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Designing an Adjustable and Transportable Staircase

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Abstract

People climb stairs every day, whether it is at work, a store, or at home; however, there are populations such as people who are elderly, with pathologies, with Parkinson's disease, or have suffered from a stroke that see climbing the stairs as a challenging task and it decreases their mobility and quality of life. Factors such as muscle weakness, strategy, and balance have been previously investigated in these populations during stair climbing. However, few studies have researched how stair climb ability, balance, and perception of difficulty are influenced by step height. The objective of this thesis is to design a staircase that can be adjustable and transportable so that the effect of step height on balance and perception of the difficulty of the task in older and pathological populations can be investigated for various stair climbing strategies to help develop safe strategies for climbing stairs of various heights. The staircase is required to have 5 steps so that a full stair gait cycle could be observed; the steps need to be able to adjust to heights that fall within the American Disability Act guidelines, and the staircase needs to have the capability of being easily transported to different locations. Using a decision matrix, the options that best fit the needs of the project were having a modified scissor lift platform and steps resembling a step ladder. Once these ideas were settled on, the rest of the work was making the two components cohesive and function in a manner that was needed to meet the design requirements. There are some aspects that still need to be added such as a handrail and there are recommendations on a different mechanism to attach the platform and the steps to each other. Overall, the effect of this project has laid the groundwork for being able to construct a functional adjustable and transportable staircase.

Introduction

Stair climbing is an everyday yet challenging activity for those who are older or have pathologies such as knee osteoarthritis, Parkinson's disease, or have had a stroke (Mustafaoğlu et al.; Whitchelo et al.; Asay et al.; Kennedy et al.). It has also been reported there have been 20,000 hospitalizations and 900 deaths every year of people 65 and over because of falls on the stairs (Hamel et al.), indicating that stair climbing is a dangerous and sometime life-threatening activity.

The reason why certain people are having difficulty when climbing stairs has been previously investigated by examining the factors of age, balance, having a preexisting fear of going up or down the stairs, muscle weakness, or pathologies (Startzell et al.; Hamel et al.; Whitchelo et al.). One study found that older people lose their range of motion in their lower limbs compared to young people, and possibly compensate for this by changing their strategy for negotiating the stairs, using two feet for every step instead of going foot over foot (Startzell et al.). This study also found that older people were more cautious because some believed that they were in engaging risky behavior because of poor footwear, walking in socks, no handrail, or when there are objects left on the stairs (Startzell et al.). This fear has also been found in another study which showed through questionnaires that older women were less confident than the men (Startzell et al.). Lacking the confidence most likely caused them to use the handrail more for support and using the two-footed strategy on every step, and a study found that this lack of confidence could be due to lower range of motion in the lower limb caused by joint stiffness or muscle weakness that occurs with aging (Hamel et al.). Furthermore, elderly people are not the only ones who have difficulty navigating the stairs, but also those with pathologies like osteoarthritis in the knee, since they often have knee pain when climbing stairs (Whitchelo et al.). One study found that having greater quadriceps and hamstring strength could help reduce the pain people with knee osteoarthritis experience when climbing the stairs (Whitchelo et al.). While these studies continue to help gain a better understanding of how different individuals ascend and descend stairs, people encounter different types of stairs throughout their day in terms of step height and width and sometimes use different approaches to climb those stairs.

One factor that has still not yet been fully explored is how step height influences a person's stair climbing ability, balance, and perception of the difficulty of the task. Few studies have investigated the effects of stair height on muscle behavior and joint kinematics and in only young healthy adults. One study investigated the muscle activation of the soleus and tibialis anterior muscles in 18 healthy females (29 ± 5.02 years) and found that there was an increase in muscle activity as the height of the stairs increased (Oskouei et al.). The results indicate that there is no preference between different stair heights in terms of muscular effort (Oskouei et al.). Another study found that in 8 healthy males and 6 healthy females (26.9 ± 9.2 years) that hip and knee flexion during ascent depends on whether the leg is leading or trailing as well as step height; the results suggest that if a person has limited flexion in the knee and hip, then the range of flexion would be reduced when using a step-over-step pattern (Smutnick et al.). Riener et al. did a broad overview of stair ascent and descent at varying step heights where the hip, knee, and ankle kinematics and joint torques were compared to that of walking in 10 healthy males (28.8 ± 2.9 years) (Riener et al.). Their findings showed that the aspects of the knee, hip, and ankle were more affected than others such as the temporal gait was not affected but the joint angles and moments showed dependency on the inclination (Reiner et al.). All these studies were working to understand the influence that stair height has on a person, so that way they could gain knowledge of how to aid those who struggle with this task.

Many of these studies are using healthy, young adults as their test subjects, but these populations do not have difficulties with climbing stairs at different heights like the elderly or people with pathologies. It still remains unknown as to how different heights and widths of steps affect balance and perception of the difficulty of the task when using different stair climbing strategies (e.g. foot-over-foot or going downstairs backwards). Such information could be used to help train patients or the elderly how to climb a set of stairs when they come across them, so that they are less likely to have difficulty, to fall, or to be scared to complete the task. In order for my advisor, Dr. Caruthers, to begin investigating these questions in her lab, she needs an adjustable and transportable staircase so that she can test various populations climbing stairs of different stair heights within different locations of the Westerville community. Therefore, the objective of my thesis is to build an adjustable and transportable staircase that can be used in studies that will test a person's ability to navigate stairs of different heights and widths using different stair climbing strategies to see how those changes affect factors such as balance and perception of the difficulty of the task.

Design Requirements

The staircase needs to be adjustable in height, easily transportable, not exceed the budget of $1,500, and can be easily adjusted and maneuvered by one or two people. The time it takes to adjust the staircase will be efficient and the components can be easily taken part for transportation. In addition, it also needs to support the weight of one person. Furthermore, when designing the staircase, safety for the participants needs to be of the utmost concern along with following the Americans with Disabilities Act (ADA) regulations (https://www.access-board.gov/guidelines-and-standards/buildings-and-sites/about-the-ada-standards/guide-to-the-ada-standards/chapter-5-stairways). Handrails will be placed on both sides of the staircase and around the platform for the user to grab in case they lose balance at any point in the ascent or descent. The staircase will be able to adjusts its heights where it must be a minimum of 4 inches tall but not exceed the maximum which is 7 inches according to the ADA (Figure 1). The treads of the steps must be at least 11 inches wide and will not have a nosing which is part of the tread that overlaps the tread bellow it (Figure 1). My advisor and I went around Otterbein's campus to collect data about the rise and tread dimensions of different stairs to some common stairs that people were climbing on a daily basis which was compiled into Table 1 along with pictures of the stairs that can be found in the Appendix. Lastly, the number of steps that the staircase will be is 5 steps where the final step will also be a platform. By having 5 steps, we are able to observe a full stair gait cycle which we would not be able to see if we had fewer stairs.

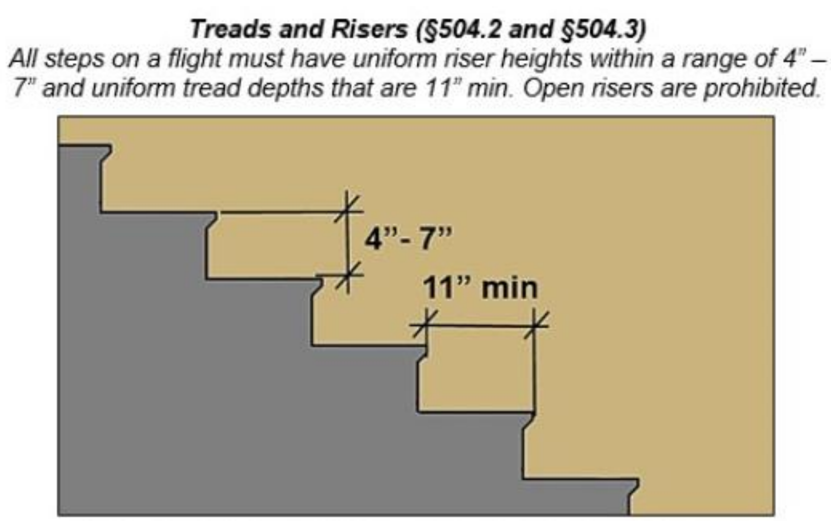

Figure 1: ADA Staircase Example

Table 1: Measurements of Staircases Around Campus

Picture	Building	Location	Step Height in Inches	Tread in Inches	Total Height in Inches
A1	Music	Outside Door 7	8.5 6.25 7.5 7	9.5 9.5 10	44.5
A2	Music	Outside Door 4	5.25	11.75	
A3	Roush	Outside Door 3	5.25	12.75 12.5	
A4	Roush	Inside Stairwell	6.5-6.75	12	
A5	Towers	Outside Door 2	7-7.5	11.75- 11.5	
A6	Towers	Outside near 110	7 6-5.75	10.5	
A7	Towers	Door 1 Inside	7 6.5	10 10	
A8 A9	Science Center	Inside Stairwell	6.5	12	
A10 A11	Outside CC	Near the Parking Lot in the Front	3.25 4.25	14.25 15	
A12	Devore	Inside Stairwell	6.5	11.75	

Pictures of these stairs can be found in the Appendix

Design Evolution

I developed the following ideas in the process of brainstorming different designs for the platforms and stairs:

Platform

"Push Pin Idea": For the platform I had the idea that I would follow a similar design that track hurdles have with push pins where the user can press the pins and then can move the hurdle to a different height (Figures 2 and 3). I thought this would be a good way to make the platform adjustable. This idea though presents challenges due to the weight of the platform and if one person would be able to adjust it on their own.

