UNIVERSITY OF MANITOBA

Space Saver Lift Design

MECH 4860: Final Design Report

Project Sponsor: Conviron

Project Advisor: Dr. Paul E. Labossiere

Submitted by Group 25: Do you even lift?

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EXECUTIVE SUMMARY

The project arises as the sponsor, Conviron, is facing several problems with current methods used to assemble their Space Saver product line of controlled environment units. The particular product consists of two main components; a lower cabinet where the controlled environment is contained, and the machine top that sits on top of the lower cabinet. Current methods for lifting the machine top on to the lower cabinet include using a fork lift, a Genie SLC-18, or manually lifting it. All three of these methods present their own set of problems, whether it be damaging the lower cabinet during installation, requiring a large amount of surface area and height to accomplish the task, or putting employees at risk of injury. For these reasons, the Do You Even Lift design team was tasked with designing a custom lift for Conviron.

The design of the lift encompasses the structural components, as well as the lifting mechanism. The overall structure was designed to maintain height that is lower than the height of the Space Saver unit being assembled, and contains height adjustments to account for a range of height restrictions. The structure wraps around the machine top when lifting to limit the footprint required for operating in tight spaces. The lift is designed to break down into four major components, resulting in a lift that is easily portable, and can be assembled and transported by a single employee if required. Furthermore, all components assembled and disassembled at the job site are connected using pins for the purpose of easing the assembly and disassembly process and help decrease required set-up time. A pulley and winch system was chosen such that the lift is able to operate anywhere in the world; not depending on any outside source such as electricity or fuel. This resulted in a reliable lift that requires less maintenance and lower operating costs.

The final dimensions of the assembled lift contains a footprint of 116 inches by 44 inches and totals a weight of 146.81 pounds. When disassembled, the largest component is 60.81 inches by 44 inches for the footprint and weighs 39.01 pounds. The total cost of the lift, including all components is $2197.03. Detailed drawings of the design, bill of materials, as well as the preliminary FEA analysis will all be found in the report.

Table of Contents

List of Figures

List of Tables

1 INTRODUCTION

The “Do You Even Lift?” design team has been tasked with designing a vertical lift device that allows for easy and safe use at different elevations and environments. The product involved is known as the “Space Saver”. The Space Saver is a controlled environment system that consists of a lower cabinet where different products can be stored, and a machine top that contains the Heating, Ventilation and Air Conditioning (HVAC) equipment. The machine top is heavy and requires a vertical lift to safely lift it onto the lower cabinet when assembling the Space Saver.

1.1 BACKGROUND

The project sponsor, Conviron, was established in 1964. Conviron is a world leader in designing, manufacturing and installation of controlled environment systems. The headquarters is located in Winnipeg, Canada. Conviron distributes its products across more than 90 countries worldwide. The company is looking to improve the lifting process used in the assembly of their product called the “Space Saver”.

The process involves lifting the machine top over a lower cabinet, feeding wires that are attached to the machine top down through the top of the lower cabinet, and then gently lowering and securing the machine top. Conviron had considered different commercial products along with a lift jig to accommodate the process. However, these solutions did not meet their expectations and they want to improve their process with a new lifting design.

The current process of lifting the Space Saver’s machine top is costly, unsafe and inadequate at certain customer locations. At locations with sufficient ceiling heights, a forklift and a lifting jig are used to safely lift and place the machine top onto the lower cabinet. A picture of the jig used to assist lifting the machine top with a fork lift is shown in Figure 1.

Figure 1. Lifting Jig

To lift the Space Saver's machine top with a forklift, the jig must first be bolted to it using four mounting points on both sides, which are shown in Figure 2. The jig's main structure is a beam that spans over top the unit that acts as the lift point for the forks to slide under. Figure 3 shows the current method used with the forklift and jig set up.

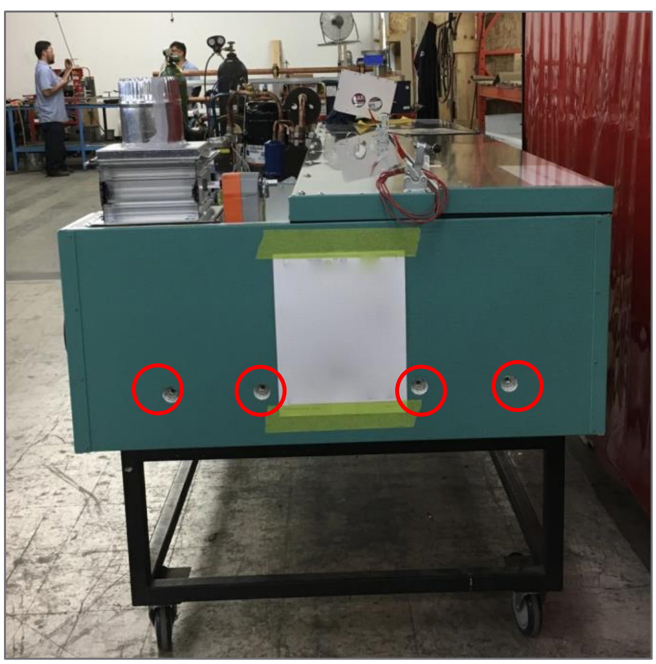

Figure 2. Mounting points on machine top

Figure 3. Current method of lifting the machine top using a forklift and jig

In some applications where floor space or ceiling height are limited, or a forklift cannot access the installation site, another lift must be used. In this case, a Genie SLC-18 is used, which is a mechanical lift that uses a pulley mechanism to lift the machine top. Instead of using the lifting jig, the Genie's forks slide directly under the machine top. The lift is in direct contact with the bottom of the unit. The drawback to lifting the machine top like this is that it must be manually pushed off the Genie to get it onto the lower cabinet once the machine top has been raised. This process is dangerous and can result in injury. The Genie SLC-18 is shown in Figure 4.

Figure 4. Genie SLC-18 [1]

Both the forklift and the Genie have masts on the forks to stop the load from sliding off the back of the forks. These masts protrude above the height of the machine top, presenting a problem when faced with lower ceilings, beams or other obstacles. In some cases, the installer has flipped the forks on a Genie lift upside down to decrease the effective height of the mast so installation was possible. This is not a desired installation technique as it increases the possibility of injury or damage to the machine top.

1.2 STAKEHOLDERS

This project involves many people connected to it in various ways. Each person has some interest in the outcome of the project and each person has some influence during the design process. The details are shown in TABLE I.

TABLE I. STAKEHOLDER INFORMATION

Stakeholders	Role	Interest	Influence	Communication Method
Phil Klaassen	Team Leader	High	High	Whats-app, Meetings, Google Drive
Anthony Lee	Team Secretary	High	High	Whats-app, Meetings, Google Drive
Jared Sowiak	Team Member	High	High	Whats-app, Meetings, Google Drive
Xiangnan Wu	Team Member	High	High	Whats-app, Meetings, Google Drive
Jonathan Li	Client	High	High	Email
Brian Mamrocha	Client	Low	Low	Email
Installation Manager	Secondary Contact with Design	Low	Low	Emails through Jonathan
Installers	Direct Contact with Design	Low	Low	Emails through Jonathan
Dr. Labossiere	Instructor/ Advisor	Low	High	Weekly Meetings, Scheduled Meetings

1.3 PROJECT GOALS

The task at hand is to improve the existing process used to lift the machine top on top of the lower cabinet of the Space Saver controlled environment system. The process will be improved by replacing the lift and jig currently being used with one unit that can perform the task effectively and efficiently while meeting the needs of Conviron that will be covered in Section 4.1. Due to the wide range of environments that Conviron constructs these units in, this lift must be mechanically operated: not relying on any additional source of power. This leads to a narrowed scope that our team can work with in tackling Conviron's current lift problem.

2 Project Objectives

Before beginning the design phase, a detailed scope of the project and deliverables must be determined. This allows the team to allocate time and resources appropriately to the most important aspects of the project.

2.1 Project Scope

The purpose of this project is to design a lifting system that replaces the current jig and forklift or Genie lift. The new system should allow for installation of the machine top onto the lower cabinet and needs to be able to operate in tight spaces where a forklift will not fit. The project itself has specific requirements to be delivered to the client and other requirements for the course.

2.2 Project Deliverables

Conviron requires a lift system to be designed that meets specific specifications. The design needs to be presented in a 3D model using Solidworks. 2D drawings must be generated based on the model. Preliminary FEA must be performed and results delivered to the client as well. A bill of materials to manufacture the lift needs to accompany the design. Weekly progress reports indicating our continuing work are required by Conviron.

In addition to the items we must deliver to the client, there are deliverables specific to the engineering design course. The course work is split into phases. In phase one, a project definition report must be completed after meeting with the client, as well as an accompanying presentation. Phase two is the concept development phase, wherein a report is required. The third phase is a detailed design wherein a report and a professional presentation are the deliverables. Throughout the project, meeting agendas and minutes need to be documented. The agendas and minutes are submitted as a deliverable for the course. The deliverables are summarized in TABLE II.

TABLE II. GENERAL DELIVERABLE SUMMARY

Items for Client	Items for Course
Updates	Project Definition Report and Presentation
3D Design Model	Meeting Documentation
Preliminary FEA Analysis	Concept Development Report
2D SolidWorks Drawings	Detailed Design Report and Presentation
Bill of Materials	
Detailed Design Report	

3 Constraints and Limitations

Constraints are areas that must be addressed to ensure customer needs are met. These are non-negotiable limitations that will affect the designs outcome. The following depicts the specific constraints of the project.

- Device uses mechanical power only.
- Must lift 700 lbs. with a factor of safety.
- A constructible and de-constructible design is required.
- Segments for the assembly of the design will be at or under 6' in length.
- Each segment is under 50 lbs. per the National Institute for Occupational Safety and Health (NIOSH). [5]
- Design segments must fit through a standard door.
- Lifting apparatus must not exceed the height of the space saver
- Single fault failures are risk mitigated.
- An adjustable mast is required that can accommodate the occasional occurrence of an 18" extension collar increasing the height
- Lift must meet all relevant ASME BTH-1 standards

To ensure a successful project, all these constraints must be met. A full detailed description of the ASME BTH-1 standards can be found in Appendix A.

4 Target Specifications

Statements from key stakeholders were collected on attributes desired in a new lift design. The customer statements gathered from this meeting were compiled, translated into appropriate needs, and then edited and verified by the client. The needs were then organized based on client priority and other safety requirements the lift must meet, allowing us to compile a list of target specifications for the design. This section discusses the analysis and quantification of the needs and target specifications.

4.1 Customer Needs

During the teams meeting with Jonathan Li and his colleague Kevin Perris, it became clear that having a lift capable of operating in small, restricted spaces, especially those with low ceilings, is a critical need of the client's that is not met by current methods. For this reason, designing a lift with a compact footprint is a major focus for the team moving forward.

Conviron has customers in countries all over the world that do not always have access to the sort of amenities we are accustomed to in North America. This means the lift design must be completely self-contained and mechanically operated. The design will not use additional power sources or special tools whose accessibility is dependent on the type of work environment.

The unpredictable environments that Conviron operates in also means that the customers can be in locations not easily accessible by roads that can handle trailers used to haul equipment and tools. Conviron needs a lift that is easily portable, regardless of the terrain travelled to reach their destinations. Portability means easy to assemble and light enough to carry the pieces by hand.

After the meeting with Jonathan Li, the team compiled a list of needs which were then weighted based on importance to the client. The safety requirements of the lift were also considered when determining the customer needs. The customer needs can be found in TABLE III.

TABLE III. PRIORITIZED CUSTOMER NEEDS

Need #	Customer Need	Rating	Priority
8	Lift can operate in tight areas/low rooms	5	1
9	Lift can support load safely.	5	2
10	Lift is designed to meet ASME BTH-1 standards.	5	3
11	Lift is self-contained	5	4
17	Lift is portable	5	5
1	Lift's storage dimensions are small enough to fit in a pickup truck.	4	6
3	Lift is the only tool required to perform lift of machine top	4	7
4	Lift maintains shape during and after use.	4	8
6	Lift is stable on uneven solid surfaces.	4	9
7	Lift is secured in position prior to lifting	4	10
2	Lift is easily constructible and de-constructible	3	11
5	Lift maintains shape after many cycles.	3	12
12	Device is ergonomic	3	13
13	Lift is resistant to corrosion	3	14
14	Lift is simple to operate	3	15
15	Device should be operable by a (minimum of 1 person) maximum 2 people	3	16
16	Assembled lift is minimized in weight and footprint	3	17

The list of customer needs in TABLE III is ordered using a rating system from 1 to 5, with 1 being the least important and a rating of 5 being the most important. The column "Need #" is the order in which the needs were brought up during the discussion with Jonathan Li. The needs were then rearranged based off the rating system and ordered in terms of descending priority to help organize the most important customer needs.

4.2 METRICS

Based on the customer needs, metrics and units were created in TABLE IV. The abbreviation "Imp" means importance. These metrics are ranked from 1 to 5 with 1 being the least important and 5 being the most important. A high ranking is given to a metric that satisfies the customer needs of higher importance. The highlighted yellow rows in TABLE IV show the most important metrics that was considered during the designing of the lift.

TABLE IV. METRICS AND IDEAL VALUES

Metric	Need #	Imp	Metric	Units	Marginal Value	Ideal Value
1	1,16,17	5	Maximum area of disassembled lift fits in standard ½ ton pick up truck	in^2	4936	<4936
2	2,3,14	1	Time to assemble/disassemble for installation process	min	15	<15
3	2	4	Additional tools required to operate/assemble/disassemble	unit	5	<=1
4	2,16,17	4	Maximum weight of each disassembled part	lb	32	<20
5	2,17	2	Number of disassembled parts	units	10	5
6	4,9,10	5	Maximum bending stress in a member	psi	22000	<10000
7	4,5,10	4	Fatigue	cycles	500000	2000000
8	6	2	Points of contact with the ground surface	#	5	3
9	8,16	5	Maximum height of assembled lift (inches below space saver height)	in	0	<=22
10	8	3	Maximum width assembled (with or without the load)	in	105	30
11	9,10	5	Minimum load capacity	lb	700	>700
12	8	5	Stress under load	psi	21000	<10000
13	8	2	Total mass of the lift	lb	300	200
14	4	2	Surface area of ground contact points	in^2	25	100
15	4,10	4	Shear stress in connectors	psi	11547	<9000
16	10,11,14	4	Bearing stress	psi	21000	<10000
17	12,14	5	Outsourced parts required to operate/assemble	#	1	0
18	12,14	4	Ease of use by operator	Subj.	80%	100%
19	12	2	Repetitive movement required to operate	Subj.	Low	Very Low
20	13	3	Corrosion Rate	Const.	Low	Very Low
21	14,15	5	Number of operators required	#	2	1
22	16	4	Base surface area when assembled	in^2	4158	<=4158
23	17	4	Size of individual assembly parts	Subj.	Manageable	Easily Manageable

TABLE IV also contains information regarding marginal and ideal values. These marginal and ideal values were generated based on the customer's needs and the Genie lift SLC-18. The team looked to meet as many of the technical specifications as possible when optimizing the lift design.

5 Detailed Design

This section outlines the specifics of the final design as well as the analysis to justify the mechanisms involved. The number of parts involved in the structure will be presented along with the mechanisms involved during the lifting process. The structure is analyzed at critical locations where failure or high deflection could occur.

5.1 Overall Layout – General Overview

The lift is a configured in the shape of a box that goes around the product to be lifted. It has four vertical posts, one at each corner. One side, the front is completely open and has no beams running across its face. This allows for a wide stable base as well as the ability to move the lift around the machine top before lifting and move the lift around the lower cabinet when positioning the machine top. The lift has upper and lower beams that run from post to post on the other three sides. The design can be seen in Figure 5.

Figure 5. Isometric view of complete lift

The vertical post extends from just above the ground to the top of the structure. Each post is telescoping to allow for height variations and condenses for transport. The posts are made from 3” square tubing with a 1/8” wall thickness. The upper telescoping section is made from slightly smaller 2.75” square tubing with a 1/8” wall thickness. This allows the smaller size to fit inside the larger post. The height adjustability is accomplished using pinned connections. The holes are located relative to critical heights that need to be achieved.

The longest members are the cross-bars running from the left side to the right side. To increase portability a pinned connection was implemented in the center of these beams at the top and bottom. Each side of the beams are hinged to their respective posts allowing them to fold compactly. When the beams are folded out they are latched in place so they do not fold in during lifting. There are two thin beams that extend diagonally across the back of the lift to form an ‘x’. These members prevent the frame from skewing. They are pinned in place; the top can accommodate multiple heights by being pinned in a different set of holes that correspond to that height.

