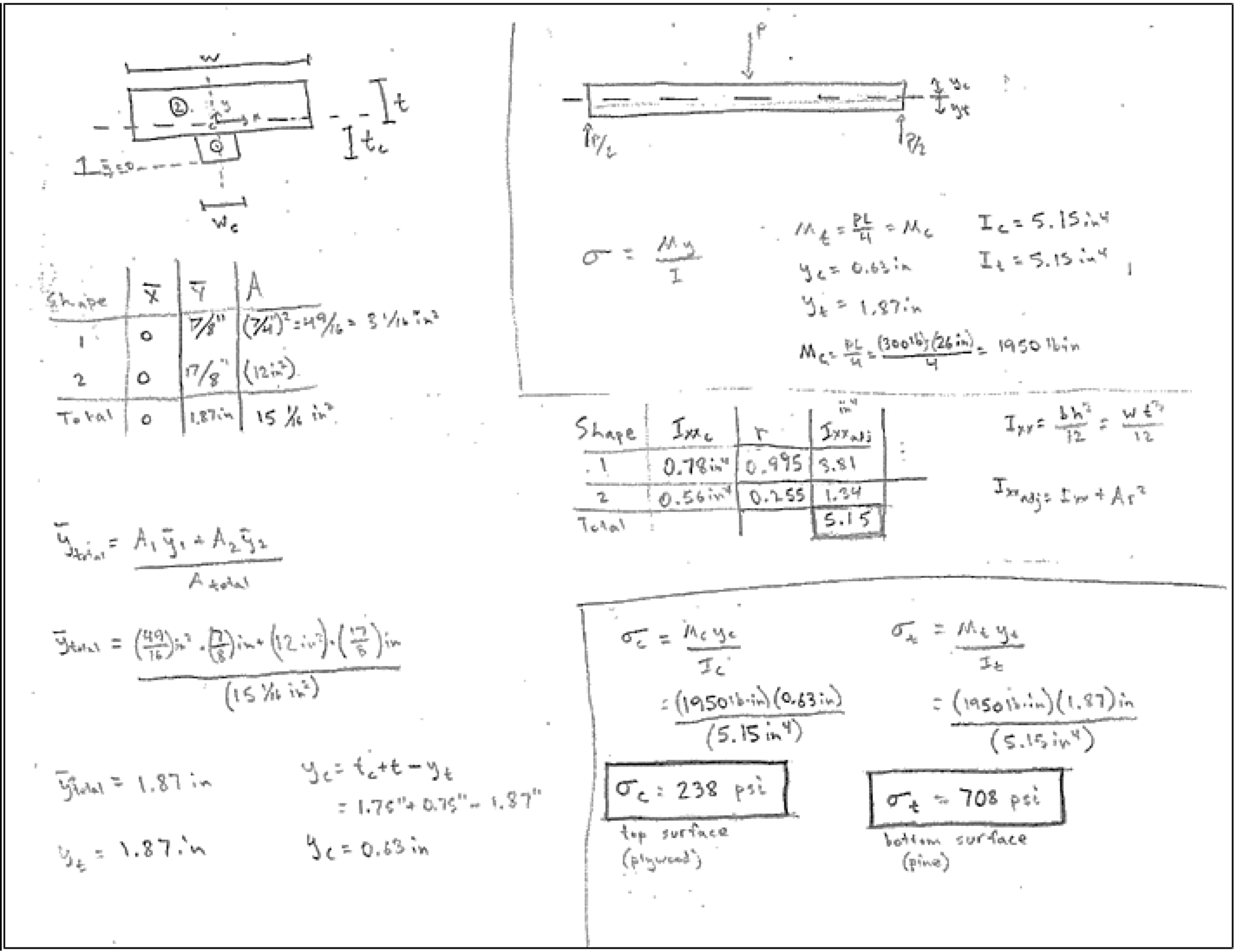
$$Q = 4.5in^3$$

$$\tau = \frac{VQ}{It} = \frac{(150lb)(4.5in^3)}{(0.5625in^4)(16in)}$$

$$\boxed{\tau_{max} = 75\ psi}$$

@ neutral axis

Platform with Crossmember:



Shape	$\bar{x}$	$\bar{y}$	A
1	0	7/8"	$(7/4")^2 = 49/16 = 3\,1/16\ in^2$
2	0	17/8"	$(12\ in^2)$
Total	0	1.87 in	$15\,1/16\ in^2$

$$\bar{y}_{total} = \frac{A_1\bar{y}_1 + A_2\bar{y}_2}{A_{total}}$$

$$\bar{y}_{total} = \frac{\left(\frac{49}{16}\right)in^2 \cdot \left(\frac{7}{8}\right)in + \left(12\ in^2\right)\cdot\left(\frac{17}{8}\right)in}{\left(15\,1/16\ in^2\right)}$$

$\bar{y}_{total} = 1.87\ in$

$y_t = 1.87\ in$

$y_c = t_c + t - y_t$

$= 1.75" + 0.75" - 1.87"$

$y_c = 0.63\ in$

$$\sigma = \frac{My}{I}$$

$M_t = \frac{PL}{4} = M_c$

$y_c = 0.63\ in$

$y_t = 1.87\ in$

$M_c = \frac{PL}{4} = \frac{(300\ lb)(26\ in)}{4} = 1950\ lb\,in$

$I_c = 5.15\ in^4$

$I_t = 5.15\ in^4$

Shape	I_{xx_c}	r	$I_{xx_{adj}}$ (in^4)
1	$0.78\ in^4$	0.995	3.81
2	$0.56\ in^4$	0.255	1.34
Total			$\boxed{5.15}$

$I_{xx} = \frac{bh^3}{12} = \frac{wt^3}{12}$

$I_{xx_{adj}} = I_{xx} + Ar^2$

$$\sigma_c = \frac{M_c y_c}{I_c} = \frac{(1950\ lb{\cdot}in)(0.63\ in)}{(5.15\ in^4)}$$

$\boxed{\sigma_c = 238\ psi}$

top surface
(plywood)

$$\sigma_t = \frac{M_t y_t}{I_t} = \frac{(1950\ lb{\cdot}in)(1.87)\ in}{(5.15\ in^4)}$$

$\boxed{\sigma_t \approx 708\ psi}$

bottom surface
(pine)