Figure 2: Push Locking Pins

Figure 3: Hurdles

"Mechanical Crank": This idea was that the platform would have a similar design to that of a scissor lift, but the only difference would be that the mechanisms used to raise and lower the platform would be a hand crank. This would be a simple way for the operator to change the height of the platform that's not too labor intensive. The downside it that all the parts needed to construct this idea would have to be bought and then machined to the dimensions required. This could increase the overall price of the staircase and amount of time needed to be spent in construction.

"Hydraulic Legs": At my internship over the summer, one of the projects were making a working table that could adjust to different heights of the employees. They used hydraulic legs that could be controlled through a button reduce the labor needed to adjust the height of the platform. My advisor and I immediately scraped the using hydraulic legs idea because the cost to buy the legs, around 700-800 dollars, only would make the project be over budget.

"Scissor Lift": After attempts at making the model and conferring with the MakerSpace operations manager, it was determined that purchasing a scissor lifting table and modifying it to our purposes would be cheaper and easier to accomplish within the time frame I had to construct the staircase and its respective components.

Stairs

“Gym Bleachers Idea”: The idea to make it transportable is similar to gym bleachers where the lowest step would fit into the previous step and continue this process until it resembles a rectangular prism. The trouble point for this idea was that there was never an easy solution to how the steps would adjust to the different heights. All the ideas that I had with the gym bleacher solution ended up being over complicated, too complex, or would never work with the design because the mechanisms that would be needed to make each step adjustable would interfere with the transportation aspect of the staircase.

“Step Ladder”: The step ladder concept is where the steps would be attached to the platform and be able to change along with the platform instead of the two being separate from each other. This simplified the mechanism that would be needed to make the steps adjust to the different heights so that it can be done by one person. (Figure 4) shows the scissor lift and ladder concept together and how the final product should look once completed.

To compare all these designs for how the platform and steps would look and function, I used a decision matrix (Table 2) that would allow me to compare the ideas to the criteria that it needs to follow (outlined in the Design Requirements) and how well that design would fulfil that requirement. I then tallied up the scores from all the ideas and found that the step ladder design when using the scissor lift platform would be the best decision and is the one that is strongly recommended to use in the construction phase of this project.

Table 2: Decision Matrix for the Platform and Staircase Ideas

		Platform				Steps	
Criterion	Weighting	Push Pin Idea	Mechanical Crank	Hydraulic Legs	Scissor Lift	Step Ladder	Gym Bleacher Idea
Can the step heights be adjusted?	4	2	1	1	1	3	1
		8	4	4	4	12	4
One person needed to operate it?	3	3	3	3	3	2	2
		9	9	9	9	6	6
Where is the mechanism going to be placed? (safety)	5	3	3	3	3	3	3
		15	15	15	15	15	15
Can it be adjusted quickly?	3	3	1	1	3	3	2
		9	3	3	9	9	6
Is it affordable?	2	3	1	1	2	2	1
		6	2	2	4	4	2
Could it be transported?	4	1	1	1	3	3	1
		4	4	4	12	12	4
Can it be made in time?	5	2	2	2	3	2	1
		10	10	10	15	10	5
Can it hold a person?	5	2	2	2	3	3	3
		10	10	10	15	15	15
Can it be taken apart?	4	2	1	1	1	3	1
		8	4	4	4	12	4
Total		79	61	61	87	95	61

(Figure 4) shows the scissor lift and ladder concept together and how the final product should look once completed.

Figure 4: Final design concept showing the staircase with wheels

Final Design Description

Throughout this entire design process, SolidWorks was an excellent tool that was utilized to create a coherent design that would be able to convey my idea to other people. It can model specific geometry that would otherwise be difficult to achieve in the real world while still working out the details of the design. The benefit of changing or editing a design is not expressed enough for how useful that is in terms of time and money. Though one might spend more time in the designing phase by using SolidWorks, the time spent in prototyping and testing would be greatly reduced.

Platform Assembly

Once the scissor lift idea was chosen, I began researching different lifting tables to find the one that would best suit the needs of the project. The criteria that was considered for the lift was the range in height it could adjust to, the size of the top, how much it can support, and the cost of the table (Appendix Table A1). Conferring with my advisor, it was decided that the Global Industrial table that has a 16-3/4”-39” height range, a 39-1/3” by 20-1/4” top, can support 1,100lbs, and is priced a $529 would be the lifting table used for the project (Figure 5) and then we discussed the plans we would need to make in order to modify it for the staircase.

Figure 5: Purchased scissor lifting table

The platform consists of the order scissor lifting table and a custom-made wood frame that is placed on top of the cart. The wood frame is beneficial in two regards. The first is that the lifting table does not have the reach to get to the height needed for the staircase which is 40 inches. The second reason is that the participants that are traversing the stairs would need the consistency of seeing the same surface as they step

Step Ladder Assembly

Step

The step was made to be 34 in by 11.5 in by 1 in that way the width can fit into doorways and the length is meeting the requirement set by the ADA. The other feature that the step has is two holes on each end so that it can be attached to the adjusting bars used in the ladder design. The holes are half an inch and then center of each hole is half and inch from the bottom of the step and one and a half inches from each respective end (Figure 6). Based off a Finite Element Analysis (FEA) done in SolidWorks for one of the steps, it was decided that steel rods should be placed in grooves underneath each step for extra support (Figure A13).

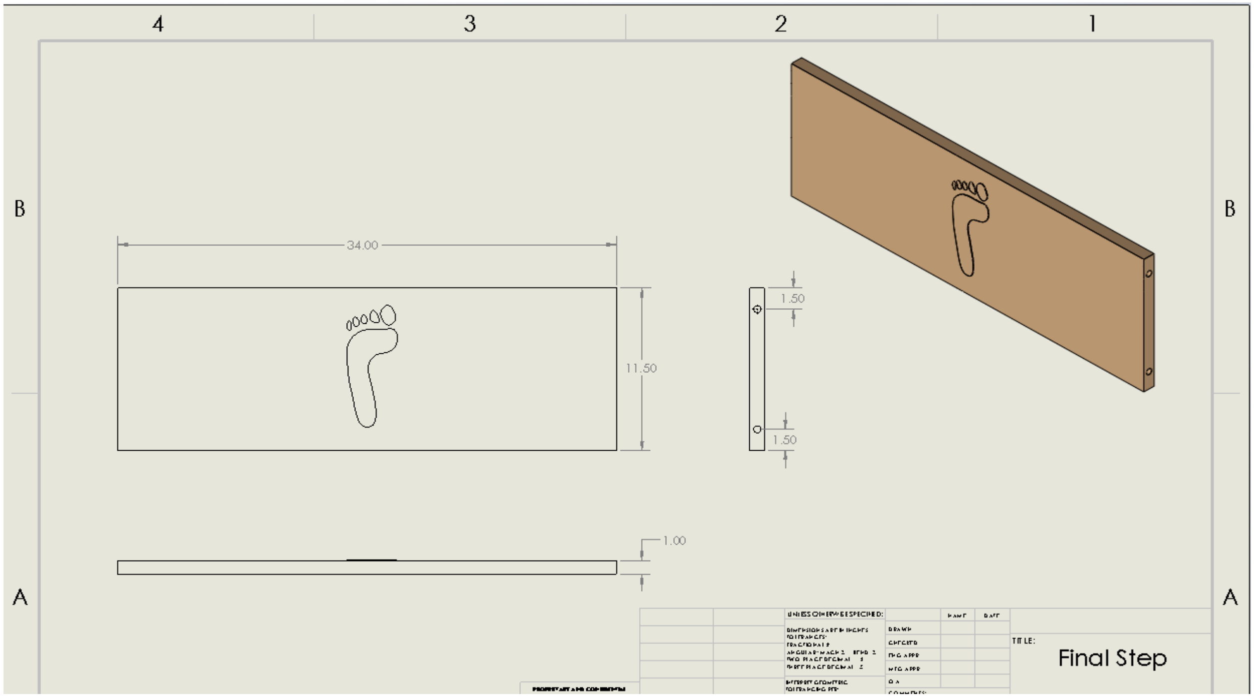

Figure 6: Step dimension drawing

The step assembly has two rods with threaded holes at each end. The rods are placed in the grooves made in the wooden step that are set 8.5 inches from the centers and are cut 3/8” into the step. The step is then lined up with the angle iron and brass bushing holes after that a shoulder bolt is inserted and threaded through the hole until it is tight. This is to be completed on all four holes on all the steps.