The top beam on each side connects the rear post to the front post. This provides a mounting point for the pulley directly above the vertical cable that is used for lifting. At the corner of the vertical post and top beam there are thin beams that cut the corners to prevent skewing. These thin beams are welded in place on the outer surface.

The bottom beam on each side connects the rear post to the front post. This beam sits outside of the vertical posts and has wheels mounted under it. This allows for a wide stable base as well as allowing the post to extend close to the floor increasing the effective lift height. There are four caster wheels in our lift. Two of them are rigid and two of them can rotate allowing for alignment when pushing the machine top over the lower cabinet.

The slider is the interface between the vertical cable used for lifting and the machine top. It bolts directly to the machine top using the four threaded inserts that exist on the machine top. The slider used the vertical posts as guides to keep the machine top from tilting during lifting. The slider has four wheels running on each post, two on the inside face of the post and two on the back of the post. The wheel configuration is in **Figure 6**.

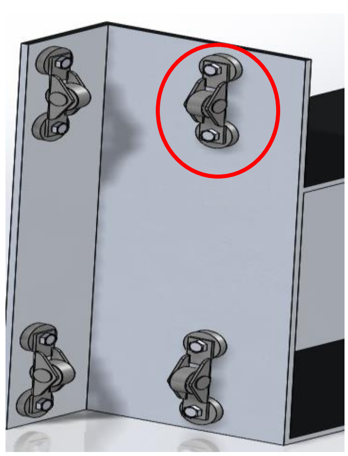

Figure 6. Roller wheels attached to slider

The slider is at a sufficient height as to not bind due to tilting that may happen during lifting. A hook is bolted to the top of the slider in the center for the cable to attach.

The cable system is will perform the work required to lift the machine top. The cable is routed from the slider around the pulley in the top beam on either side. Then it traverses through the pulleys necessary to bring it to the left side on the rear where the left and right cables are joined to a common pulley axle. The red lines in Figure 7 shows how the steel wire is routed through the pulley system and its attachment to the block and tackle system.

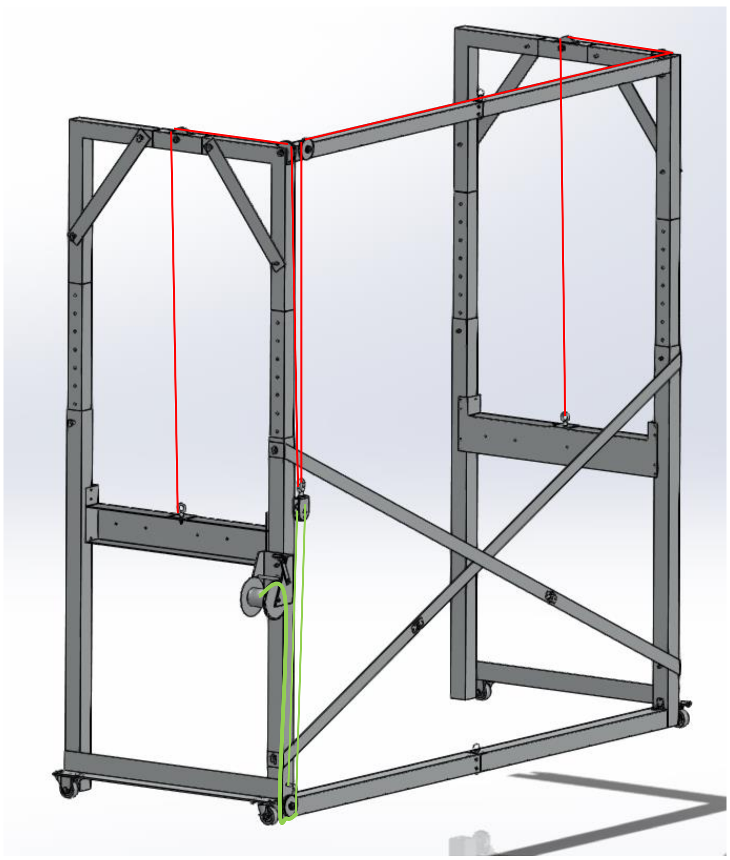

Figure 7. Steel wire locations on design

The green cable shows the second cable which represents the block and tackle system attached to the winch. This creates a mechanical advantage allowing for the user to feel less weight while turning the winch. This system also helps increase the lifting range for the lift device. It effectively pulls the pulley where the two lifting cables join downward.

5.2 COMPONENT BREAKDOWN

This section breaks down the different components ranging from structural members, connections between the members, caster wheels, pulley and winch mechanism as well as the material selected.

5.2.1 STRUCTURE

The structure consists of four telescoping posts that extend to the height of the lift. The telescoping post utilize a 3” square tube with a slightly smaller 2.75” square tube the slides into it. The smaller post contains multiple holes where a pin can be inserted to set the height. The outside post has one hole where the pin is to be inserted through to connect to the inside post. The four posts are positioned at the corners of the machine top that it will be lifting.

On the two shorter sides, there are cross-bars that run from the front post to the rear post on the top and bottom. The cross-bar on the top runs straight from post to post. The bottom cross-bar sits on the outside of the posts with the wheels mounted under it. This allows additional range of motion of the lift by bringing the bottom of the lift closer to the ground. Both cross-bars are to be welded permanently in place. The slider functions of the inside of the post and can reach all the way to the ground. At the corners between the post and the cross-bars there are gussets that cut the corner creating a triangle for added rigidity and skewing resistance. The gussets will be welded in place permanently. Figure 8 shows the side profile of the structure as well as the braces on the side.

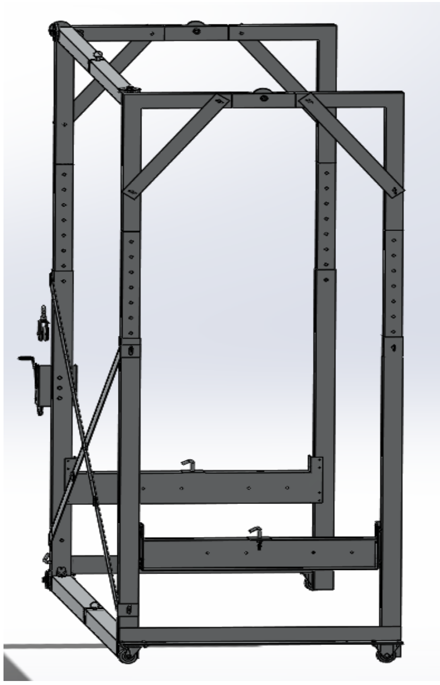

Figure 8. Side view of lift

The rear cross-bar extends from the left to right post. The members are connected in the middle using a pinned connection similar to the telescoping posts but only at one location. One side will be slightly larger and slip over the other side, where they overlap a pin will be inserted. The half of the cross-bar is hinged on the post of its respective end. Both beams hinge forward to allow compact transportation configuration. The member has a latch for when they are 90 degrees relative to the sides, this is their lifting configuration. The latch keeps the beams from folding during the lifting process.

There is an X across the back to prevent skewing of the frame. The X extends to the bottom most corner to a location 108” from the bottom on the post. The X pieces are pinned in place at the top and bottom and can be removed if necessary. The structure is built to accommodate and 18” variation in lifting height as well as lower ceiling clearances. The X can adjust to different frame heights through the ability to be pinned in different holes that are designed with the same increments as the height adjustment. The X stops any skewing action that may occur and provides additional rigidity to the structure. The following figure shows the X members stretching across the back of the frame.

Figure 9. Rear view of lift

5.2.2 ASSEMBLY SYSTEM

The lift has many features to assist in efficient assembly. These features include pinned vertical posts, pinned cross bracing, pinned and hinged long member and quick disconnect cables.

Some of the connections between the members are pinned for convenience and disassembly. The vertical posts are pinned to set the height for each lifting application. The height adjustability is discussed in more detail in the 5.2.1 section. The 'X' brace across the back is also pinned in place allowing it to be rigid during use and unpinned for transportation. The long members across the rear on the top and bottom have a slip fit that is pinned through the larger and smaller beam to secure it. The pins are tethered near their location of use to prevent them from being lost.

The top and bottom cross-bar are on hinges to allow for ease of portability. The hinges on the bottom cross-bar fold upwards. The top cross-bar folds forward to not interfere with the bottom bar that was folded up. The purpose of folding the members in is to reduce the volume during transportation of the lift.

5.2.3 Caster Wheels

The caster for the lift was chosen based on the load capacity required and low cost since these are the primary needs from Conviron. In the teams design, we used two rigid casters and swivel casters with 3" diameter 75D durometer rubber wheels.

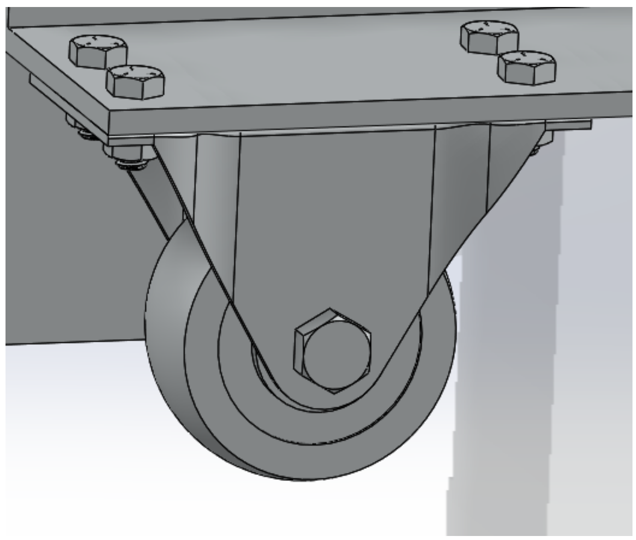

Figure 10. Example of the swivel with 3" diameter 75D durometer rubber wheel [2]

The caster wheels with 3" diameter 75D durometer rubber wheel have a load capacity of 270 lb. and a relatively lower cost when compared with the other wheels under the same category. The one with the swivel function allow the design to be easy to maneuver during operation, since the machine top needs to be lowered accurately onto the top of the lower cabinet.

5.2.4 Attachment System

The attachment system was designed so the machine top would be stable when lifting a load of 700 lb. from ground level to 8 feet in height, the attachment system contains the slider body, eye wire rope hook and conveyor rail bearings. The slider body attached with one side of the machine top with four bolts. The conveyor rail bearings ensure that the slider moves smoothly going to up or down; with or without the load. The slider body is made of aluminum plates and L shaped angles shown in the Figure 11.

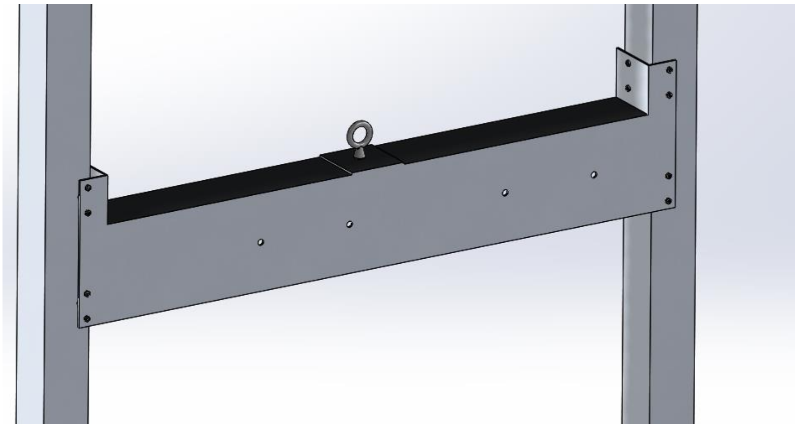

Figure 11. Attachment system

The attachment system requires welding at the connections between the plates. The aluminum plates are welded together to limit the need of a bolt connection since the attachment system needs to remain light according to the customer's needs. The eye wire rope hook has a lifting capacity of 500 lbs. The capacity is considered reasonable as only one slider carries half the load.

5.2.5 Pulley System and Winch

A block and tackle pulley system will be used as the foundation of the lifting mechanism. It will act in a way such that the left and right-side lifting cables will be attached to the free block of the block and tackle system. This will allow for both lifting cables to move at the same rate and also be anchored to a single winch that can operate the lift mechanism. The attachment of the right and left side lifting cables to the free block pulley is shown in Figure 12.

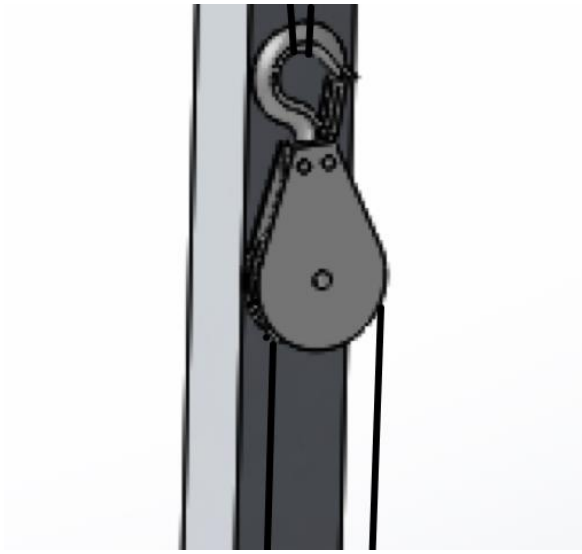

Figure 12. Free-standing block pulley

The free-standing block pulley is also attached to the winch that controls the height of the lift. As the cable on the winch is reeled in, the free-standing pulley is pulled downward, which causes the two lifting cables to begin raising sliders. Conversely, when the winch reels the cable outwards, it will give slack to the free-standing cable. Since the free-standing cable is also attached the upper cabinet, this counter-force then pulls the free-standing pulley upwards, thus lowering the upper cabinet. Figure 13 shows how the winch is connected to the free-standing pulley.

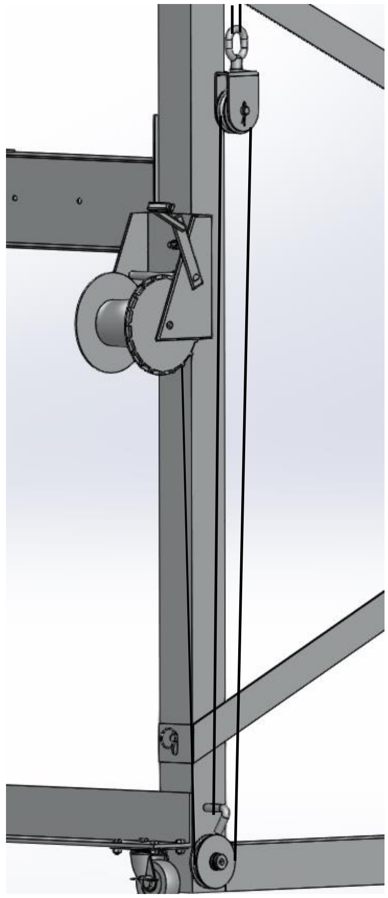

Figure 13. Winch and free-standing block pulley

It can be seen from Figure 13 that the end of the winch-cable is secured to a hook that is located just above the lower pulley (1). Fixing the free-end of the winch-cable is what allows the free-standing cable to move vertically as the winch reels the cables inward and outward.

Pulleys are positioned to redirect the cables to appropriate lifting points located at the center of the upper members. The pulleys responsible for redirecting the cables are supported by shafts that are inserted through the frame of the lift. A shoulder screw is used to act as the shaft, with a nut fastened to the end of the bolt to secure the shoulder screw. This is shown in Figure 14.

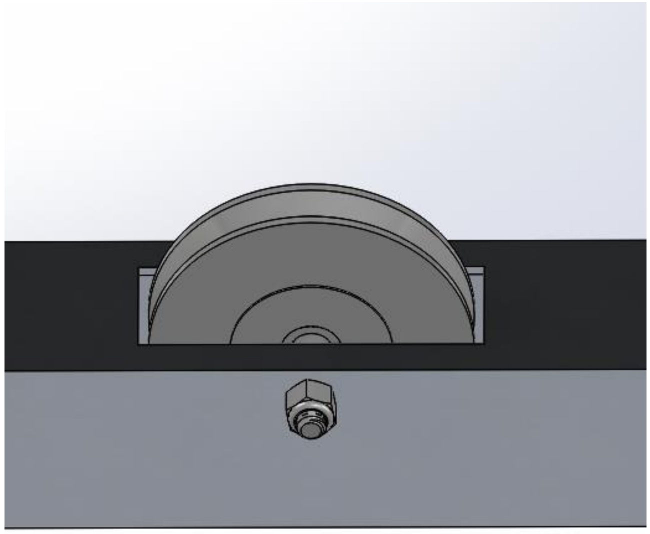

Figure 14. Shaft-mounted pulley set-up

Once the cables are directed to the lifting points of the lift they are fed down through the center of the frame where they will then attach to the slider mechanisms. This is shown in Figure 15.