$$Q_x = \int y\,dA = y_1 A_1 + y_2 A_2$$

$$= (0.875\text{ in})(3.0625\text{ in}^2) + (2.125\text{ in})(12\text{ in}^2)$$

$$Q_x = 28.18\text{ in}^3$$

$$I_x = 5.15\text{ in}^4$$

$$t = w = 16\text{ in}$$

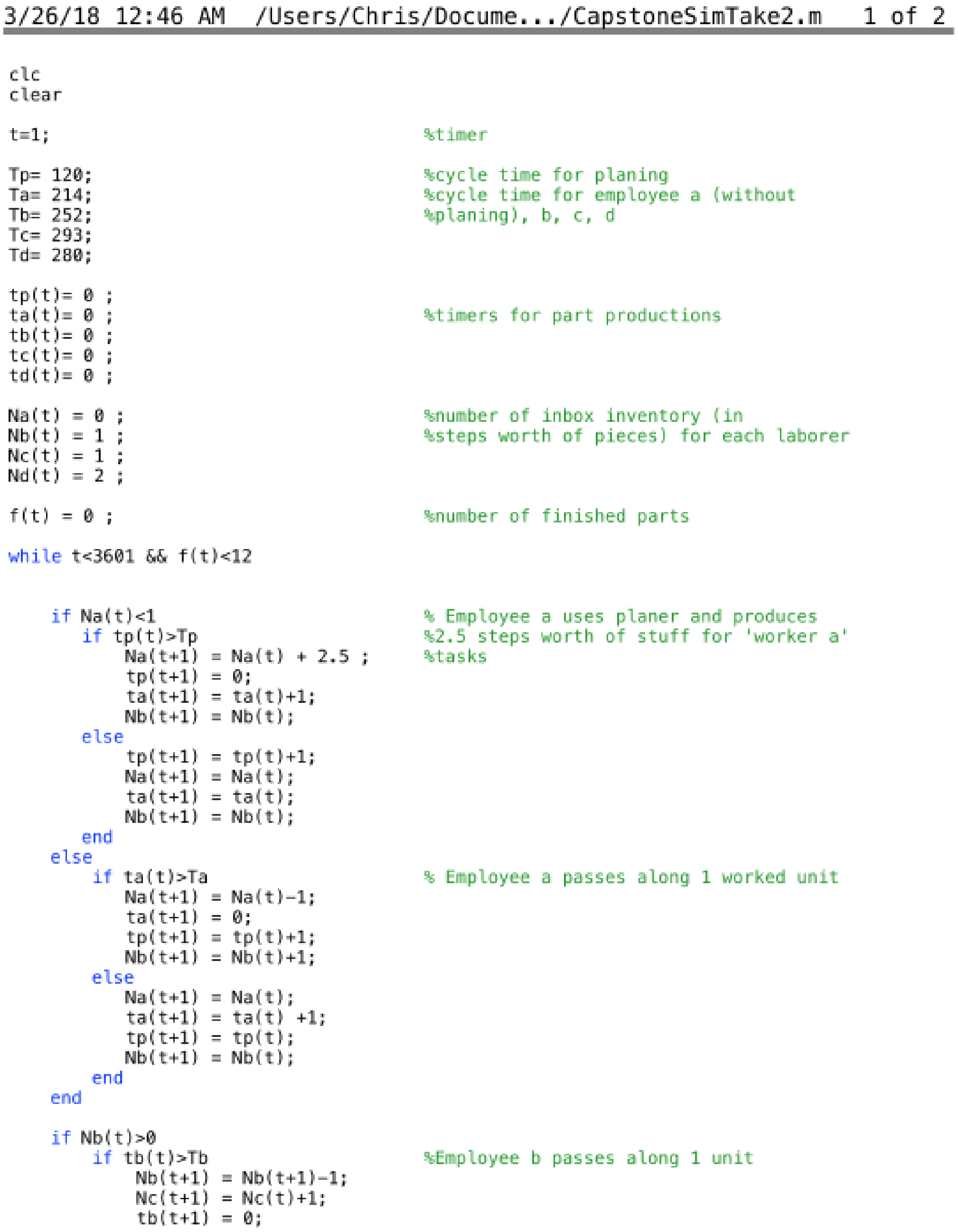
$$V_{max} = P/2 = 150\text{ lb}$$

$$\tau = \frac{VQ}{It} = \frac{(150\text{ lb})(28.18\text{ in}^3)}{(5.15\text{ in}^4)(16\text{ in})}$$

$$\boxed{\tau_{max} = 51.3\ \text{lb}/\text{in}^2}$$

@ neutral axis
(plywood)