Step Frame

The step frame is made up of four pieces of angle iron that have been drilled with holes as a way to attach the steps and the platform to the frame. The steps use brass bushings and shoulder bolts for the attachment while the angle iron to the platform uses a turning screw. Each angle iron bar has a wheel that is welded on to the bottom of it as a way to reduce friction and make it easier for the assembly to move as one during transition periods shown in Figure 7.

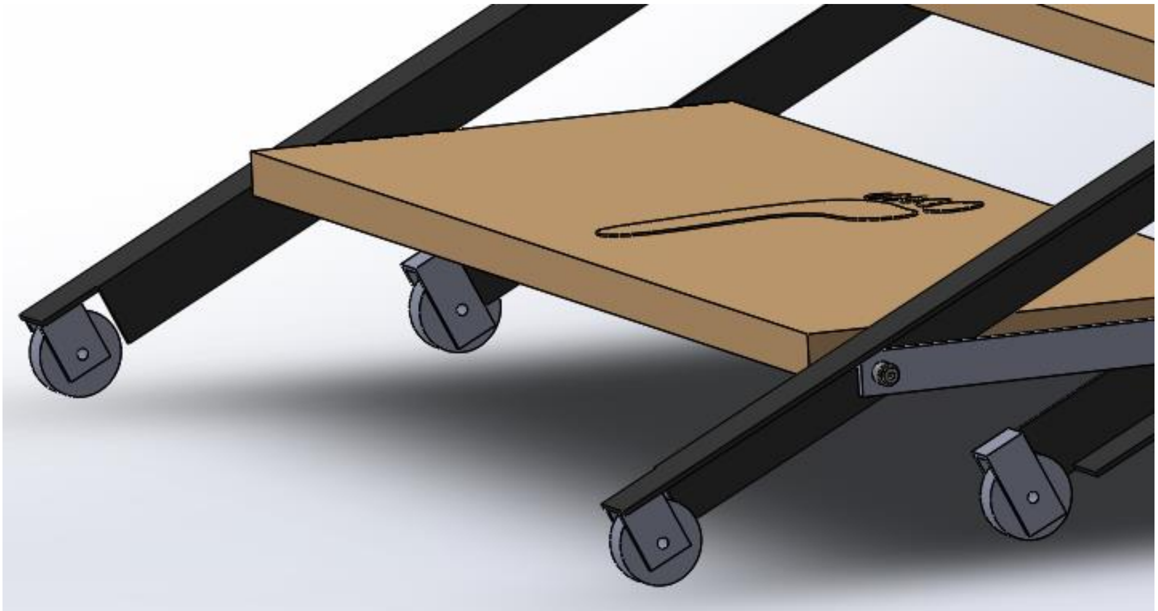

Figure 7: Angle iron bars with attached wheels

The steps in the ladder concept (Appendix Figure A14) work by figuring out the length of the bars that they attach and where the holes should be place. Since the length of the bars can not change when the staircase goes to different heights, then the length needs to be the maximum that it needs to be which would be when the platform is 40 inches tall (8 inches for five steps). Once this was calculated, the holes where then added to by using trigonometry to discern where the holes for the first step were to be place and then repeating that pattern for the rest of the length. (Figure 8) shows the scissor lift and ladder concept together and how the final product should look once completed.

Figure 8: Final design concept showing the staircase with wheels

Construction Materials

The following tables outline the quantity and cost to construct the platform and the stairs.

Table 3: Material Lists for Making the Stairs

Stairs			
Material	Dimensions	Quantity	Cost
Wood	34x11.5x1	4	$43.44
Metal Rod	34" and 1/2" dia.	8	$50.74
Brass Bushing	OD 1/2" ID .252" Thickness 3/8"	32	$65.92
Shoulder Bolts	Shoulder Dia. 1/4" Shoulder Length 1"	16	$99.84
Steel Bars	3' by 3' sheet Thickness 1/4"	8	$28.88
Angled Iron	1.5"x1.5"x1/8" round corners 5 feet long	4	$326.40
Wheel Chocks	We will make ourselves	1	$0
Thumb Screws	Pack of 5: 2" long with 1" threaded 1/4-20	4	$8.75
	Total		$623.97

Table 4: List of Materials for Making the Platform

Platform			
Material	Dimensions	Quantity	Unit Cost
Lift		1	$529
Wood Top	34x42x1	1	$51.60
	Total		$581

Construction Plan

Platform

The main feature of the platform is the mobile scissor lifting table and the wood top would be placed in a frame that will be constructed around the top of the lifting table to ensure that it will be kept in place as participants step on it, walk, and turn around before going back down the stairs. The wood top would also need holes that the bars of the ladder concept could attach to connect the platform and stair component.

Steps

The steps would be sized and follow the dimensions shown in the drawing (Figure 6) and the parts listed in (Table 1). The stairs would fit the metal rod in the holes on the edges. The exposed end of the metal rod would have a threaded hole that would match the threads of the shoulder bolt. The shoulder bolt goes through a hole in the angle iron which also contains a brass bushing before it reaches the metal rod in the step. The brass bushing is there to allow the angle iron to be able to rotate when the platform is changing to different heights. The shoulder bolt however ensure that the step does not rotate while the platform is in motion and keeps it level the entire time.

Adjustments made for the step described above was that there is double the amount of brass bushing because the size of the shoulder bolt is longer than the width of the angle iron. The reason for this was that shoulder bolt that would be the correct length had a smaller threaded diameter that my advisor and I did not think would be supportive enough for holding the steps in place. This led us to going into the next size up which is the one used in the final design and adding a supportive steel bar that spans the width of the step in Figure 9.

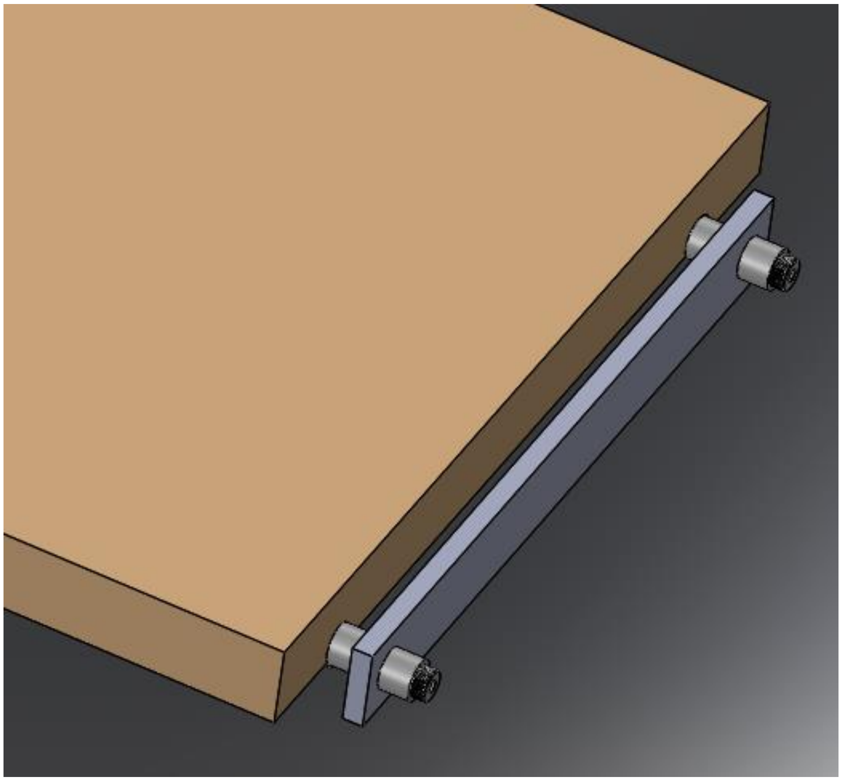

Figure 9: Adjustments made to the step assembly

Further Design Recommendations for Construction

With this design, I was unable to incorporate a handrail design to the staircase, but in the future, there will need to be one before it can be tested and used. I have given thought on how it could be constructed, but not in the detail that it will need to be to be able for it to be coherent in the current design. I feel that the handrail needs to be broken up into two parts where one is connected to the platform and the other is a part of the step ladder assembly. The handrail could be made out of steel tubing or PVC to achieve that curved shape that is seen by most handrails. To ensure that it is able to change with the rest of the assembly, I suggest the use of a hinge or a ball and socket joint at the point where the two pieces of the handrail are to attach to each other.