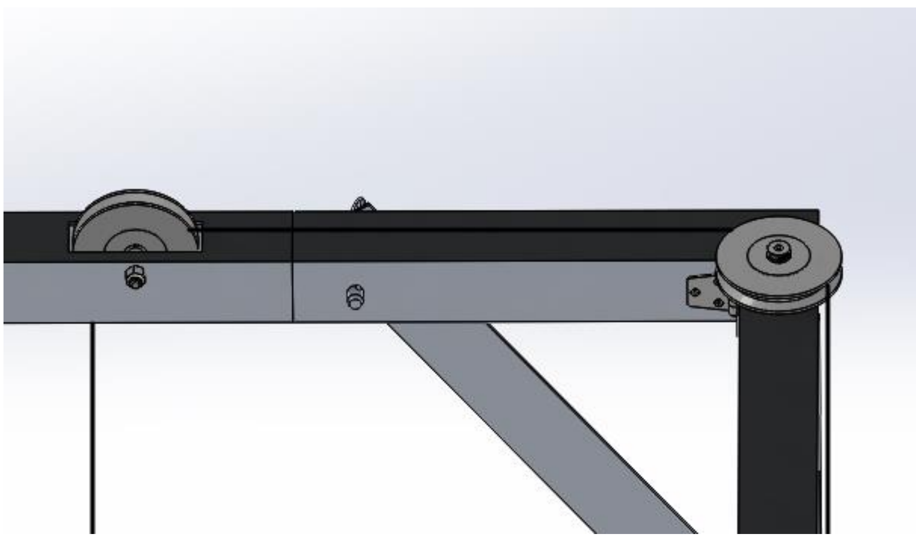

Figure 15. Pulley redirection at lift point

The final lift-point pulleys along with all other pulleys used are lift rated pulleys and will be analyzed in detail later in the report.

5.2.6 Material Selection

For the team's design, the primary need is to minimize weight and cost of the lift. Based on these two needs, the material Aluminum 6061-T6 for the main frame structure and attachment system were chosen. Aluminum 6061-T6 is one of the commonly used aluminum's in many industries. Aluminum 6061-T6 also has better corrosion resistance then steel which was another preference for Conviron.

6 Analysis of Final Design

This section will analyze the final design components and mechanisms. This analysis will determine the structures capabilities. Using these calculations, the lift design can be optimized to meet the ASME BTH-1 standards. The analysis will cover critical locations where the lift design may expect failure.

6.1 Structural Analysis

To analyze the structure and its dimensions we must understand the forces and how they are transmitted through the structure. Using the forces, stresses and dimensions we determined if the design is adequate for our application or if a redesign is necessary.

6.1.1 Posts

The posts support the entire vertical load as well as some smaller loads due to stability. The post must withstand all the forces imposed on them with an applied factor of safety. Buckling is a major concern when it comes to the posts. Buckling occurs before the onset of yielding. The following equation is used to analyze at what vertical force the post will buckle.

$$P_{cr} = \frac{\pi EI}{(KL)^2} \tag{1}$$

In this equation P_{cr} is the force at which the post will buckle. E is Young's modulus of the material being used. I is the moment of inertia of the geometry. K is a modifying factor that depends on the boundary conditions of the post. L is the length of the post.

Since we are using 3” square tubing with 1/8” wall thickness for our post, the moment of inertia, I is equal to 1.984 in^4. Our material of choice is 6061-T6 aluminum which has a modulus of elasticity, E, is 10000 ksi. Our post is fixed at both ends such that the modifying factor is 1.0. The critical load for a single post is 5,340 lbf. Which is much larger than the actual force on each post that is 175lbf.

6.1.2 Bending

The weight of the control unit causes the supporting beam to bend. The bending causes stress in the beam. The stress can be calculated because the load and dimensions of the beam are known. The following is a figure of showing the simple bending case as well as the shear forces and moments transferred throughout the beam. The figure is isolating one side.

Figure 16. Simple beam in bending, shear stresses and moments [3]

The force P is equal to half of the total weight of the control unit, the force is transferred through the pulley to the connection point on the frame. The moment diagram is derived from the shear force diagram. Shown in Figure 16 the maximum moment is experienced at the middle of the beam. The following equation calculates the stress at the center of the beam.

$$\sigma_b = \frac{Mc}{I} \quad (2)$$

The moment depends on the width of the frame, the length of the beam. With a width of 40" the maximum moment in the beam is 3500lb-in. The value of c is the distance from the neutral axis to the point of interest, in this case the outer edge of the beam. For our 3" beam the distance is 1.5". The moment of inertia, I, is dependent on the dimensions, with a 3" square tube that has a 1/8" wall thickness the moment of inertia is 1.984in^4. The bending stress is 2646.17psi. Which is much lower than the yield strength at 42,000psi.

6.1.3 ECCENTRIC LOADING

The way the pulleys are attached on the outside of the structure introduces the force at a location outside of the center line. This introduces a moment onto the member. Figure 17 shows the loading present on the top crossbar of the frame.

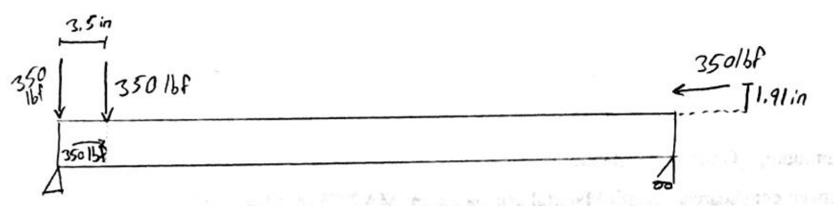

Figure 17. Loading diagram for top rear crossbar

The moment is equivalent to the force multiplied by the distance from the force application point to the center of the beam. There are two eccentric forces that cause moments in the in the beam. The force is 350lbf, the moment diagram for the force on right is shown in Figure 18.

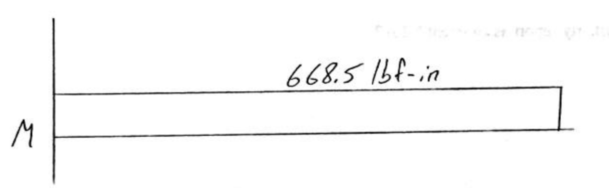

Figure 18. Moment diagram force right most eccentric force

The force on the side of the beam causes a moment of equal magnitude. The moment runs from the force to the right side of the beam. It is in the XZ-Plane rather than the XY-Plane. The two moments will add up and concentrate in a corner of the square beam. The vertical forces will produce shear stress in the beam. Figure 19 shows the shear force in the beam due to forces. The shear force is then used to generate the moment diagram over the length of the beam.

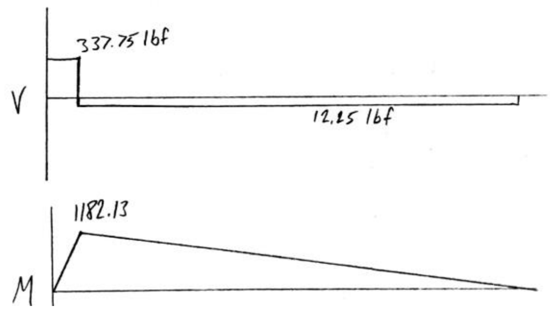

Figure 19. Shear force and moment diagrams for the vertical forces acting on the beam

The moments can be added together to find the total moment present in the beam. The moment addition is based on the moment diagrams. Figure 20 shows the result of the moment addition.

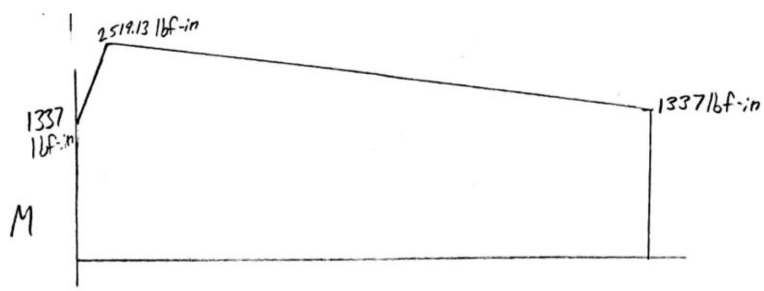

Figure 20. Combined moments in the top cross-bar

Figure 20 has added the moment effects of the two eccentric forces as well as the shear forces present in the loading scenario of the top cross-bar of the structure. The maximum moment experienced is 2519.13 lbf-in at the left side of the beam. The following equation calculates the maximum stress in a beam in the case of eccentric loading.

$$\sigma = \frac{F}{A} + \frac{Mc}{I} \tag{3}$$

The force, F, is the applied force. The moment, M, is the force multiplied by the offset distance from the center line of the square beam. "A" is the cross-sectional area of the beam. “c” is the distance from neutral axis to the point of interest. The moment of inertia, I, depends on the dimensions of the beam.

The beam of interest is the top rear member in the teams lift. This beam is 3” square tubing with a wall thickness of 1/8”. The moment of inertia is 1.984in^4. The distance c is the 1.5”. The moment is 350 lbf multiplied by half the beam height plus half the pulley width. The area, A, is 1.4375 in^2. This results in a stress of 1400 psi. Which is lower than the yield strength of the material that is 42,000 psi.

6.1.4 FORCE IS X FRAME

When the control unit is moves from side to side a force is generated. The X-frame comes into tension to stabilize the frame and bring it back to equilibrium. The tension depends on the dimensions of frame. Assuming flexible connections of the X-frame to the outer frame square, the forces are transferred directly through the members. The following equation calculates the force transmitted through the diagonal members.

$$V = \sqrt{\left(\frac{F}{2}\right)^2 - \left(\frac{F \cdot 77.5}{2 \cdot 102}\right)^2} \tag{4}$$

Where F/2 is the force caused by movement of one half on the control unit. The numbers are the dimensions of the frame design. This equation gives us a force of 265.9 lbf. The x-frame should be built to sufficiently handle the load. The shear force experiences by the post in this scenario is 243.5 psi, this is very small.

6.1.5 TIPPING STUDY

The safety of the structure is very important. Some simple calculations were performed to evaluate how prone to tipping the structure was.

Consider a worker pushing on the back of the frame at approximately shoulder height, while the control unit is at the maximum lift height. How much force can the worker apply before the lift will feel unstable? How much force before the lift starts to tip? Figure 21 shows how the tipping study was conducted.

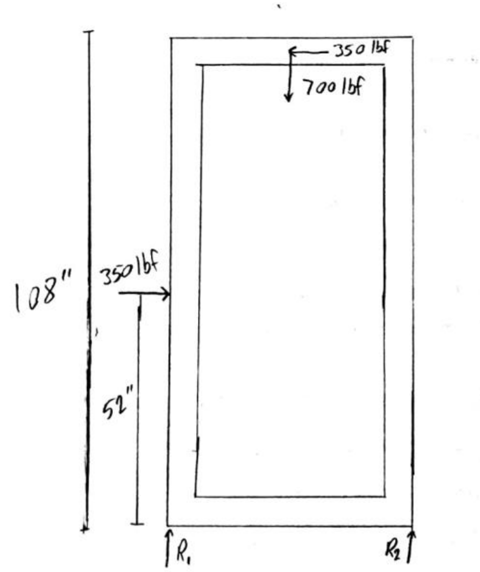

Figure 21. Frame tipping scenario

The shoulder height used was 52". The frame height and point at which the force from the control unit acts was 108". When the force on the one set of wheels becomes less than 200lb the lift is said to feel unstable. When the force equals to zero on one set of wheels the lift will tip. The width of the frame is 40". Using static force equations, sum of the forces in the x and y directions as well as the sum of the moments about a point, the maximum forces were determined, they are listed in TABLE V.

TABLE V. TIPPING STUDY CALCULATED VALUES

	Pushing	Stuck on a crack
Max Force Unstable	107.14lbf	55.56lbf
Max Force Tips	250lbf	130lbf

6.1.6 Required Length of the Slider

For a linear bearing such as the one being used, there is a ratio of the length of the slider to the width required to prevent binding.

TABLE VI. LINEAR BEARING LENGTH-WIDTH RATIOS

Minimum Ratio	L/D > 1.0
For small eccentric loading scenarios	L/D ≥ 1.6
For large eccentric loads and smooth operation	L/D ≥ 3.0

Since we have a large eccentric load and want no binding while lifting, we will use L/D larger than 3.0. The width, D, of the slider is 3” as we are using 3” boxed tubes. Therefore, the length of the slider should be 9” or larger for smooth operation.

6.2 Assembly Analysis

This section will analyze the connections of the structure and determine the required pins and fasteners to prevent breaking at the joints of the lift design.

6.2.1 Pinned connections

The connections between the members are pinned for convenience and disassembly. The connections are designed to handle the forces that are being imposed on it. The most critical pinned connection is the connection between the vertical post with the cables running up it. This post experiences 175lbf from the load, plus 700lbf from the cables, for a total vertical load of 875lbf. Figure 22 shows a source online that calculates the stress in pinned connections.

Figure 22. Pinned Connection Analysis Values

6.2.2 HINGES

The top and bottom cross-bar are on hinges to allow for ease of portability. This hinges will be subject to stress from loading. The stress will be transferred through the pin of the hinge. The following equation calculates the stress experienced by the pin.

$$\tau = \frac{F}{A} = \frac{F}{\frac{\pi}{4}d^2} \qquad (5)$$

Where τ is the shear stress in the pin, F the shear force, and d is the diameter of the pin. The force experienced by the hinge on the top cross-bar is equal to the tension in the cable that is 350 lbf. We will assume that all the force goes through the hinge. Assuming an aluminum pin with 1/4in diameter the shear stress in the pin is 7130 psi which is below the allowable shear stress of 10000 psi. If a steel pin is with a diameter of 3/16 in. then the shear stress in the pin is 12675 psi but the allowable shear stress of steel is much higher at 16000psi. Again, this is assuming all the force is going through the pin at one location. If the stress is distributed more effectively the forces experienced by the pin will be less.

6.2.3 OVERLAP

When the vertical posts are fully extended there needs to be some overlap so the post can withstand lateral loads. The amount of overlap will be a product of the magnitude of the lateral force that the structure should be able to handle. In the tipping study, we assumed a lateral load of 350 lbf, we will use the same lateral load to determine the overlap necessary. The following normal stress equation calculates the required overlap.

$$\sigma = \frac{F}{A} = \frac{F}{W \cdot H} \tag{6}$$

Where σ=allowable normal stress, for aluminum this is 28000 psi, F = 350 lbf and W = 1/8 in, the width of the inside square tube. Inputting all values the minimum overlap is 0.2 in. A much larger value is recommended to accommodate tolerance between the inner and outer tube, as well as provide stability and a location for the pin.

The following TABLE VII shows the allowable values determined by the lifting code and the actual values that our lift experiences during use.

TABLE VII. APPLICABLE CODES FOR THE STRUCTURE

Code	Allowable	Maximum Actual	Component
Compression member	3703.6 psi	848.9 psi	Vertical post with winch
Major axis bending of compact sections	22000 psi	2646.2 psi	Crossbar with pulley
Shear on bars, pins and plates	11547 psi	7715 psi	Pin located in vertical post with winch
Combined axial and bending stresses	1.0	0.169	Top rear crossbar
	1.0	0.0935	
	1.0	0.0858	

6.3 Caster Analysis

The four casters of the design must support a minimum weight of 700 lbs. plus the weight of the design which is approximately 150 lbs., therefore each caster needs to support minimum of 212.50 lbs. The casters chosen for the design is the rigid and swivel casters with 3" diameter 75D durometer rubber wheels having a load capacity of 270 lbs.

6.4 Attachment System Analysis

The attachment system is required to take a minimum of 350 lbs. Since each slider must be capable of holding half the weight of the machine top. The sliders are considered solid bodies with the machine top, where the slider attached with the machine top has eight (grades 8) steel bolts with a torque of 20 ft-lb. This torque value is taken from Conviron’s current lifting jig.