MatLab Production Simulation



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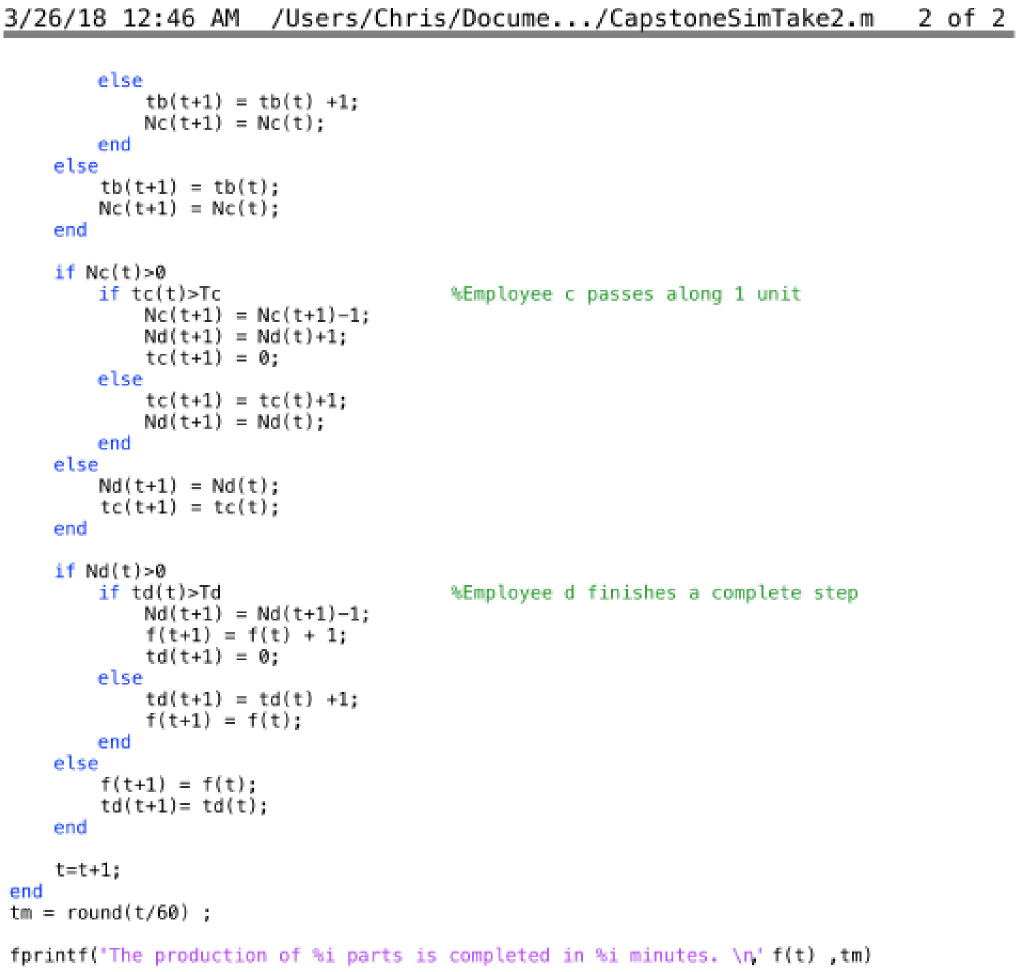
```
clc
clear

t=1;                                   %timer

Tp= 120;                               %cycle time for planing
Ta= 214;                               %cycle time for employee a (without
Tb= 252;                               %planing), b, c, d
Tc= 293;
Td= 280;

tp(t)= 0 ;
ta(t)= 0 ;                             %timers for part productions
tb(t)= 0 ;
tc(t)= 0 ;
td(t)= 0 ;

Na(t) = 0 ;                            %number of inbox inventory (in
Nb(t) = 1 ;                            %steps worth of pieces) for each laborer
Nc(t) = 1 ;
Nd(t) = 2 ;

f(t) = 0 ;                             %number of finished parts

while t<3601 && f(t)<12


    if Na(t)<1                         % Employee a uses planer and produces
       if tp(t)>Tp                     %2.5 steps worth of stuff for 'worker a'
           Na(t+1) = Na(t) + 2.5 ;     %tasks
           tp(t+1) = 0;
           ta(t+1) = ta(t)+1;
           Nb(t+1) = Nb(t);
       else
           tp(t+1) = tp(t)+1;
           Na(t+1) = Na(t);
           ta(t+1) = ta(t);
           Nb(t+1) = Nb(t);
       end
    else
        if ta(t)>Ta                    % Employee a passes along 1 worked unit
           Na(t+1) = Na(t)-1;
           ta(t+1) = 0;
           tp(t+1) = tp(t)+1;
           Nb(t+1) = Nb(t)+1;
        else
           Na(t+1) = Na(t);
           ta(t+1) = ta(t) +1;
           tp(t+1) = tp(t);
           Nb(t+1) = Nb(t);
        end
    end

    if Nb(t)>0
        if tb(t)>Tb                    %Employee b passes along 1 unit
            Nb(t+1) = Nb(t+1)-1;
            Nc(t+1) = Nc(t)+1;
            tb(t+1) = 0;
```



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```
        else
            tb(t+1) = tb(t) +1;
            Nc(t+1) = Nc(t);
        end
    else
        tb(t+1) = tb(t);
        Nc(t+1) = Nc(t);
    end

    if Nc(t)>0
        if tc(t)>Tc                        %Employee c passes along 1 unit
            Nc(t+1) = Nc(t+1)-1;
            Nd(t+1) = Nd(t)+1;
            tc(t+1) = 0;
        else
            tc(t+1) = tc(t)+1;
            Nd(t+1) = Nd(t);
        end
    else
        Nd(t+1) = Nd(t);
        tc(t+1) = tc(t);
    end

    if Nd(t)>0
        if td(t)>Td                        %Employee d finishes a complete step
            Nd(t+1) = Nd(t+1)-1;
            f(t+1) = f(t) + 1;
            td(t+1) = 0;
        else
            td(t+1) = td(t) +1;
            f(t+1) = f(t);
        end
    else
        f(t+1) = f(t);
        td(t+1)= td(t);
    end

    t=t+1;
end
tm = round(t/60) ;

fprintf('The production of %i parts is completed in %i minutes. \n', f(t) ,tm)
```

V. REFERENCES

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