Another recommendation would be that the attachment method that I came up with for the original design was that of a turn screw which at the time seemed like the best method of attaching the stair/ladder to the platform. Upon further research of other methods, I found a similar design that uses clamps instead as seen in Figure 10. This could be an improvement to the overall staircase because it might allow for the dimensions of the angle iron in terms of the placement of the holes that give the steps their correct height.

Figure 10: Clamp attachment design

Discussion

Due to unforeseen events, I was unable to accomplish the task of constructing the finished staircase, so in the end I was only able to produce a final design, a list of materials, and how to construct the staircase. The work that has been done thus far should make a smooth transition from 3D modeling to real world applications.

The beginning of the project taught me that identifying the problem is key in determining how to proceed with the design. With this project it was clear that developing a way for the staircase to be transportable and able to adjust to the necessary height. It was not as straightforward as I thought it would be. It took many iterations and asking questions about what it needed to be able to do in order to narrow down what it could be. For example, I originally thought of gym bleachers and their ability to stack on top of one another for a way to make the staircase adjustable; however, the mechanics to make it adjustable would have complicated the system too much in order to make it work. This led me to more research and going back to the drawing board in pursuit of more realistic ideas for solving these problems that the staircase needed to face.

Though I was unable to complete the construction of the staircase, I was still able to learn a great deal from this experience through the design process. One of the important aspects that I learned through this process was how essential measurements of the components are before any steps should be made in construction. The part that relates the most to this concept are the angle iron bars that are used as the frame of the stairs/ladder assembly. The placement of the holes are critical in ensuring that the steps remain at the same height throughout the process of the platform being wither raised or lower. The attachment to the platform and the first step were the hardest to figure out how to place the holes so that all five steps were the same height as the platform changes to the determined height.

Knowing what resources and equipment were available was also crucial for determining the feasibility of the project. My advisor and I also discussed the staircase with the operations manager of the Maker Space to learn about what he thought about the design, any suggestions he had on ordering the parts, and what components needed to be machined in the MakerSpace. His advice helped give the project a better direction to how the final product would look. His experienced led to the change of steel bar to angle iron bars that are used in the frame of the stair/ladder assembly and he also gave the idea of using brass bushing and a shoulder bolt as a way to attach the components in the above mentioned assembly. The work done in this phase of the project guided me to find products out in the market that could be used as feasible components of the design.

This project has given me real world experience about how the designing and construction process would be like at a company where careful planning, asking the right questions, and taking advice from others will increase the likelihood that your project will succeed. I learned that when you get answers to your questions, it also leads to more questions, and that it is to be expected as you are working out the details of your design. Lastly, I learned that when under taking any project you need to understand why are you doing it which can help explain the benefits of the features that you are implementing and explain to others why you are pursuing those features for the project. All of these factors are essential in the engineering field where the work done for this thesis reflects the work, I am likely to pursue in the future.

Conclusion

This project was the most complex problem that I have ever attempted where the pieces built of each other and effected how the rest would function. I am grateful for the opportunity to attempt such and endeavor even though I was unable to complete what I set out to do. I am confident that this thesis lays out the groundwork of the design and the strategy to achieved building an adjustable and transportable staircase at a later date.

Acknowledgments

I would like to thank the professors in my committee Dr. Hudoba and Dr. Tansey for taking time out of their schedule to listen and read my thesis. I would also like to thank Curtis Smith, who is the Operations Manager of the MakerSpace, for giving expert advice on the project in order to make it feasible and your reliable input on any questions I had concerning the mechanisms for the staircase. I appreciate that you were willing to teach me how to operate the machines that were necessary for the construction of the staircase. Lastly, I want to thank my advisor Dr. Caruthers who has been nothing but supportive throughout this journey. She has guided me throughout this entire process, and I could not have asked for a better mentor. I thankful for everything you have done for me over my last two years at Otterbein and I will never forget it.