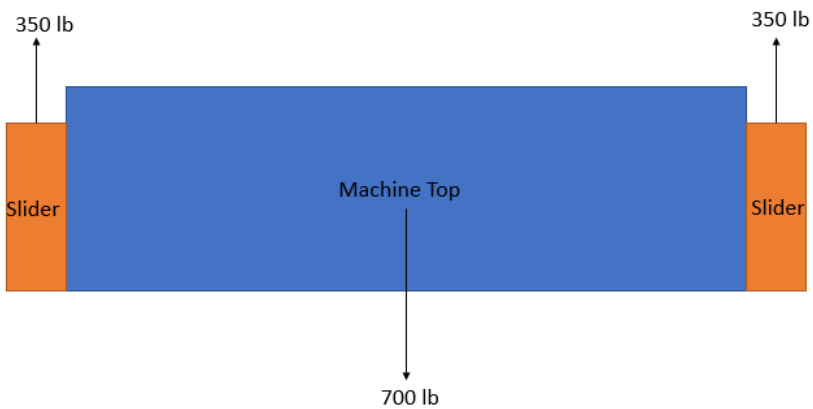

Figure 23. FBD of slider attachment system

Since the machine top only applies downward vertical force and the attachment system connects to the machine top with bolts, the solid connection results in only an upward force in the attachment system. Therefore the slider wheels force towards the structure is negligible. The free body diagram shown in Figure 24, the bolt connects the slider and machine top will experience both shear stress and bearing stress where the vertical force from the machine top applies 700/8 = 87.5 lb in the downward direction.

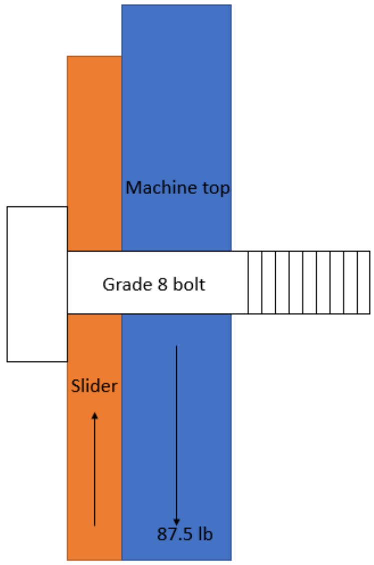

Figure 24. FBD of single bolt connection for the attachment

The bolt connection in the attachment system was analyzed and shown in Figure 24. FBD of single bolt connection for the attachment where the shear stress, bearing stress and torque value of one bolt was calculated.

TABLE VIII. SUMMARY OF STRESSES EXERTED OF A SINGLE BOLT ON THE ATTACHMENT SYSTEM

Description	Equation	Value
Shear stress	$= \frac{4F}{\pi d^2}$	792.639 psi
Bearing stress	$= \frac{F}{td}$	77.7 psi
Toque value	$= cDF$ [4]	6.5 in-lbs

The stresses calculated from TABLE VIII is compared with the ASME BTH-1 codes in Appendix A, where the required minimum values are met to satisfy the standard codes.

6.5 PULLEY SYSTEM AND WINCH ANALYSIS

This section will analyze the reaction forces, shear and bending stresses in the pulleys, and shafts along with shear, tensile, and bearing stresses that the structure experiences at critical areas of the lift design. Figure 25 shows the full pulley system with each pulley having assigned numbers that will be referred to throughout the section.

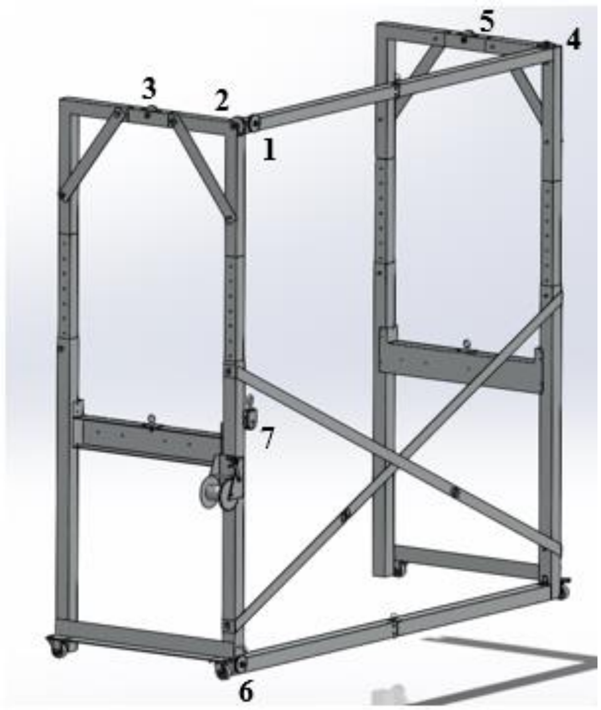

Figure 25. Numbered pulleys on lift

From Figure 25, a total of 7 pulleys are shown, with six of them being shaft-mounted pulleys while pulley #7 is the free-standing-block pulley.

6.5.1 SHAFT-MOUNTED PULLEY ANALYSIS

The pulleys that are mounted to the lift are mounted via shafts that are inserted directly through members of the structure. Figure 26 shows the dimensions of the mounted pulleys used on the lift.

Figure 26. Shaft-mounted pulley diagram [5]

All pulleys used on the lift are rated to support a load of 1550 lbs. and require a 5/16" steel wire rope. The reaction force acting on the pulley must be found in order to determine if it is sufficiently rated. A free body diagram of the forces acting on the pulley is shown in Figure 27.

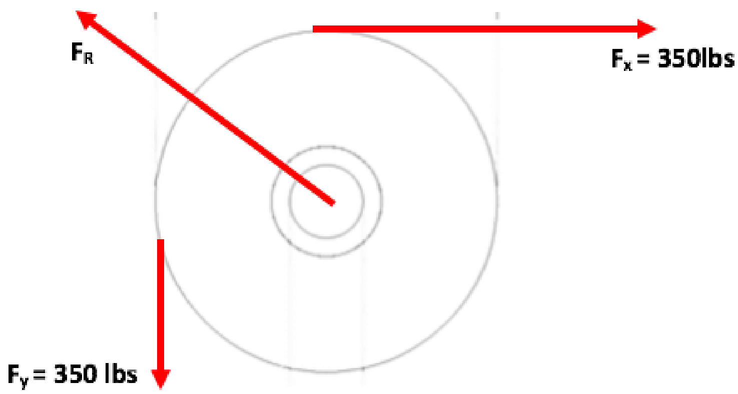

Figure 27. Free-body diagram of pulley

The reaction force in Figure 27Figure 26 can be calculated using (7):

$$\sqrt{{F_x}^2 + {F_y}^2} = F_R \tag{7}$$

Note that all pulleys redirecting the cable at a 90-degree angle will experience the same reaction force as shown above.

6.5.1.1 Stress on Frame

Shear, tensile, and bearing stresses in the frame can be generalized using the following equation:

$$S = \frac{F}{A_i} \tag{8}$$

Where S is stress, F is the applied force, and A_i is the area specific to the type of stress being determined. Different stress areas are defined for shear, tensile and bearing stresses within the frame. The corresponding stress areas for each of these stresses are outlined in Figure 28.

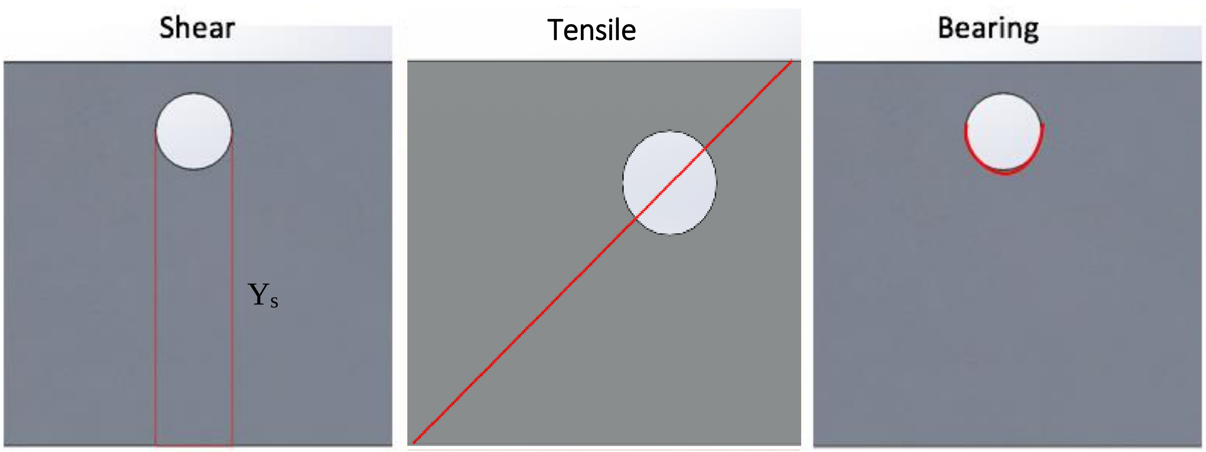

Figure 28. Shear, tensile, and bearing stress areas

For shear stresses, the area considered is defined by the shear planes which are shown as Y_s in Figure 28. Shear area is found in the y-direction since the smallest shear area is defined in this direction, and the pulley is directing the cable downward at this location. The y-component of the applied force will be considered for the shear area, which is 350 lbs in this location. However, as an extra precaution, the team will consider the entire 495 lbs reactionary force that is experienced in the pulleys. Shear area was found using (9):

$$A_s = 4Y_s * t \tag{9}$$

Where A_s is the shear area, Y_s is the shear plane, and t is the thickness of the member that the shaft is inserted through.

Tensile area, A_t, is defined as the linear cross-section that is perpendicular to the direction of the reaction force from the pulley. The tensile area corresponding to the pulleys supported by shafts in the frame can be found from (10) below.

$$A_t = \left(\frac{h}{\sin 45} - d\right) * (2t) \tag{10}$$

Where *h* is the height of the member, and *d* is the diameter of the hole.

For bearing stress the area described, $A_{b,}$ is the area of both holes in the frame the shaft is inserted through that are under compression, which is one half the total area of the hole. Therefore, the total bearing stress area within the frame is found using (11).

$$A_b = \pi d * t \tag{11}$$

Solutions to (9), (10), and (11) can now be substituted into (8) to find shear, tensile, and bearing stresses within the frame caused from shafts supporting the pulleys. TABLE IX summarizes dimensions and results calculated on the frame at the pulley locations.

TABLE IX. RESULTS OF ANALYSIS ON FRAME AT PULLEY LOCATION

Description	Symbol	Units	Value
Force	F	lbs	495.00
Shaft Hole Diameter	d	in	0.3125
Member Wall Thickness	t	in	0.125
Shear Length	Ys	in	2.13
Member Height	h	in	2.75
Shear Area	As	in^2	1.065
Tensile Area	At	in^2	0.894
Bearing Area	Ab	in^2	0.123
Shear Stress	Ss	psi	464.79
Tensile Stress	St	psi	553.69
Bearing Stress	Sb	psi	4033.62
Yield Strength	Sy	Psi	40000.00

TABLE IX shows that the stresses caused from the shaft of the pulley on the frame of the lift are below the yield strength of Aluminum 6061-T6.

6.5.1.2 Stress on Shaft

Stress analysis must also be done to account for stresses experienced within the shaft supporting the pulleys. Based on the shaft mounted pulley's chosen, a ¾ inch diameter shaft is required. A ¾ inch diameter shoulder screw was chosen to act as the shaft for easy manufacturing purposes as well as its high shear and tensile strength. A drawing of the selected shaft [5] can be seen in Figure 29.

Figure 29. Pulley shaft drawing [5]

Shear and bending stresses will be observed in the shaft from forces exerted by the lift frame as well as the pulley. The shaft is made of carbon steel that has a yield strength of 75000 psi. A free body diagram showing forces on the shaft is shown in Figure 30.

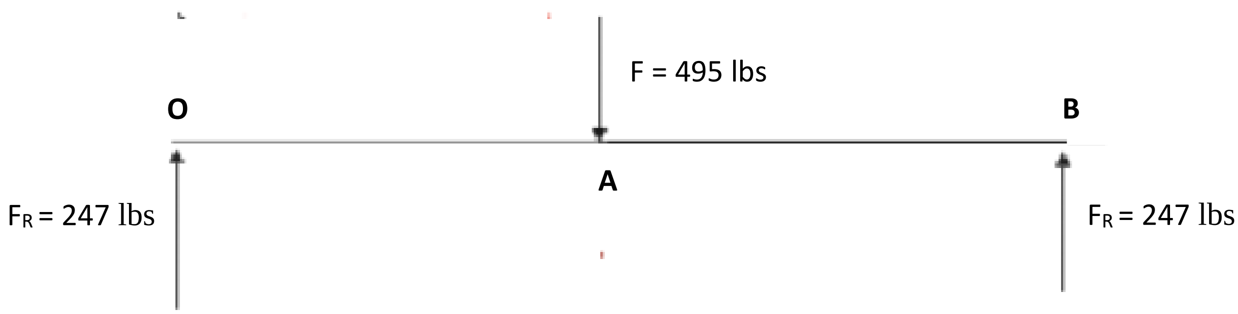

Figure 30. Free body diagram of shaft mounted in frame

Shear stress and bending moment diagrams were generated using the reaction forces above to calculate the stresses. These diagrams are shown below in Figure 31.

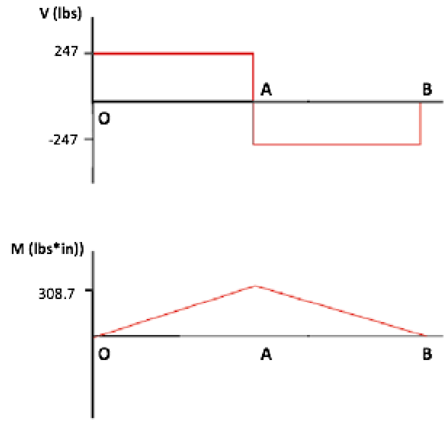

Figure 31. Shear force and bending moment diagrams of shaft

It can be seen from Figure 31 that max shear and bending stresses will be observed at A, and can be calculated using equations (12) and (13) respectively. The equations are as follows:

$$\tau_{max} = \frac{4V}{3A_{shaft}} \tag{12}$$

$$\sigma_{max} = \frac{32M}{\pi {d_s}^3} \tag{13}$$

Where V is the shear stress at A, A_{shaft} is the cross-sectional area of the shaft, M is the bending moment at A, and d_s is the diameter of the shaft. TABLE X summarizes pulley shaft dimensions and stresses in the shafts supporting pulleys.

TABLE X. SUMMARY OF SHAFT ANALYSIS

Description	Symbol	Units	Value
Shaft Diameter	d_s	in	0.75
Shaft Length	L	in	2.5
Shaft Cross Sectional Area	A_{shaft}	in^2	0.44
Max Shear Force	V	lbs	247
Max Bending Moment	M	lbs*in	308.7
Max Shear Stress	τ_{max}	psi	748.48
Max Bending Stress	σ_{max}	psi	7453.37
Minimum Shear Strength	τ_y	psi	80000
Tensile Strength	σ_y	psi	140000

From TABLE X, it is shown that the shafts supporting the pulleys on the lift can support the force exerted by the pulleys with a minimum factor of safety requirement of 3.

6.5.2 FREE-STANDING PULLEY ANALYSIS

The free-standing block pulley, used to connect the two lifting cables to the winch cable, supports two separate cables that are each in tension at 350 lbs. A free body diagram of forces in this free-standing cable is shown in Figure 32.

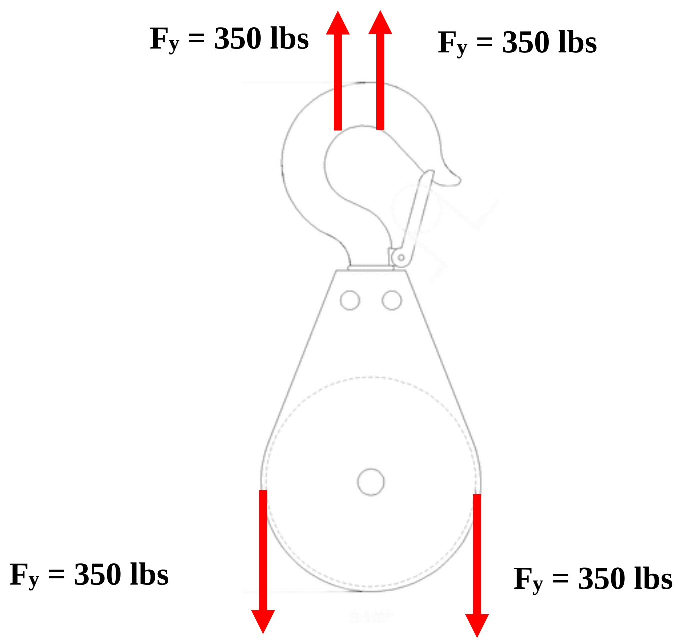

Figure 32. Free-standing pulley free-body diagram

In the case of the free-standing pulley, a total internal force must be calculated using (14).

$$F_{tot} = \sum |F_y| \tag{14}$$

TABLE XI shows the reaction forces of each pulley and the allowable force that each corresponding pulley can withstand.