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Appendix

Figure A1: Music Building Outside Door 7

Figure A2: Music Building Outside Door 4

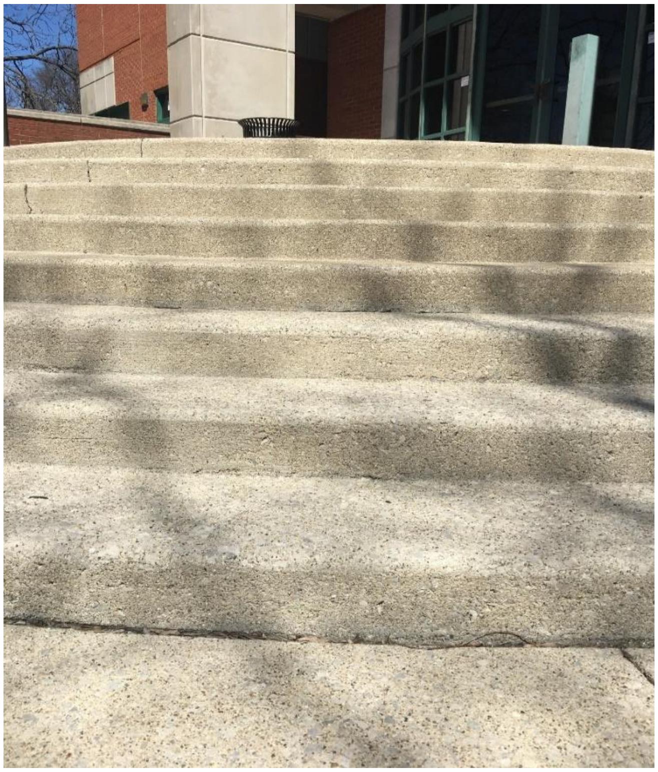

Figure A3: Roush Hall Outside Door 3

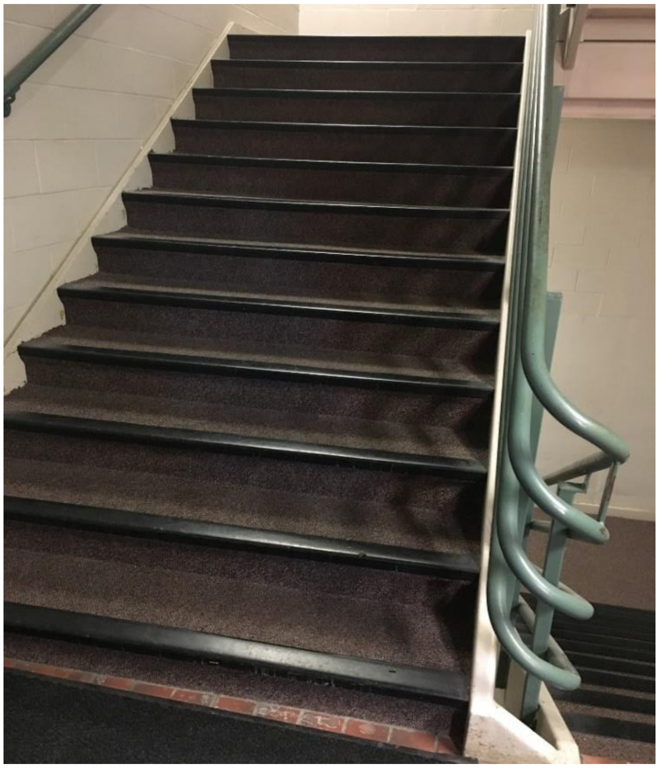

Figure A4: Roush Hall Inside Stairwell

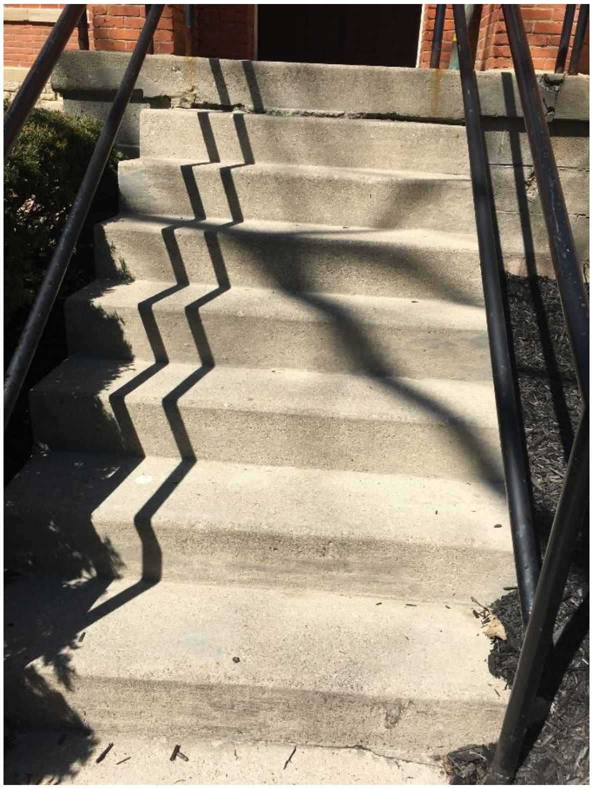

Figure A5: Towers Outside Door 2

Figure A6: Towers Outside Near 110

Figure A7: Towers Door 1 Inside

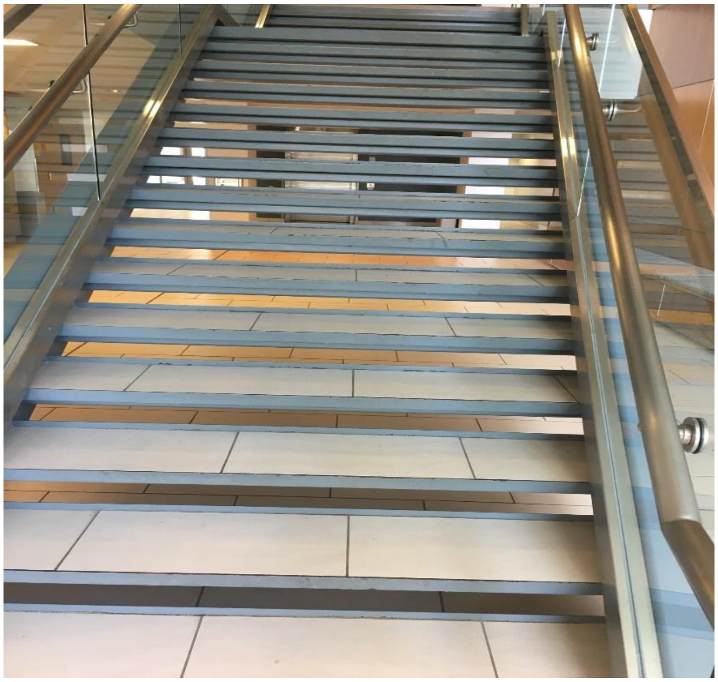

Figure A8: Science Center Inside Stairwell

Figure A9: Science Center Inside Stairwell

Figure A10: Outside the CC Near the Front Parking Lot

Figure A11: Outside the CC Near the Front Parking Lot

Figure A12: Devore Hall Inside Stairwell

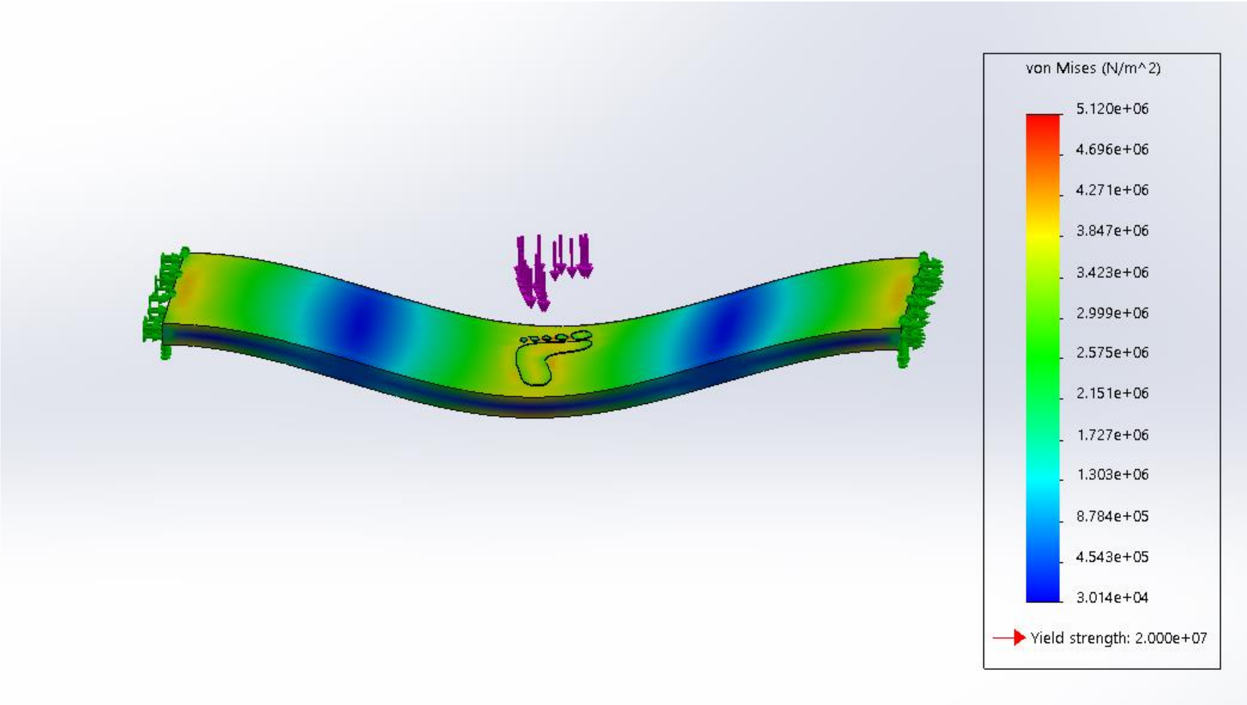

Figure A13: FEA of a single step

* This finite element analysis of a single step is fixed on the sides and the force applied was 300 pounds in the center of a balsa wood step showing the stress that the step would experience.*

Table A1: Mobile Lifting Table Comparison

		Top Dimensions		Height Range					
Company	Model Number	Length	Width	Min	Max	Weigh Capacity	Lifting Strokes	Single/Double Scissors	Price
Global Industrial	T97988932	63"	32"	11.25"	36"	1,100 lbs	55	Single	$719
Global Industrial	T97168075	39-1/3"	20-1/4"	16-3/4"	39"	1,100 lbs	55	Single	$529
Harbour Freight	60438, 69148	32"	20"	11"	34-1/2"	1,000 lbs	Not Found	Single	$280
ULINE	H-1783	40"	20"	16-1/2"	39-1/2"	1,760 lbs	Not Found	Single	$705
ULINE	H-1784	36"	20"	13-3/4"	51"	770 lbs	Not Found	Double	$675