TABLE XI. REACTION FORCES OF PULLEYS

Pulley #	Reaction Force [lbs]	Allowable Force [lbs] [6]
1	495	1550
2	495	1550
3	495	1550
4	495	1550
5	495	1550
6	700	1550
7	1400	1550

From TABLE XI, it can be seen that the reaction force of each pulley falls below the allowable force that the pulleys have been rated for by the manufacturer [6] [5].

6.5.3 WINCH ANALYSIS

Due to the block and tackle system used for this lift, the tension in the winch cable is decreased by a factor of 2. By expanding on Figure 32, we can show how forces are distributed throughout the lift. This distribution analysis is shown below.

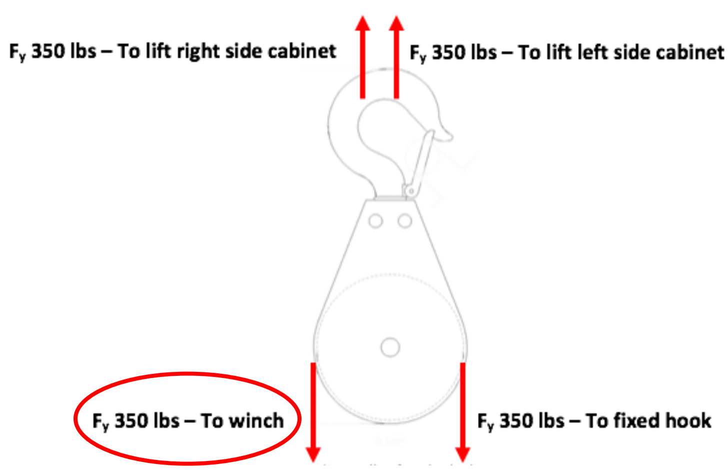

Figure 33. Distribution of forces throughout lift

Figure 33 shows the free-standing block pulley is able to distribute the total 700 lbs. of force in the upper cabinet by creating two reaction forces with one single pulley in the y-direction. One of these reaction forces is then transferred to the fixed hook attached to the bottom of the lift frame, while the other half of the force is transferred to the frame.

Therefore, only 350 lbs of force will be carried by the winch. A model of the winch the team selected is shown in Figure 34.

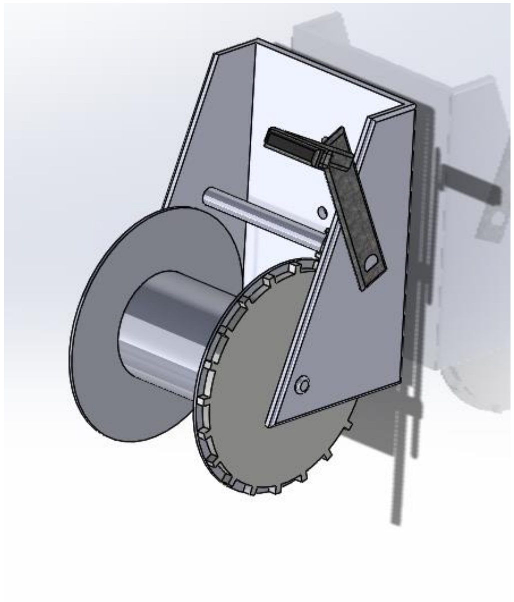

Figure 34. CAD model of winch [5]

The winch shown above is capable of withstanding a load of 1000 lbs when fully wound, and has a maximum load capacity of 2500 lbs. Even when fully wound, this winch is rated for enough weight to be considered feasible to use on the lift.

6.5.4 WIRE CABLE ANALYSIS

When sourcing the free-standing block pulley, a constraint was encountered that forced us to select a 5/16th inch diameter cable, as the only suitable pulley for handling a 1400 lbs load required a 5/16th inch cable. Two different types of cable with this diameter will be used on the lift; the winch cable and the lifting cables.

6.5.4.1 Winch Cable

The winch cable was selected to assist in the ease of assembly. Since the free-end of the winch cable will be fixed to a hook, a cable with a spring-loaded clamp attached to the end was decided. The cable and the attached hook is shown Figure 35.

Figure 35. Winch cable with latched hook [5]

The attached hook will also aid in assembly and disassembly time as it eliminates the need for screwing and unscrewing fasteners or that may have been required for fixing the cable onto the hook.

6.5.4.2 Lifting Cables

Lifting cables were also chosen for the purpose of easing assembly and disassembly. The lifting cables must attach to the screw in hooks extruding from the top side of each slider, thus cables with looped ends were selected. The chosen lifting cables are shown in Figure 36.

Figure 36. Lifting cable with eye [5]

A summary of the winch and lifting cables dimensions and lift rating are shown below in TABLE XII.

TABLE XII. SUMMARY OF CABLE ANALYSIS

Description	**Cable Diameter (in)**	**Exerted Tension (lbs)**	**Load Capacity (lbs)**
Winch Cable	5/16	350	1900
Lifting Cables	5/16	350	2000

It should be noted that all cables are rated with a safety factor of 5 by the manufacturer, meaning these cables are sufficient for the lift requirements.

6.6 Preliminary Finite Element Analysis

The lift design required to provide Finite Element Analysis (FEA) along with the other deliverables. Since the team does not have a professional Engineer, preliminary FEA was used to approach the design for the computational analysis. The team used SolidWorks to do the FEA analysis on the structure and the slider assembly. It should be noted that this analysis is preliminary and should be further investigated using proper finite element methods by a professional in order to certify the design.

6.6.1 Structural FEA

The analysis involved simplifying the design into a structure with the same shape and used 3” aluminum beams with 1/8” wall thickness. The structure was treated as a one piece solid. This is a sufficient assumption for preliminary FEA in order to see how the load being applied affects the structure. By analyzing the structures stresses, we can critical points that may cause failure or should be carefully analyzed during optimization.

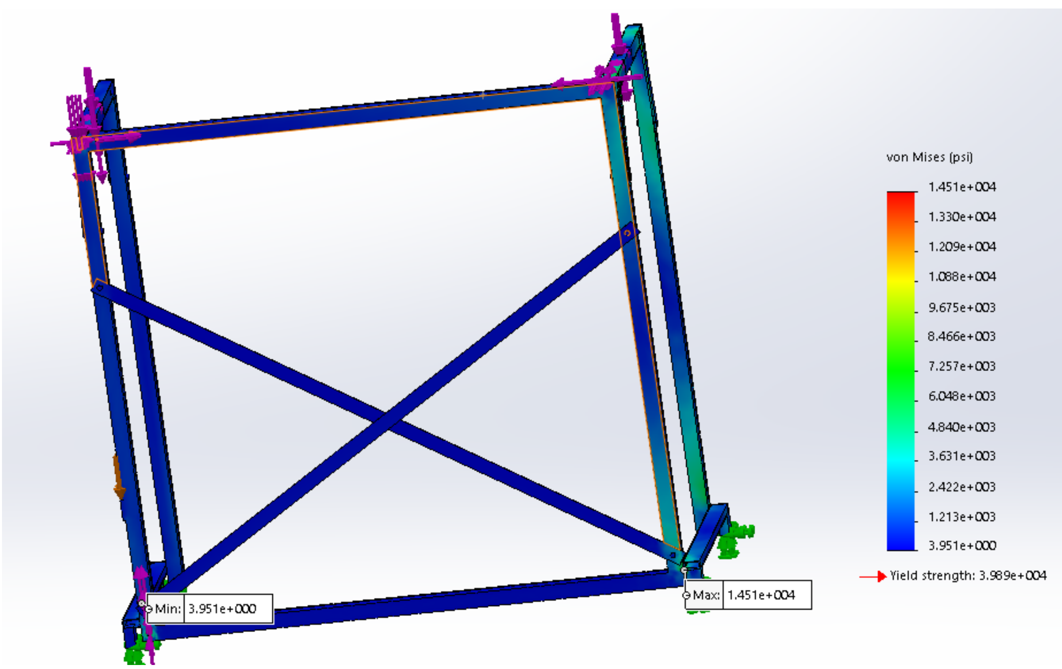

Figure 37. Basic structure Von Mises schematic with SolidWorks FEA

Figure 37 shows the schematic given by SolidWorks FEA. Analyzing the graph we can notice that the structure is well within yield stress with a factor of safety of 2.78 for the highest stress point. The max stress is shown at the connection between the caster member and the lower support away from the winch side (left side). This is makes sense, as the locations furthest away from the cranking location would experience more imbalance of forces due to the moment created. Figure 38 shows the deflection of the structure.

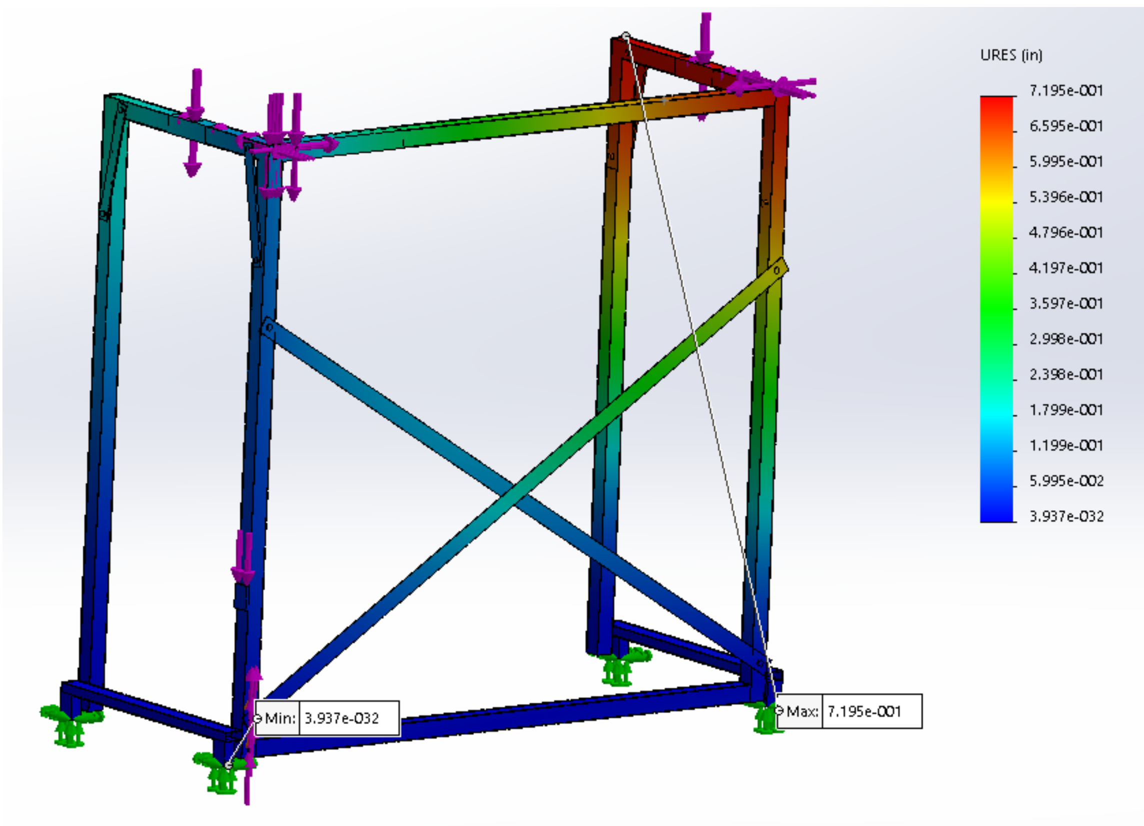

Figure 38. Deflection of basic structure using SolidWorks FEA

The deflection of the basic structure shows high stresses at the aluminum beam containing the pulley furthest away from the winch location. The braces were not extended as far, so some improvements were looked into to maintain a lower deflection. 0.7" was not satisfactory. This showed that the moment created by having the winch on one side has created large deflections on the opposing side of the structure. Using this information, the braces at the corners were further expanded to prevent this deflection. This created increased structural strength and stability in the final design and did not require extra material cost since it only required a different orientation of the same short braces at each side. Conviron has also expressed that deflection is not of high concern, as long as the structure follows ASME BTH-1 standards and is under the yielding criteria.

6.6.2 Slider Assembly FEA

The Slider Assembly attached to the structure required Finite Element Analysis. By analyzing the stresses through the slider assembly, the team determined the structural integrity of the slider design. Figure 39 shows a schematic of the von mises graph for the slider assembly.

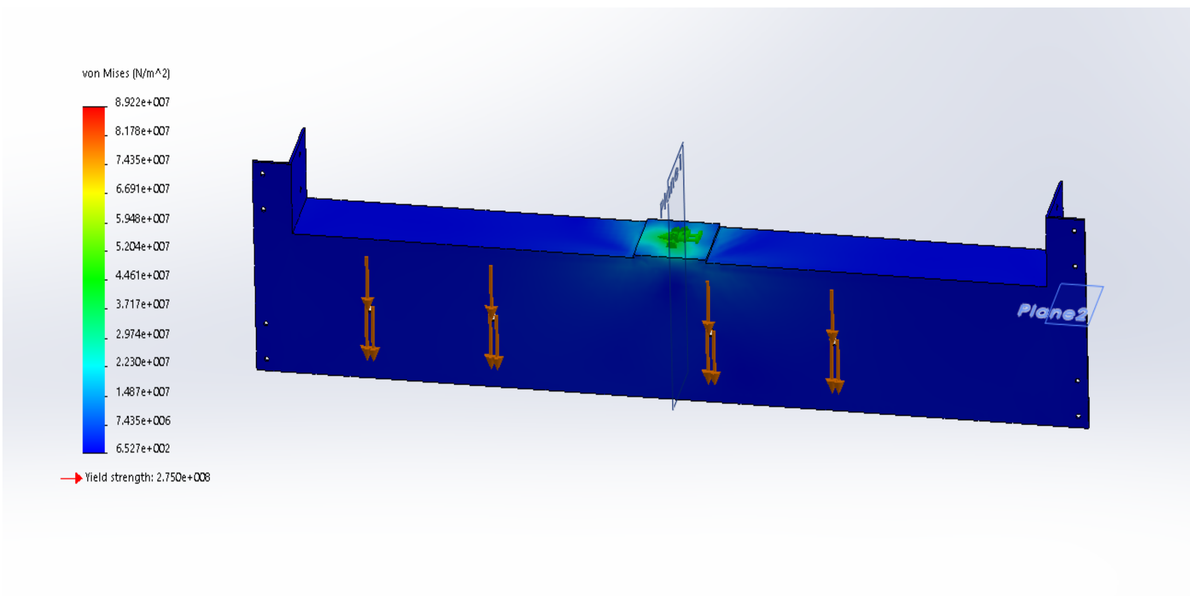

Figure 39. Slider Assembly Von Mises schematic using SolidWorks FEA

The Von Mises graph for the Slider Assembly clearly shows that the critical location can be found at the joint where the eye bolt is located, as well as the lifting points. Based off the graph the structure was within the yield strength of the material.

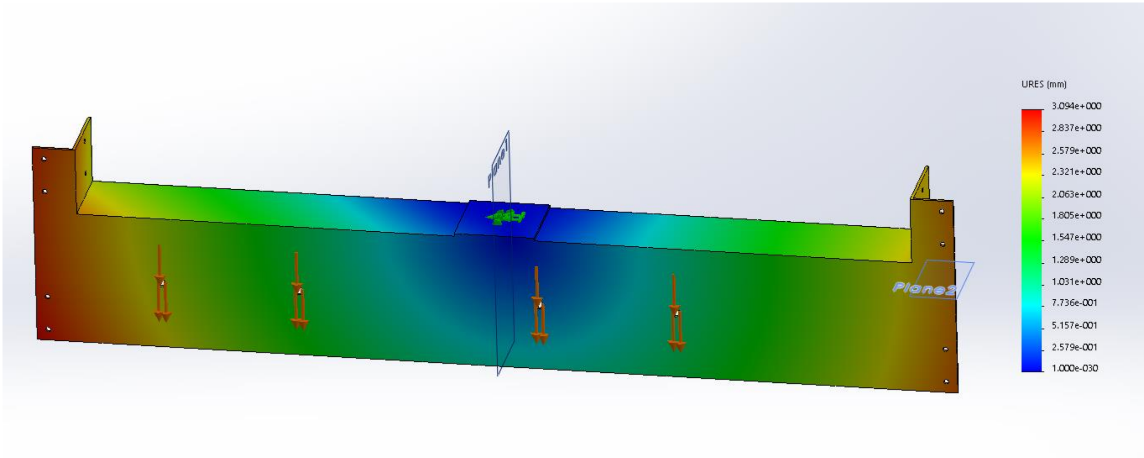

Figure 40. Slider Deflection using FEA

Figure 40 shows the deflection experienced by the structure. Analyzing the graph, the slider can almost be treated as a beam in bending based off the deflection pattern shown. As the slider is being pulled from the center by a steel wire rope and pulley system, the slider experiences high deflections at the ends. This deflection pattern shows that the roller wheels at the ends help prevent movement along the posts. The deflection shown is also reasonable at 3 mm according to the client.