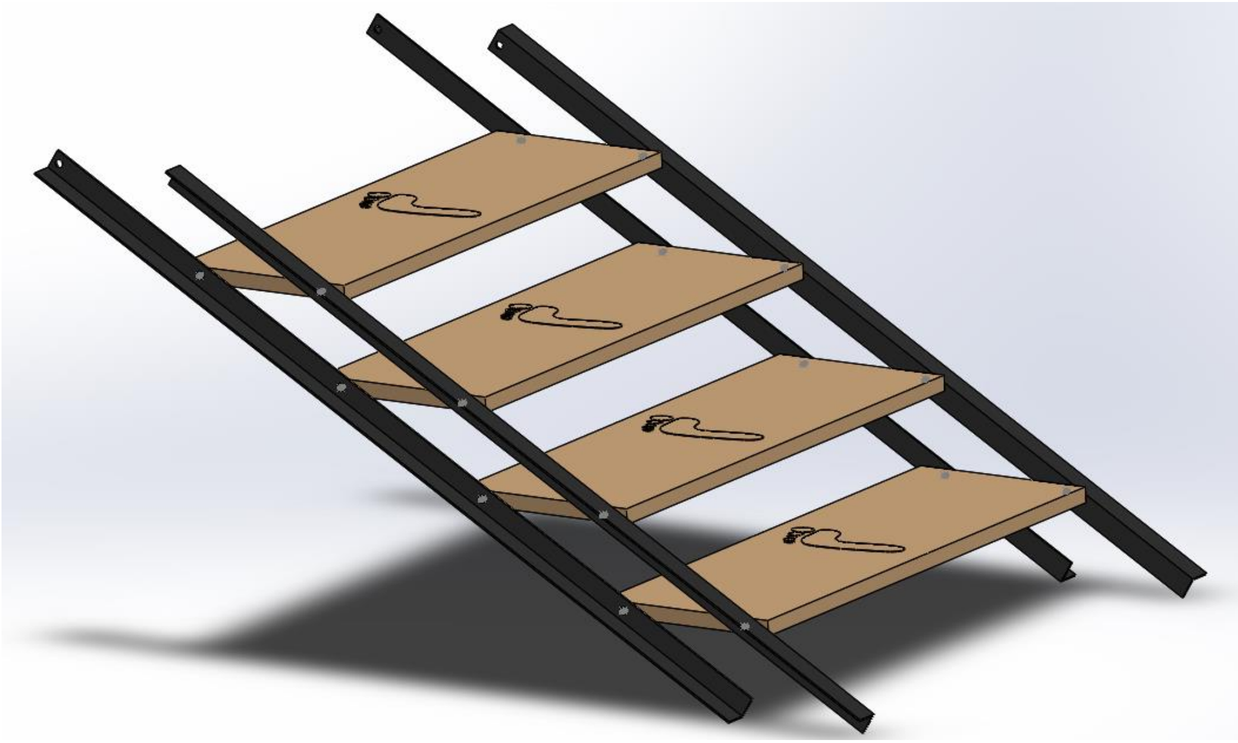

Figure A14: Ladder concept/how the steps relate to each other

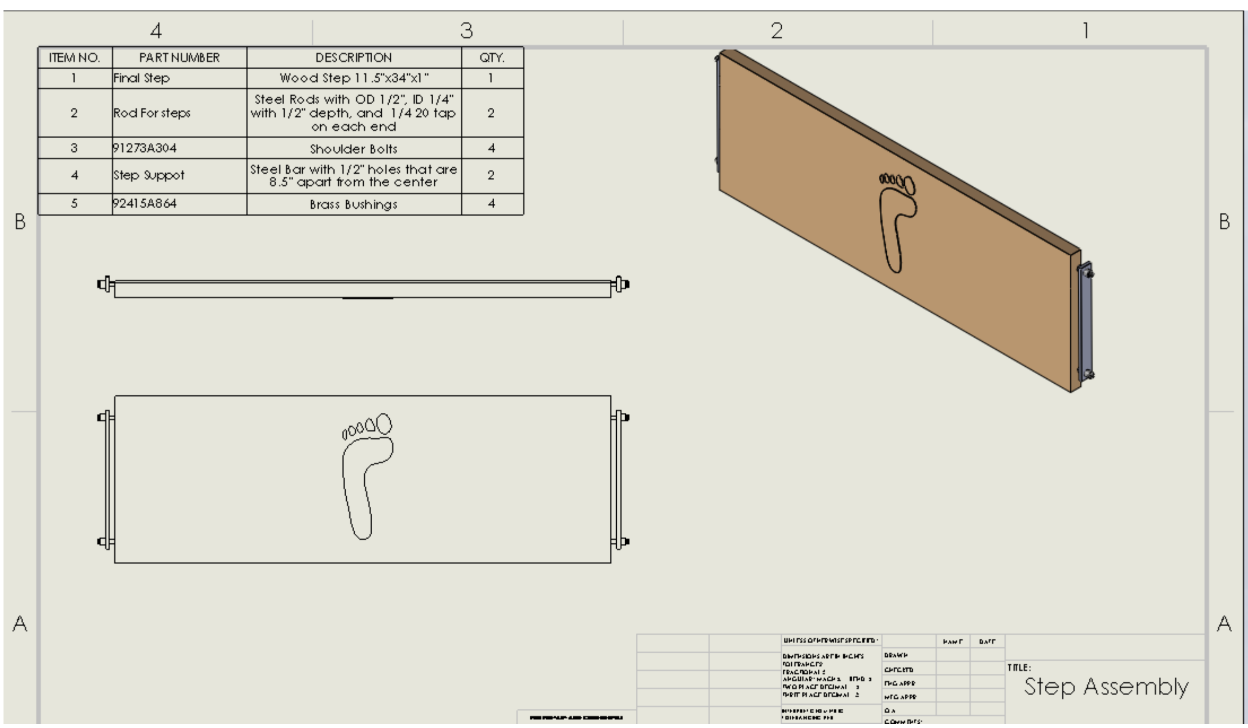

Figure A15: Step assembly for final design

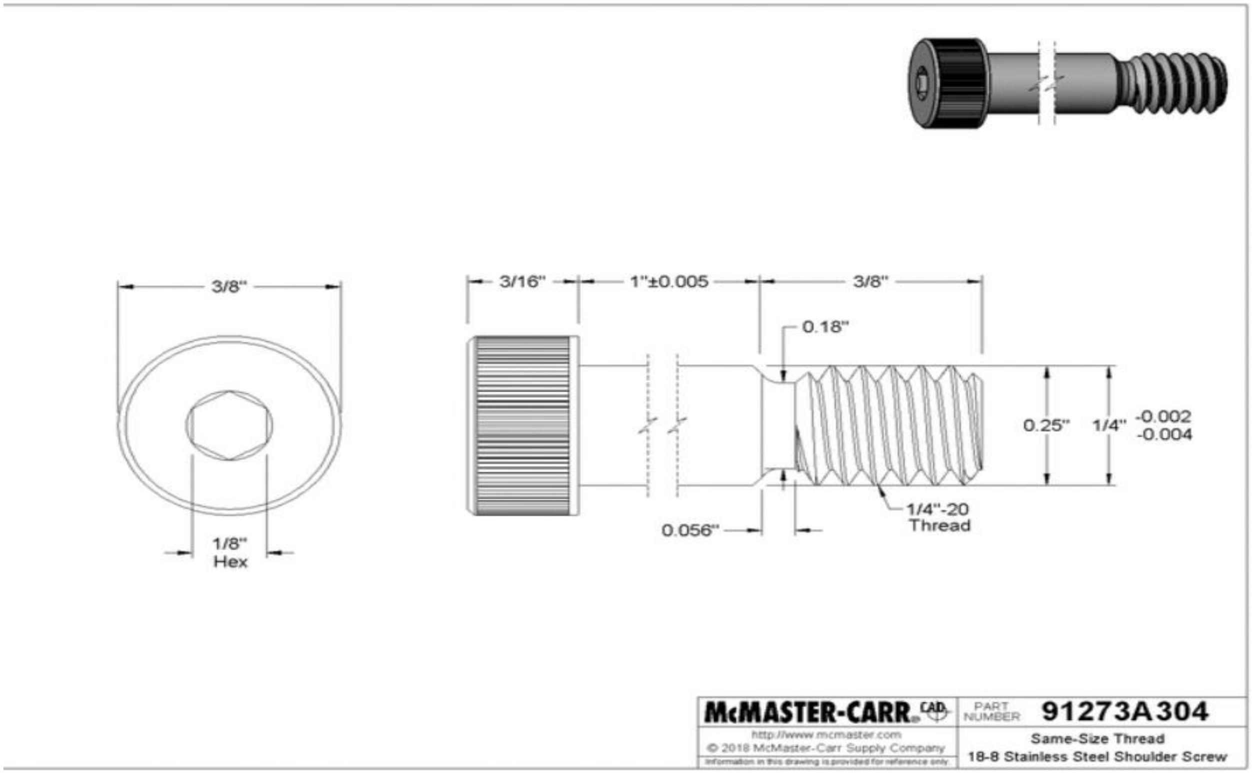

Figure A16: Shoulder bolt dimensions

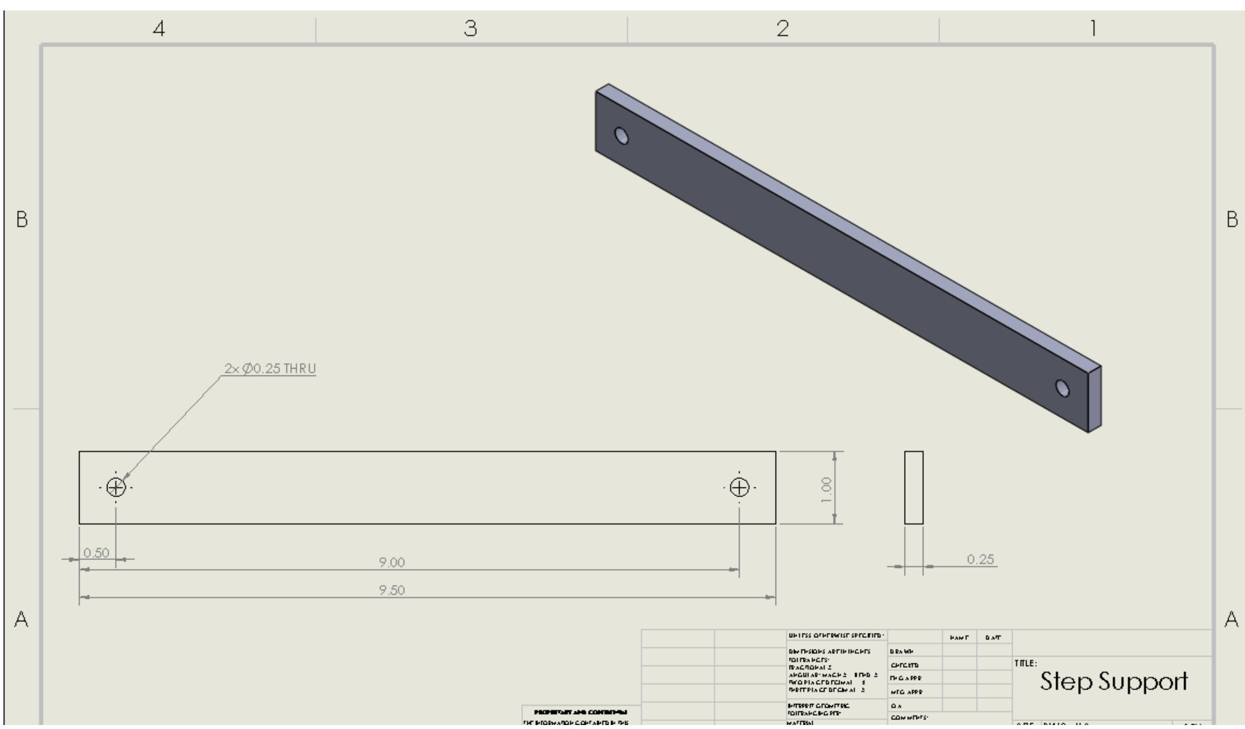