7 FINAL DESIGN SPECIFICATIONS

This section will explain how the design met the customer needs as well as the cost the materials. The metrics of highest importance that were considered at the beginning of the project will be highlighted and receive a grade based on whether we met are target specifications. Appendix B discusses further detail on the process for deciding the important metrics and giving a quantitative value to meet the client's expectations.

7.1 COMPARISON OF DESIGN TO TARGET SPECIFICATIONS

TABLE XIII shows the original target specifications compared to the actual values that have been achieved. Each metric was assigned a pass ideal, pass marginal or fail based on how well the metrics were met.

TABLE XIII. COMPARISION OF TARGET SPECIFICATION AND ACTUAL VALUES

Metric	Imp	Metric	Units	Marginal Value	Ideal Value	Actual Value	Pass/Fail
1	5	Maximum area of disassembled lift fits in standard ½ ton pick up truck	in^2	4936	<4936	2741	Pass Ideal
2	1	Time to assemble/disassemble for installation process	min	15	<15	12 min	Pass Ideal
3	4	Additional tools required to operate/assemble/disassemble	unit	5	<=1	0	Pass Ideal
4	4	Maximum weight of each disassembled part	lb	32	<20	39.5	Fail
5	2	Number of disassembled parts	units	10	5	4	Pass Marginal
6	5	Maximum bending stress in a member	psi	22000	<10000	2626.2	Pass Ideal
7	4	Fatigue	cycles	500000	2000000	n/a	n/a
8	2	Points of contact with the ground surface	#	5	3	4	Pass Marginal
9	5	Maximum height of assembled lift (inches below space saver height)	in	0	>=22	17.125	Pass Marginal
10	3	Maximum width assembled (with or without the load)	in	105	30	106.5	Fail
11	5	Maximum load capacity (FOS=2)	lb	700	>700	800	Pass Ideal
12	5	Stress under load	psi	21000	<10000	1400	Pass Ideal
13	2	Total mass of the lift	lb	300	200	145	Pass Ideal
14	2	Surface area of ground contact points	in^2	25	100	Small	Fail
15	4	Shear stress in connectors	psi	11547	<9000	7715	Pass Ideal
16	4	Bearing stress	psi	21000	<10000	7715	Pass Ideal
17	5	Outsourced parts required to operate/assemble	#	1	0	0	Pass Ideal
18	4	Ease of use by operator	Subj.	80%	100%	80%	Pass Marginal
19	2	Repetitive movement required to operate	Subj.	Low	Very Low	Low	Pass Marginal
20	3	Corrosion Rate	Const.	Low	Very Low	Low	Pass Marginal
21	5	Number of operators required	#	2	1	1	Pass Ideal
22	4	Base surface area when assembled	in^2	4158	<=4158	5104	Fail
23	4	Size of individual assembly parts	Subj.	Manageable	Easily Manageable	Manageable	Pass Ideal

Overall, the design was able to meet all the highlighted metrics within the target specification decided in the proposal phase. The calculations and the process for determining these values can be found in Appendix A.

7.2 BILL OF MATERIALS AND COST BREAKDOWN

This section will cover all of the materials required to build the design. The lift design will be separated into purchased parts and manufactured parts. The costs associated with the purchased parts are according to McMaster Carr and are readily available for purchase. The manufactured part costs were based on taking raw materials also found on

McMaster Carr and determining the amount of aluminum that would be required for each part. The labor cost for welding certain parts was also calculated in order to get a closer estimate for the total cost of the design. A complete list of the required parts for purchased parts and manufactured parts are shown in TABLE XIV and TABLE XV.

TABLE XIV. PURCHASED PARTS FOR LIFT

Purchase Parts					
ITEM NO.	PART NUMBER	DESCRIPTION	QTY.	COST PER UNIT	UNIT
1	3434T121	5/16" Rope Dia., 3-1/2" OD Steel pulley	6	$14.50	1
2	91259A846	3/4" Dia, Lg. 2-3/4" shoulder screw	3	$10.08	1
3	91259A848	3/4" Dia, Lg. 3-1/4" shoulder screw	2	$10.45	1
4	95615A250	5/8"-11 UNC, locknut (Grade 5)	6	$9.34	25
5	1549A590	surface mount hinge	6	$7.38	1
6	91253A126	5-40 UNC, 3/8" Lg. Flat head screw	36	$8.98	100
7	92865A537	1/4"-20 UNC, 1/2" Lg. Hex head screw	8	$7.38	100
8	95462A029	1/4"-20 UNC, Steel hex nut	8	$4.40	100
9	98320A510	1/2" Dia., 3" Lg. Quick release pin	12	$2.66	1
10	2407T640	CART-SMART CASTER (rigid)	2	$5.98	1
11	2407T740	CART-SMART CASTER (swivel w/ brake)	2	$9.19	1
12	92865A581	5/16"-18 UNC, 1/2" Lg. Hex head screw	16	$11.19	100
13	95462A030	5/16"-18 UNC, Steel hex nut	16	$6.44	100
14	3196T64	Hand Winch	1	$125.56	1
15	91259A849	3/4" Dia, Lg. 3-1/2" shoulder screw	1	$11.03	1
16	92865A641	3/8"-16 UNC, 4" Lg. Hex head screw	3	$6.18	5
17	95462A031	3/8"-16 UNC, Steel hex nut	3	$6.34	100
18	94846A523	1/2"-13 UNC, Steel hex thin nut	1	$7.23	50
19	91592A195	1/2"-13 UNC, 5" Lg. Steel hold-down bolt	1	$3.17	1
20	98320A515	1/2" Dia., 3-1/2" Lg. Quick release pin	4	$2.79	1
21	90730A006	5-40 UNC, Narrow Hex nut	12	$5.49	100
22	1714A500	Cabinet Drawer and Door Roller	16	$1.19	1
23	91525A324	1/4" Screw, 0.281" ID Flat Washer	32	$10.86	25
24	91592A185	1/2"-13 UNC, 4" Lg. Steel hold down bolt	1	$2.94	1
25	90107A033	1/2" Screw, 0.531" ID Flat washer	1	$8.82	25
26	93075A148	6-32 UNC, 1/2" Lg. Hex head screw	32	$4.57	100
27	90480A007	6-32 UNC Steel hex nut	32	$1.24	100
28	95505A605	1/2"-13 UNC Steel hex nut	2	$8.50	100
29	3099T22	Free hanging pulley	1	$29.79	1
		TOTAL COST ESTIMATE:		$477.59	
***All purchased parts are selected from Mcmaster Carr as of November 2017					

TABLE XV. MANUFACTURED LIFT PARTS

Manufactured Parts					
ITEM NO.	PART NUMBER	DESCRIPTION	QTY.	COST PER UNIT	UNIT
1	topleftUpart	Top left body (U shaped)	1	$197.40	1
2	topleftextension	Extruded aluminum beam	1	$65.80	1
3	topmiddlepiece	Middle extension piece	1	$15.01	1
4	shortbrace	Brace	4	$24.62	1
5	toprightUpart	Top right body (U shaped)	1	$197.40	1
6	toprightextension	Extruded aluminum beam	1	$65.80	1
7	lowerleftsupportpart	Lower body (two beams w/ L beam)	1	$228.47	1
8	bottomleftextension	Extruded aluminum beam	1	$79.26	1
9	bottommiddlepiece	Middle extension piece	1	$18.73	1
10	Lowerrightsupportpart	Lower body (two beams w/ L beam)	1	$228.47	1
11	bottomrightextension	Extruded aluminum beam	1	$79.26	1
12	longbraceright	Long thin extruded aluminum	1	$106.61	1
13	longbraceleft	Long thin extruded aluminum	1	$106.61	1
14	SliderB	Slider frame (Holes adjusted to right)	1	$84.97	1
15	SliderA	Slider Frame (holes adjusted to left)	1	$94.97	1
		TOTAL COST ESTIMATE:		$1,667.24	
***Raw material prices are based off Mcmaster Carr as of November 2017					

Overall the purchased parts cost a total of $477.79. The manufactured parts was approximated to be $1667.24 according to raw material costs.

Certain pieces of the assemblies will require welding to obtain the desired shape. This includes the U-shaped pieces at each end, and the L-beam that contains the casters will be welded to the lower supports. Assuming the welding will be done across the circumference of each hollow beam the total amount of welding is approximately 64 inches. A good estimate for welding time is 2 inches/min. [7] Resulting in a welding total time of approximately 32 minutes. Assuming the welding setup time is around 30 minutes, it would take about an hour for a lead hand welder to make the assembly. The cost for a lead hand welder is on average $50/hr. [8] Therefore the total labor for welding is $52, this value does not include the labor involved in the assembly or during the making of the manufactured parts. TABLE XVI shows the total costs for the lift design without overhead.

TABLE XVI. TOTAL ESTIMATED COST

Purchase Parts	$477.79
Manufactured Parts	$1667.24
Welding Labor	$52
Total Cost	**$2197.03**

The cost of the design can be reduced by buying the materials from a distributor other than Mcmaster Carr, as they do not specialize in manufacturing these raw materials. By buying directly from the metal manufacturer, cost towards the manufactured parts can be greatly reduced.

8 Assembly and Operating Instructions

8.1 Assembly and Disassembly Instructions

In this section, the lift assembly and disassembly instructions were explained in detail. The lift from our design has four main subassemblies. Each subassembly will required to be built and manufactured by Conviron. The four main subassemblies are shown in Figure 41, subassembly A and B make the top structure of the lift, and subassembly C and D make the bottom structure of the lift.

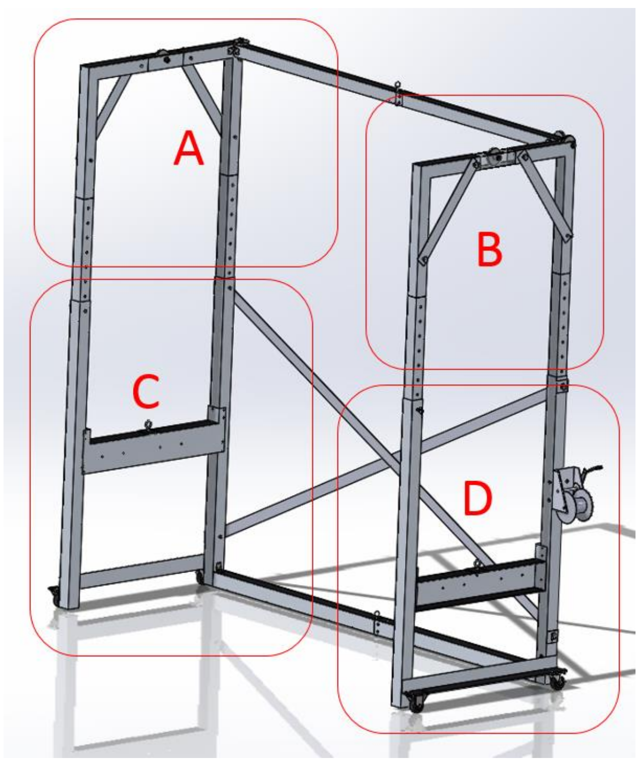

Figure 41. The lift with 4 subassemblies, A, B, C and D.

Step 1, subassembly C and D are connected first by sliding the lower horizontal beams into each other, then secure the connection with a pin shown in Figure 42.

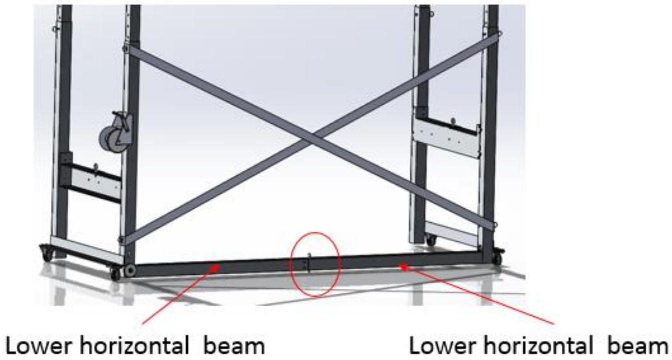

Figure 42. Connecting subassembly C and D

Step 2, install subassembly A onto subassembly C, secure the connections with pins shown in Figure 43. Pinned locations may be adjusted with different height requirement, detailed information will be explained in the operation manual of Section 8.2.

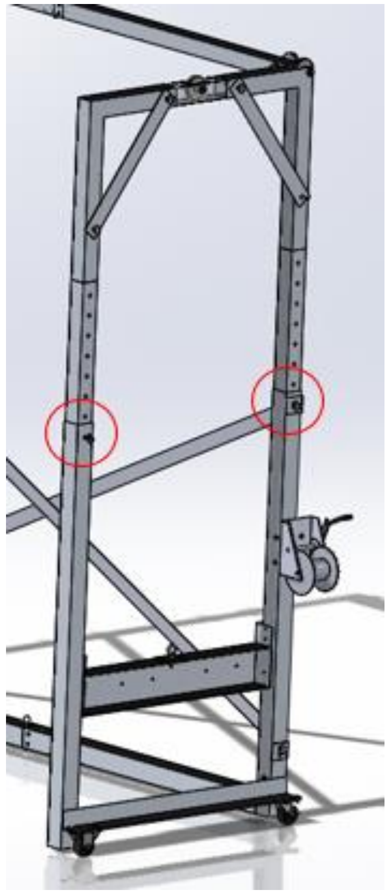

Figure 43. Connecting subassembly A and C

Step 3, install subassembly B onto subassembly D by following Step 2. Connect the upper horizontal beams by sliding them into each other, then secure the connection with pin shown in Figure 44.

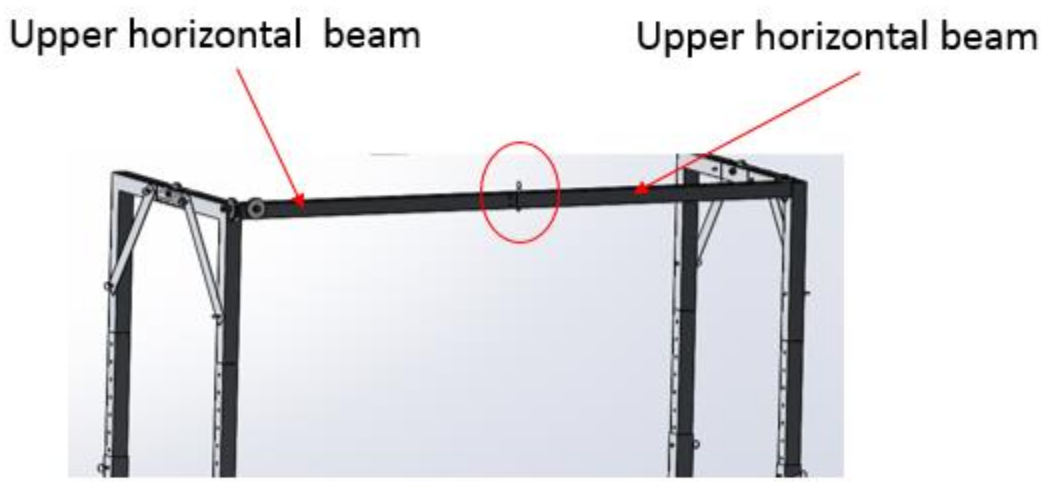

Figure 44. Connecting subassembly B and D

Step 4, install cross bars onto the structure, remove the pin connections at location A and reconnect the pin connection with the cross bars. Connect cross bar at location D with a pin. Repeat step 4 for the other cross bar at location B and C. Finally, secure both cross bars by using the pin connection at location E shown in Figure 45.