Figure A17: Step Support dimensions

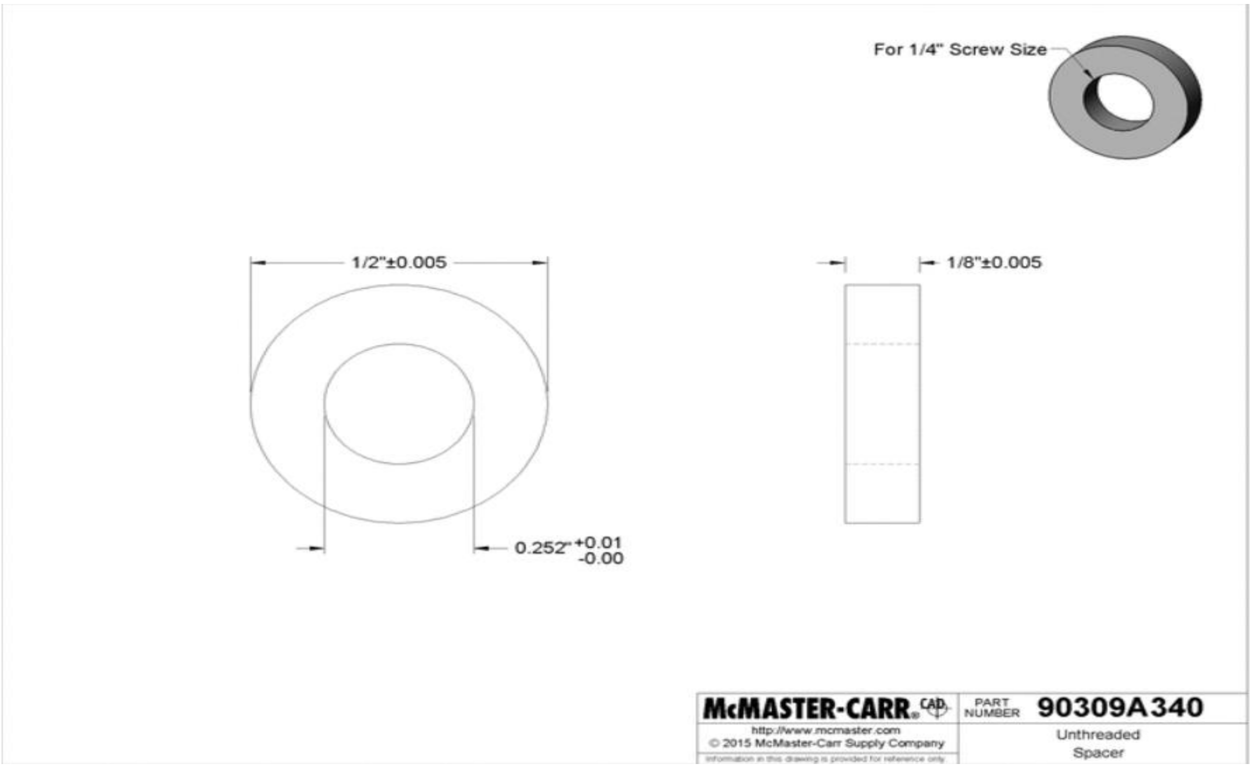

Figure A18: Brass bushing dimnesions

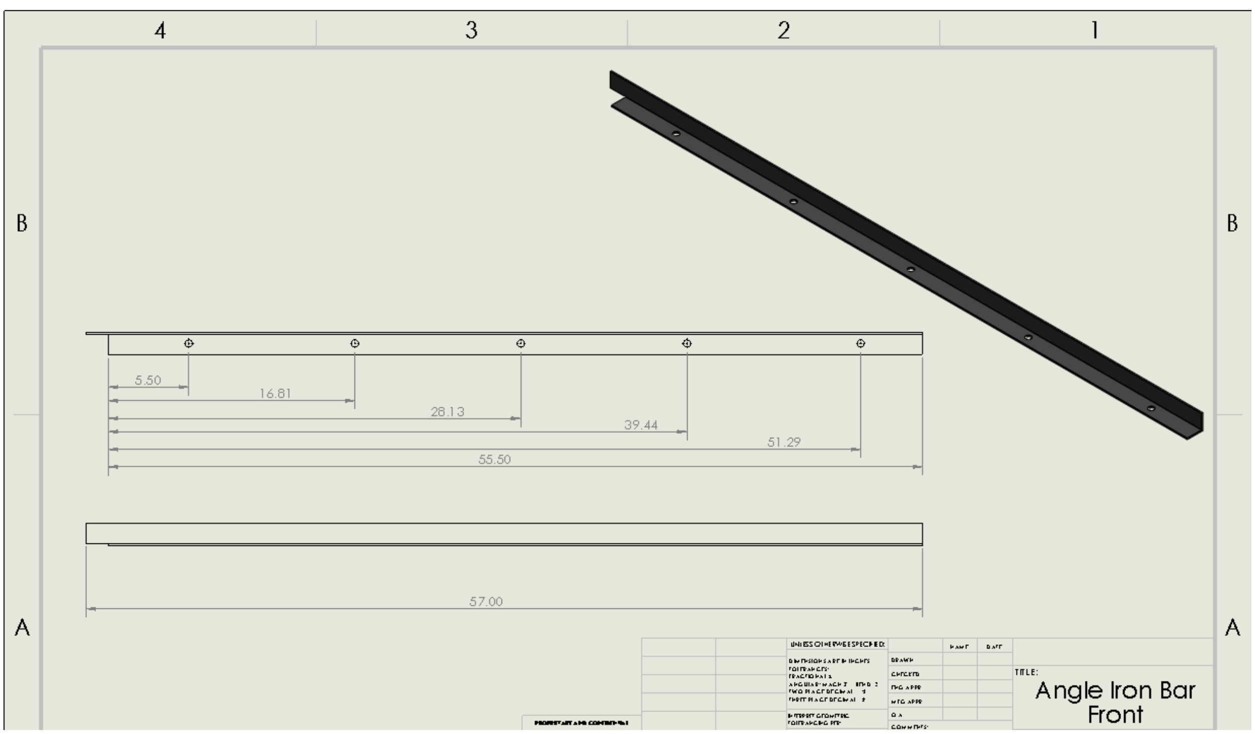

Figure A19: Front angle iron bar dimnesions

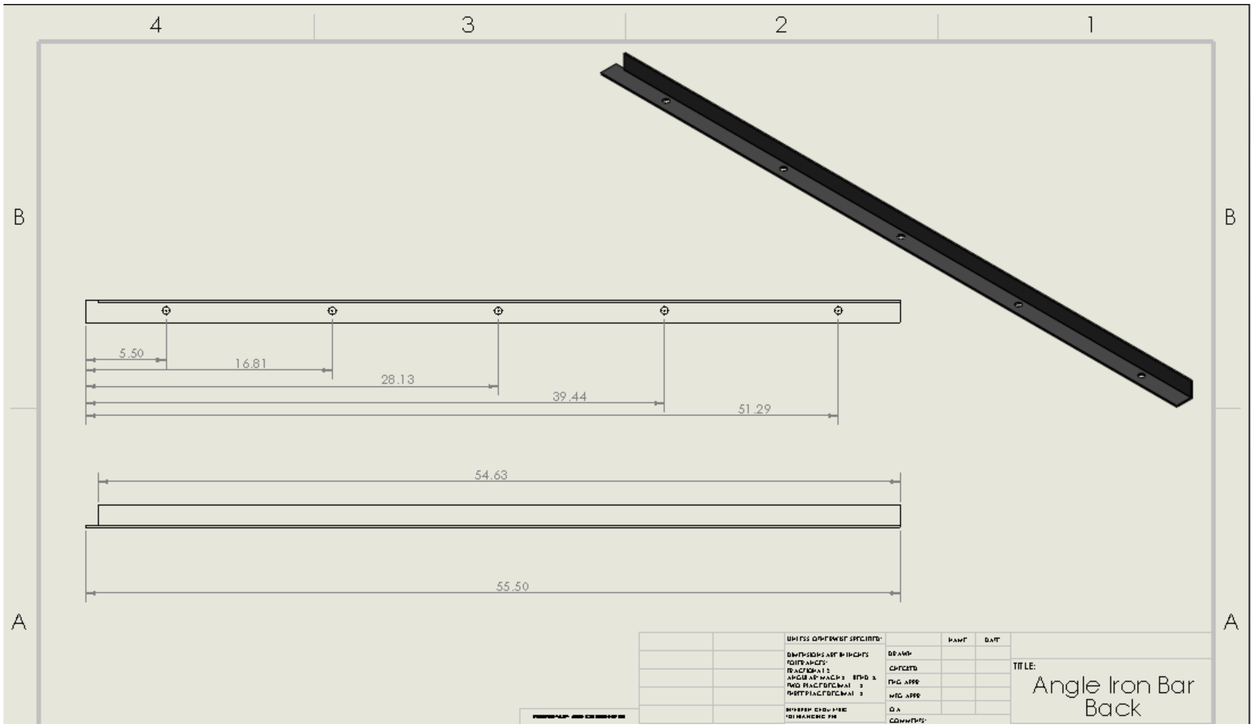

Figure A20: Back angle iron bar dimensions

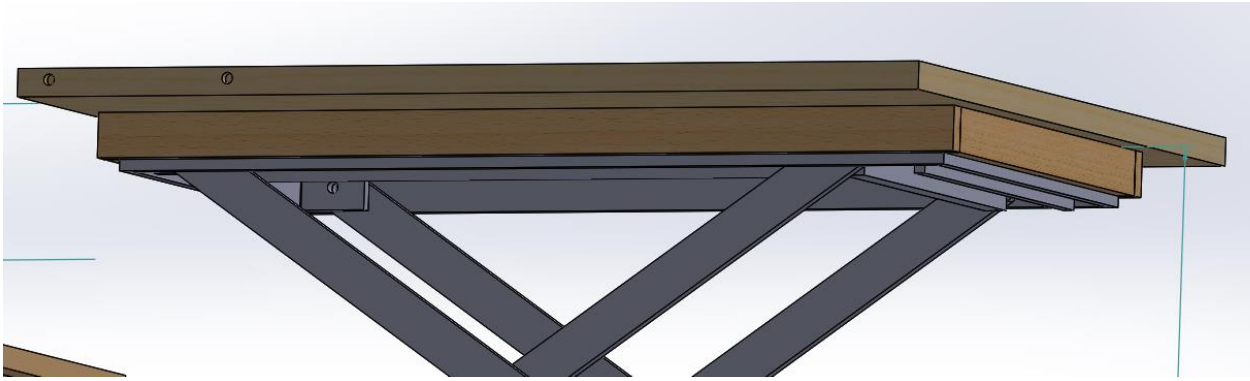