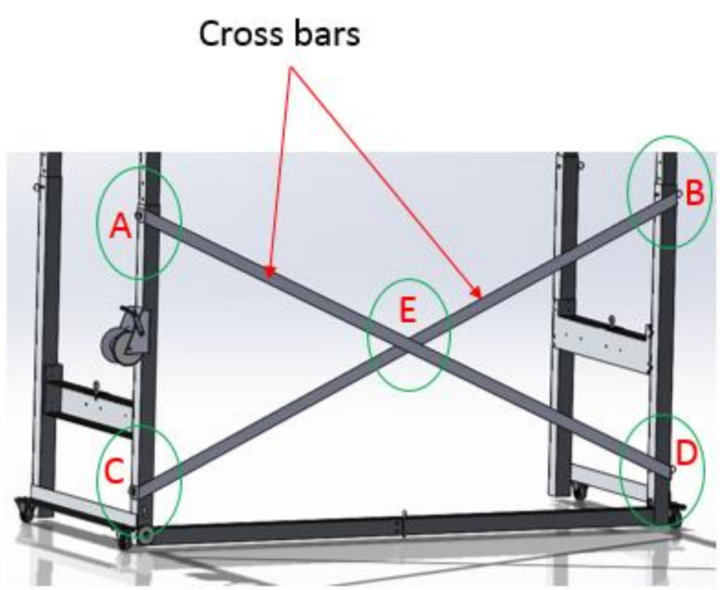

Figure 45. Cross bars installation

Step 5, install the lifting cable in the lift, the lifting cable was pre-set in the upper structure where the shorter lifting cable goes into the subassembly B and the longer lifting cable goes into the subassembly A. For initial assembly, the lifting cables needed to be feed through the pulleys. Feed the shorter lifting cable though pulley number 4, 3 and 7 from subassembly B with one loop end and following the direction shown in Figure 46.

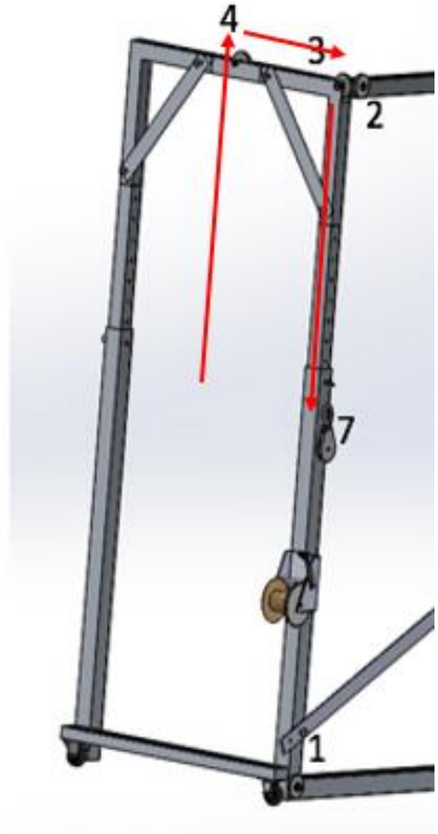

Figure 46. Lifting cable installation for subassembly B

For subassembly A, feed the longer lifting cable though pulley number 2, 5, 6 and 7 in the direction shown in Figure 47. Attach both lifting cables with the free-standing pulley at pulley number 7.

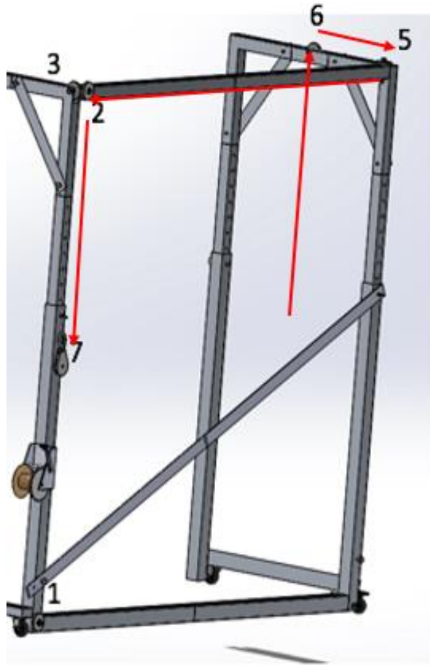

Figure 47. Lifting cable installation for subassembly A

Step 6, connect the sliders eye hook with the lifting cable hook shown in Figure 47, and lower the slider to desire height by unwind the winch.

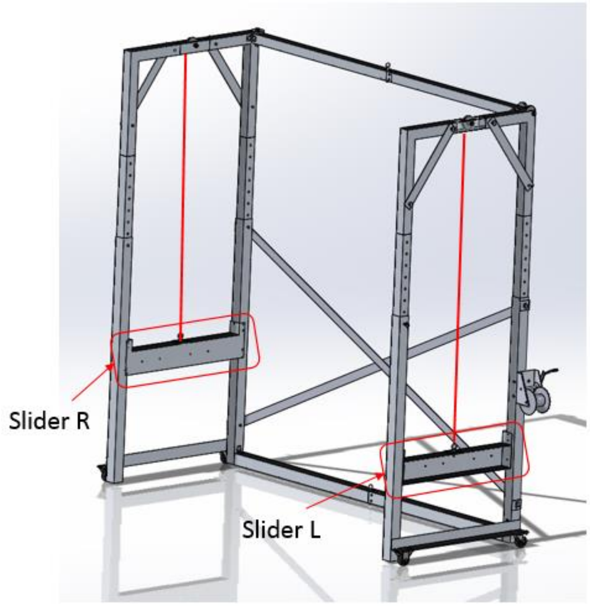

Figure 48. Slider installation

For the disassembly instructions, simply reverse the assembly steps.

Step 1, remove the sliders from the lifting cable hooks.

Step 2, unwind the lifting cables from subassembly A and B.

Step 3, remove the cross bars.

Step 4, disconnect the top horizontal beams from subassembly A and B.

Step 4, remove the top subassembly A and B from subassembly C and D.

Step 5, disconnect the bottom horizontal beams from subassembly C and D.

8.2 OPERATING INSTRUCTIONS

1. Ensure the lift is fully assembled and all pin and bolt connections are secure and all pulley cables are properly positioned on the proper pulleys (refer to the assembly manual for more info.

2. Position the lift around the machine top, so that the horizontal members on the left and right sides of the lift are parallel with the sides of machine top.

3. Align the four holes on the slider with the screw-in lift points of the machine top.

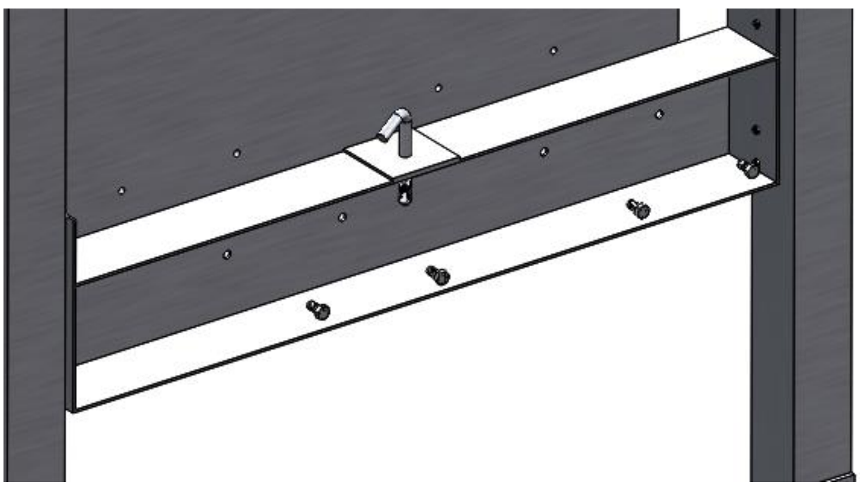

Figure 49. Aligned slider holes and machine top lift points

4. Using a 9/16th inch ratchet or a cordless drill, screw in bolts into each of the four lift points on each slider, screwing the bolts through the outside of the sliders and into the screw in lift points in the machine top.

5. Lock the swiveling casters at the back of the lift by pushing the locking mechanism downward.

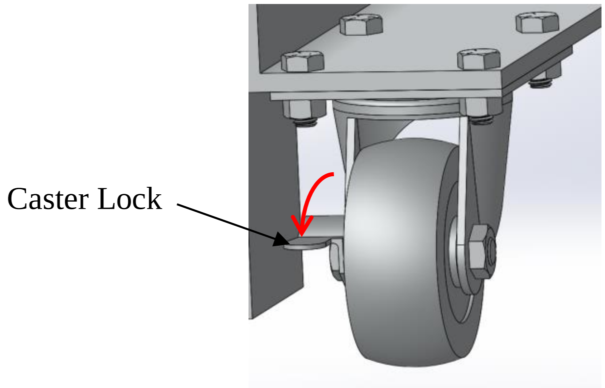

Figure 50. Swiveling Castor Wheel

6. Slowly crank the winch handle clockwise to begin raising the sliders. Raise the sliders until the cables tighten and the machine top raises an inch off of the pallet.
7. Re-examine all pin and bolt connections, as well as the pulley points to ensure the lift is still properly assembled.
8. Turn the winch-crank clockwise until the height of the bottom of the machine top exceeds the height of lower cabinet by 1 inch, or until the sliders hit the stops on the lift frame.
9. Unlock the back casters by pulling the lifting mechanism upward.
10. If operating the lift as a single operator, follow instruction 8a. If operating the lift with the assistance of an additional operator, follow instructions 8b.
    a. Position yourself behind the lift, facing forward towards the lower cabinet and machine top. Align the middle of your body with where the cross members at the back of the lift connect. Using both hands, grab the lift by the upper cross-members at the back of the lift (grab the upper-left cross-member with your left hand, and grab the upper right cross member with your right hand). Applying equal pressure with your left and right hands, push the lift forward, slowly, ensuring the left and right sides of the frame remain parallel with, and outside, the lower cabinet walls.

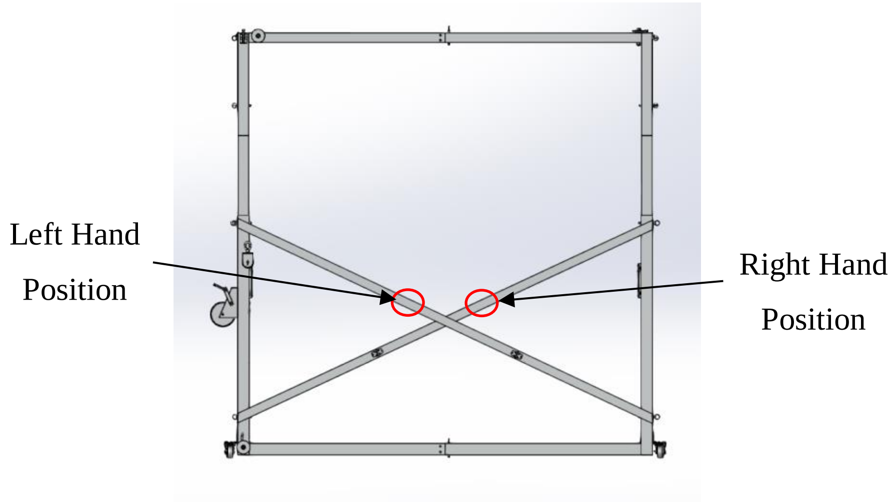

Figure 51. Rear view of lift with single operator hand positions when pushing

Continue pushing the lift forward until the machine top is positioned directly above the lower cabinet so that all four corners of the lower cabinet and machine top are aligned.

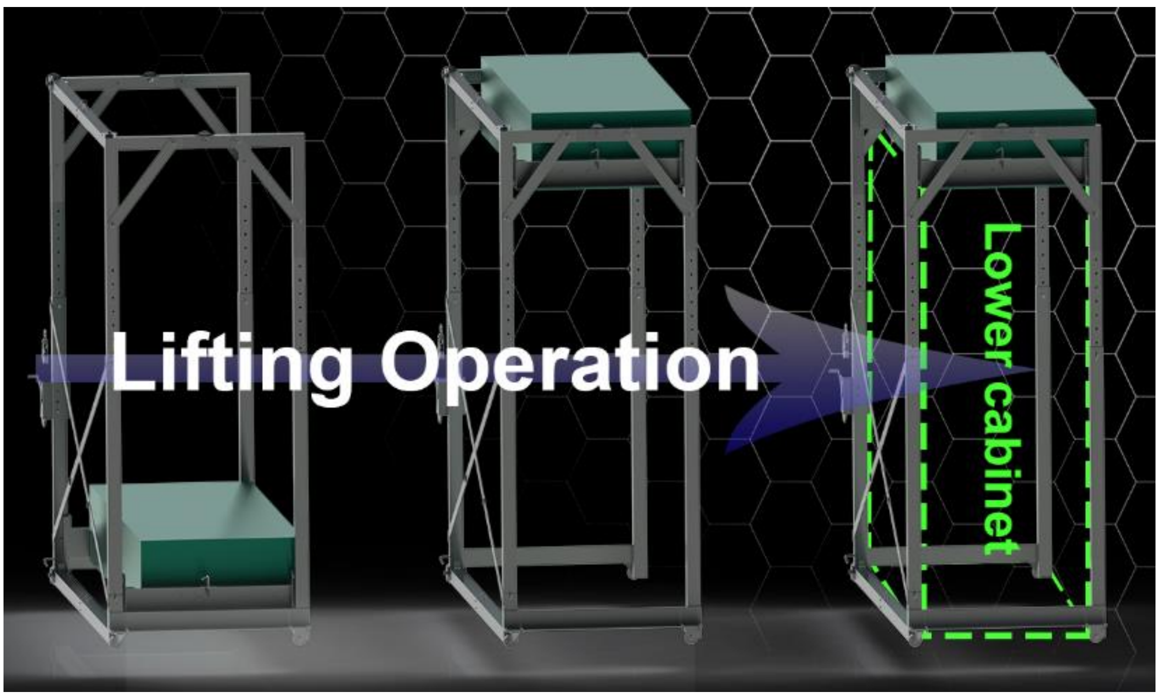

Figure 52. Lifting Operation

b. Position yourself behind the lift, facing forward towards the lower cabinet and machine top. Align the middle of your body directly behind one of the corner, vertical members. The second operator should be in the same position, at the corner vertical member, on the opposite side of the lift. Using both hands, grab the vertical member. If cables are present, place your hands *over* the cables. (Note: DO NOT apply pressure on pulleys when pushing lift). At the same time as the other operator, apply equal pressure with your left and right hands, and push the lift forward, slowly and at the same rate as your operating partner.

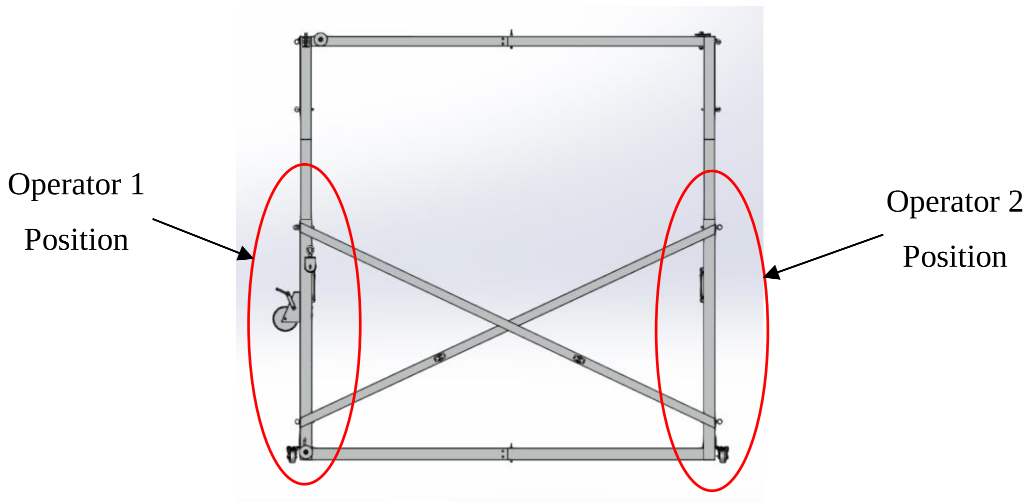

Figure 53. Rear view of lift with dual operator pushing positions

Ensure the left and right sides of the frame remain parallel with, and outside, the lower cabinet walls. Continue pushing the lift forward until the machine top is positioned directly above the lower cabinet so that all four corners of the lower cabinet and machine top are aligned.

11. Lock the back swiveling casters.
12. Attach the wire connections extruding from the bottom of the machine top into the outlets on the back of the lower cabinet. See figure below for proper connection points. Position all wires inside the lower cabinet and away from its edges to ensure that the wires don't get pinched once the machine top is lowered.