Figure A21: Wood Frame that covers the top of the lifting table

Figure A 22: Platform piece for wood frame dimensions

F

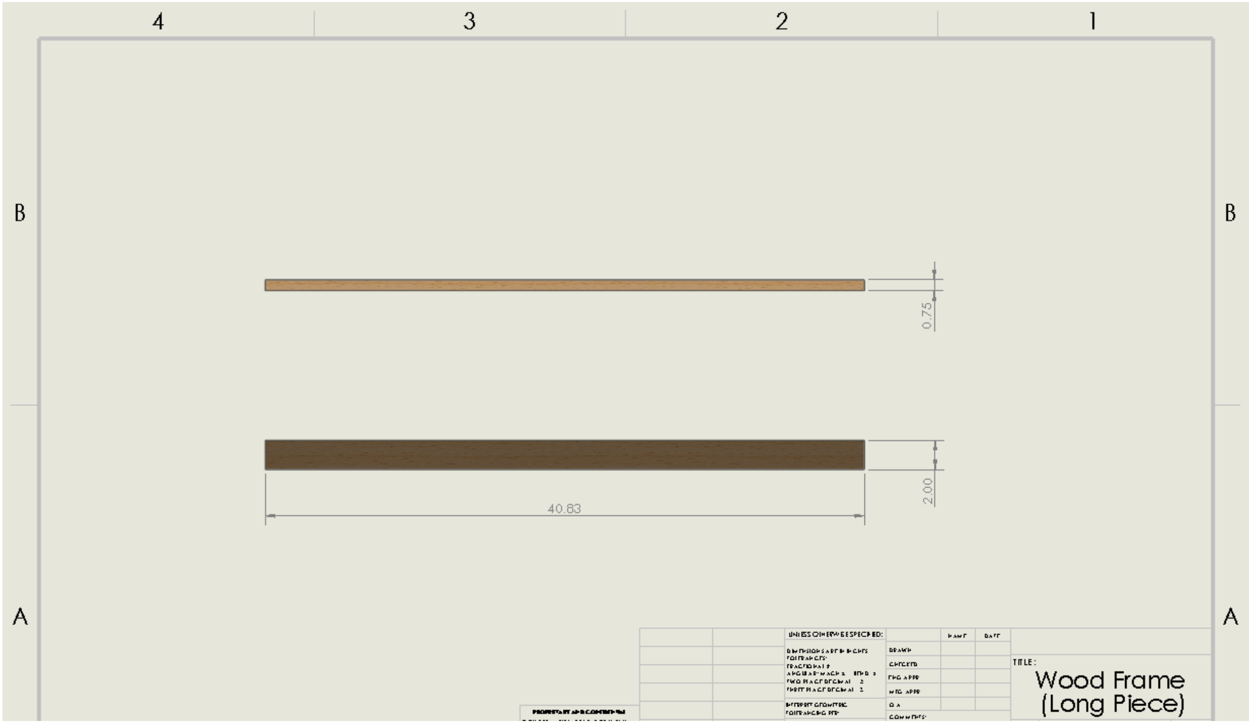

Figure A23: Long wood piece for frame dimensions

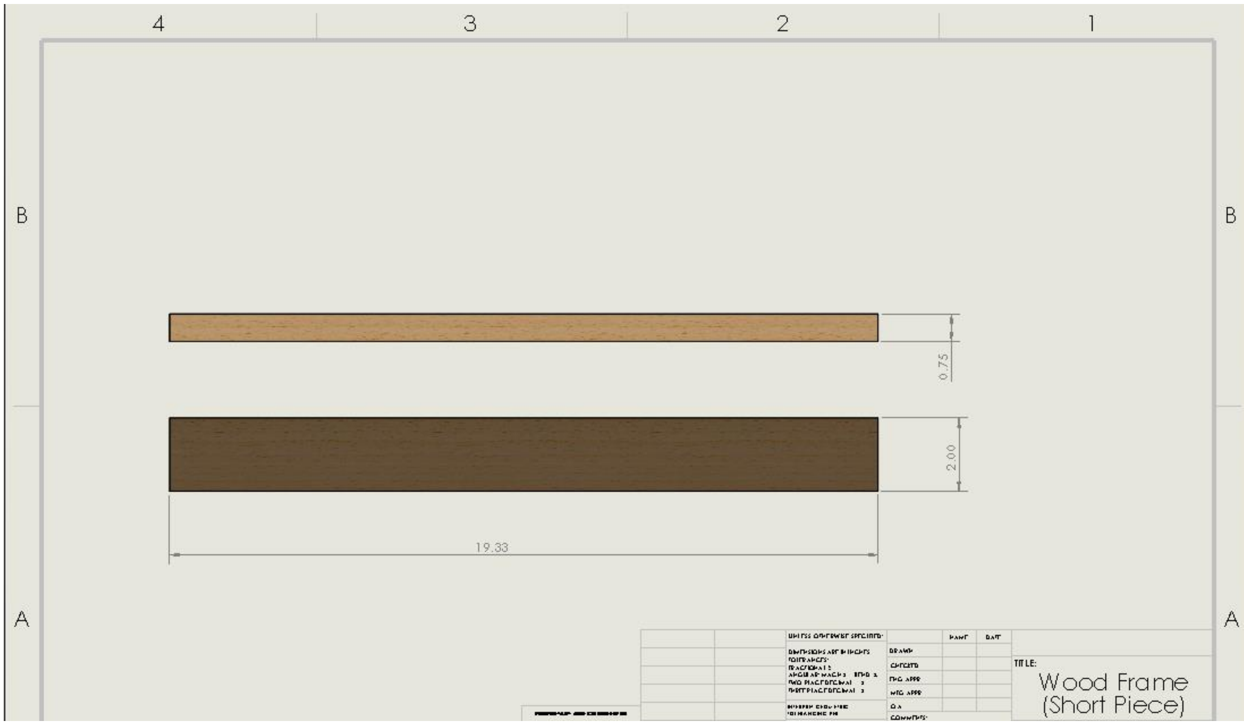

Figure A24: Short wood piece for frame dimensions