13. Turn the winch-crank counter clock wise to begin lowering the machine top onto the lower cabinet, ensuring the corners of the machine top and lower cabinet remain aligned as the machine top is lowered. Continue lowering the machine top until all of the weight of the machine top is resting on the lower cabinet and the sliders disconnect from the screw-in lift points.
14. Unlock the back casters
15. Slowly pull the lift straight backwards, ensuring the left and right sides of the frame remain parallel with the assembled control unit. Pull the lift a safe distance from the control unit
16. Begin the disassembly process.

9 CONCLUSION

The lift that has been designed by the "Do You Even Lift" design team was modeled to adhere to Conviron's needs outlined at the beginning of the project. Extra attention was given to five of these needs prioritized by Conviron: a lift that is operable in rooms with varying height restrictions, can be easily assembled and disassembled on the job site, all components of the lift can be stored in the bed of a standard sized pick-up truck when disassembled, it is mechanically operated, and meets all relevant ASME BTH-1 standards and codes.

Due to the static nature of the lift frame, along with the ability to lift the machine top beyond the height of the frame, the lift was designed to always maintain a maximum height that is lower than the height of the assembled controlled environment unit. Therefore, the team guaranteed the lift would never impede on the height restrictions when installing a machine top. The lift was designed to fit closely around the machine top when lifting, thus minimizing the overall footprint and allowing for a stable lift during operation.

The lift was designed to consist of four main components; two top sections and two bottom sections. The was lift constructed of only four major components resulting in a much less complex assembly and disassembly operation as opposed to a design that would be dismantled into many pieces. Furthermore, pin connections were used at all points where the components and braces of the frame are attached, allowing for quick assembly and eliminating the need for tools during the process.

Due to the lift only consisting of four major components, the size and weight of the components became an issue. This was resolved by installing hinges at certain "permanent" connection points of the frame during the manufacturing process. The hinges allowed for certain members of the frame to fold up, permitting these large components to fit in the back of a pick-up truck that otherwise would not fit.

A simple block and tackle pulley system along with a hand winch were chosen to act as the lifting mechanism. The pulley system eliminated the need for any outside source of power, such as gas or electricity, while providing a light weight, simple, and more reliable means of operating the lift compared to other options such as hydraulics or pneumatics.

Most importantly, all major stress points of the lift were analyzed in detail to ensure that the lift met all ASME BTH-1 codes and standards, ensuring safety and satisfaction of Conviron and their employees.

In addition to meeting the prioritized needs, several other benefits have been realized from the design of this lift. These benefits include an overall light weight structure in which each component would be easily handled by a single employee, a simple lifting operation that can be performed by one employee, as well as an easily manufacturability and lower-cost lift due to being constructed almost entirely of parts purchasable from most supply companies such as McMaster Carr.

10 RECOMMENDATIONS

Due to time constraints associated with this project, not all ideas or features were able to be implemented, and potential to further optimize the lift in regard to stability, weight, manufacturability, and operator convenience is possible. For this reason, the team generated a number of recommendations for Conviron to consider.

When the lift is disassembled, current methodology suggests the cables be wound in a loop and stored individually. The team recommends that a number of loop hooks could be installed on the frame for the cables to wrap around in order to minimize the number of individual components that must be transferred. A Velcro strap could also secure the cables to the frame.

Connection pins are currently stored in a box or bag as individual components must be removed each time during assembly. The team recommends tethering each pin to the frame at the various locations in which they are to be inserted. This increases the convenience and also speeds up the time to assemble and disassemble the lift.

The dimensions of the lift members and various components, such as the pin connections, were selected intuitively based on standard sizing currently used in similar applications. Analysis was done to verify that the strength in the members satisfied ASME BTH-1 standards. There is clear room to further reduce the sizing of certain members, as analysis shows stresses are much lower than corresponding yield strength. Reducing the size of these members will result in the overall weight of the lift and components to decrease as well.

Structurally, one improvement the team recommended was to add latches around the corners of the frame where hinges are present. Although the overlap of the members where the components are connected will restrict the hinges from folding in during operation, extra measures could be taken to mitigate any potential for this risk to occur. Installing rigid latches around the corner locations will act as braces to counter the potential rotational movement.

The machine top has ½" clearance on either side relative to the lift slider. We recommend making the overall lift length of the lift smaller to lessen this clearance as the slider is designed to butt against the machine top and roll along the vertical posts. A recommended clearance is 1/32" on each side. Giving 1/16" of wiggle room when rolling the lift around the machine top.

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Appendix A Applicable Codes

Various codes were researched and will be applied to the team's design. These codes were gathered from ASME BTH-1 2017 Standards [8] as required by Conviron. The codes apply to various types of lift designs and are required for the design concept selected.

Table of Contents

A.1 STRUCTURAL DESIGN

Codes and standards that define the minimum strength for a structure based on dimensions and material properties.

A.1.1 LOADS

The load in imperial units is pounds mass. The code says to design for actual loads.

A.1.2 DESIGN FACTOR

The design factor is a value that is multiplied or divided to create a stronger than necessary product so failure is much less likely. There are different categories depending of the use the lift will experience. A is the least number of cycles and C is the highest. N_d = 2.0 for design category A lifters

A.1.3 TENSION MEMBERS

This applies to members being pulled apart due to forces in use.

$$F_t = \frac{F_y}{N_d} \tag{15}$$

$$F_t = \frac{F_u}{1.20N_d} \tag{16}$$

Where,

F_t = Allowable tensile stress, ksi (MPa)

F_y = minimum yield stress, ksi (MPa)

F_u = minimum tensile strength, ksi (MPa)

A.1.4 COMPRESSION MEMBERS

This applies to member being that are being compressed during normal operation.

$$F_a = \frac{\left[1 - \frac{\left(\frac{Kl}{r}\right)^2}{2C_c^2}\right]}{N_d\left[1 + \frac{9\left(\frac{Kl}{r}\right)}{40C_c} - \frac{3\left(\frac{Kl}{r}\right)^3}{40C_c^3}\right]} \tag{17}$$

Where,

F_a = allowable axial compressive stress, ksi (MPa)

K = effective length factor based on the degree of fixity at each end of the member

l = the actual unbraced length of the member, in. (mm)

r = radius of gyration about the axis under consideration, in. (mm)

$$C_c = \sqrt{\frac{2\pi^2 E}{F_y}} \tag{18}$$

When Kl/r exceeds Cc,

$$F_a = \frac{\pi^2 E}{1.15 N_d \left(\frac{Kl}{r}\right)^2} \tag{19}$$

A.1.5 Major axis bending of solid rectangular bars

This applies to rectangular members being bent about their axis where they have the greatest stiffness while in operating conditions.

If $\frac{L_b d}{t^2} \leq \frac{0.08E}{F_y}$ Then use Equation 20.

If $\frac{0.08E}{F_y} < \frac{L_b d}{t^2} \leq \frac{1.9E}{F_y}$ Then use Equation 21.

If $\frac{L_b d}{t^2} \leq \frac{1.9E}{F_y}$ Then use Equation 22 where,

$$F_b = \frac{1.25F_y}{N_d} \tag{20}$$

$$F_b = C_{LTB} \times C_b \left[1.52 - 0.274\left(\frac{L_b d}{t^2}\right)\frac{F_y}{E}\right]\frac{F_y}{N_d} \leq \frac{1.25F_y}{N_d} \tag{21}$$

$$F_b = C_{LTB} \times \frac{1.9EC_b}{N_d\left(\frac{L_b d}{t^2}\right)} \le \frac{1.25F_y}{N_d} \tag{22}$$

Where,

L_b = distance between cross sections braced against twist or lateral displacement of the compression flange; for beams not braced against twist or lateral displacement, the greater of the maximum distance between supports or the distance between the two points of applied load that are farthest apart

d = depth of the section, in (mm)

F_b = allowable bending stress, ksi (MPa)

t = thickness of the plate, in (mm)

For beams braced against twist or lateral displacement of the compression element at the ends of the unbraced length, $C_{LTB} = 1.00$.

For unbraced ends,

$$C_{LTB} = \frac{3.00\sqrt{EI_x/GJ}}{L_b/t} \tag{23}$$

Where,

I_x = major axis moment of inertia, in.^{4} (mm^4)

G = shear modulus of elasticity, ksi (MPa)

J = torsional constant, in.^{4} (mm^4)

A.1.6 MINOR AXIS BENDING OF COMPACT SECTIONS, SOLID BARS AND RECTANGULAR BARS

This applies to beams that are being bent about their axis that they are less stiff during operation.

$$F_b = \frac{1.25F_y}{N_d} \quad (24)$$

A.1.7 SHEAR ON BARS, PINS AND PLATES

This applies to any bar, pin or plate that experiences two opposing forces that try to slice the object in half.

$$h/t \leq 2.45\sqrt{E/F_y} \quad (25)$$

where,

h = clear depth of plate parallel to the applied shear force at the section under investigation. in. (mm)

Shall not exceed,

$$F_v = \frac{F_y}{N_d\sqrt{3}} \quad (26)$$

Where,

F_v = allowable shear stress, ksi (MPa)

A.1.8 COMBINED AXIAL AND BENDING STRESSES

Members that experience both axial tension or compression and bending must adhere to this code.

Statements must be true for structure to be safe,

$$\frac{f_a}{F_a} + \frac{C_{mx}f_{bx}}{(1-\frac{f_a}{F_{ex}})F_{bx}} + \frac{C_{my}f_{by}}{(1-\frac{f_a}{F_{ey}})F_{by}} \leq 1.0 \quad \textbf{(27)}$$

$$\frac{f_a}{F_y/N_d} + \frac{f_{bx}}{F_{bx}} + \frac{f_{by}}{F_{by}} \leq 1.0 \quad \textbf{(28)}$$

$$\frac{f_a}{F_a} + \frac{f_{bx}}{F_{bx}} + \frac{f_{by}}{F_{by}} \leq 1.0 \quad \textbf{(29)}$$

Where,

f_a	= computed axial compressive stress, ksi (MPa)
C_{mx}, C_{my}	= coefficient applied to bending term in interaction equation about the x- or y-axis.
f_{bx}, f_{by}	= computed bending stress about the x- or y-axis, ksi (MPa)
F_{bx}, F_{by}	= allowable bending stress about the x- or y-axis, ksi (MPa)
F_{ex}, F_{ey}	= Euler stress about the x- or y-axis, divided by the design factor, ksi (MPa)

A.1.9 COMBINED NORMAL AND SHEAR STRESSES

Member that experience both normal and shear forces must be within the following code.

Critical stress for combined normal and shear stress is found using the following equation:

$$f_{cr} = \sqrt{f_x^2 - f_x f_y + f_y^2 + 3f_v^2} \leq F_{cr} = \frac{F_y}{N_d} \quad (30)$$

Where,

f_{cr}	= allowable critical stress, ksi (MPa)
F_{cr}	= allowable critical stress due to combined shear and normal stresses, ksi (MPa)
f_v	= computed shear stress, ksi (MPa)
f_x	= computed normal stress in the x direction, ksi (MPa)
f_y	= computed shear stress in the y direction, ksi (MPa)

A.1.10 LOCAL BUCKLING

Buckling is common in long slender members under compression. It is the bowing out of a member. To avoid it, unbraced length must be kept to a minimum. If the member is within the following code it will not buckle.

The width-thickness ratios of compression elements shall be less than or equal to the values calculated in compressed elements. This is shown in TABL.

TABLE A-1. WIDTH-THICKNESS RATIO TO PREVENT LOCAL BUCKLING

Width-Thickness Ratio	Limiting Width-Thickness Ratios for Members Subject to Axial Compression	Limiting Width-Thickness Ratios for Members Subject to Flexure	
		Compact	Non-compact
b/t	$1.4\sqrt{E/F_y}$	$1.12\sqrt{E/F_y}$	$1.4\sqrt{E/F_y}$

A.2 CONNECTION DESIGN

Codes and standards for joining two or more members together based on dimensions and material properties.

A.2.1 GENERAL

In connection design, bolts shall not be considered as shearing stress in combination with welds. When the gravity axes of connecting, axially stressed members do not intersect at one point, provision shall be made for bending and shear stresses due to eccentricity in the connection.

The allowable bearing stress, F_p, on the contact area of milled surfaces, fitted bearing stiffeners, and other steel parts in static contact is calculated from the follow equation.

$$F_p = \frac{1.8F_y}{1.20N_d} \tag{31}$$

The allowable bearing load, R_p, in kips per inch of length (N/mm) on rollers.

$$R_d = \frac{a}{1.20N_d}\left(\frac{F_y - f}{20}\right)c \tag{32}$$

Where,

a = 1.2 if d ≤ 25 in. (635mm)

= 6.0 if d > 25 in. U.S. Customary units (F_y, ksi)

= 30.2 if d > 635 mm SI units (F_y, MPa) c = d if d ≤ 25 in. (635mm)

= $\sqrt{d}$ if d > 25 in. (635mm)

d = diameter of roller

f = 13 U.S. Customary units (F_y, ksi)

= 90 SI units (F_y, MPa)

F_y = lower yield stress of the parts in contact

A.2.2 BOLTED CONNECTIONS

Bolt spacing and edge distance shall be determined by an accepted design approach to provide a minimum design factor of $1.20N_d$ with respect to fracture of the connected parts in tension, shear or block shear.

$$F_t = \frac{F_u}{1.20N_d} \tag{33}$$

The actual tensile stress, F_t, shall be based on the tensile stress area of the bolt tension due to the applied loads. The tensile stress in the bolt due to preload is not to be considered in the calculation of f_t.

$$F_v = \frac{0.62F_u}{1.20N_d} \tag{34}$$

The actual shear stress, F_v. shall be based on the gross area of the bolt if the shear plane passes through the bolt shank, or the root area if the shear plane passes through the threaded length of the bolt and the bolt shear due to the applied loads.

$$F_t' \sqrt{F_t^2 - 2.60f_v^2} \tag{35}$$

The allowable shear capacity, P_s, of a bolt in a slip-critical connection in which the faying surfaces are clean and unpainted.

$$P_s = m\frac{0.26A_sF_u}{1.20N_d} \tag{36}$$

Where,

A_s = tensile stress area

m = number of slip planes in the connection

The hole diameters for bolts in slip-critical connections shall not be more than 1/16 in. (2mm) greater than the bolt diameter.

The slip resistance of connections in which the faying surfaces are painted or otherwise coated shall be determined by testing.

Bolts in slip-critical connections shall be tightened during installation to provide an initial tension equal to at least 70% of the specified minimum tensile strength of the bolt. A hardened flat washer shall be used under the part turned during installation. Washers shall be used under both the bolt head and nut of ASTM A490 bolts when the connected material has a specified minimum yield stress less than 40 ksi (276 MPa). Only ASTM A325 or ASTM A490 bolts shall be used in slip-critical connections.

A.3 Pinned Connections

Codes that pertain to the joining of two members using a pin that penetrates both surfaces.

A.3.1 Static Strength of the Plates

The strength of a pin-connected plate in the region of the pinhole shall be taken as the least value of the tensile strength of the effective area on a plane through the center of the pinhole perpendicular to the line of action of the applied load, the fracture strength beyond the pinhole on a single plane parallel to the line of the applied load, and the double plane shear strength beyond the pinhole parallel to the line of action of the applied load.

$$P_t = C_r \frac{F_u}{1.20N_d} 2tb_{eff} \quad \textbf{(37)}$$

Where,

P_t = Allowable tensile strength

b_{eff} = effective width to each side of the pinhole

$$C_r = 1 - 0.275\sqrt{1 - \frac{D_p^2}{D_h^2}} \tag{38}$$

Where,

D_h = hole diameter

D_p = pin diameter

The values of C_r may be taken as 1.00 for values D_p/D_h greater than 0.90.

The effective width shall be taken as the smaller of the two values calculated in Equations 39 and 40.

$$b_{eff} = 4t \leq b_e \tag{39}$$

$$b_{eff} = b_e \frac{F_u}{F_y}\sqrt{\frac{D_h}{b_e}} \leq b_e \tag{40}$$

Where,

b_e = actual width of a pin-connected plate between the edge of the hole and the edge of the plate on a line perpendicular to the line of action of the applied load

$$P_b = C_r \frac{F_u}{1.20N_d}\left[1.13\left(R - \frac{D_h}{2}\right) + \frac{0.92b_e}{1 + \frac{b_e}{D_h}}\right]t \tag{41}$$

Where,

R = distance from the center of the hole to the edge of the plate in the direction of the applied load

$$P_v = \frac{0.70F_u}{1.20N_d}A_v \tag{42}$$

Where,

A_v = total area of the two shear planes beyond the pinhole and is found from the following equation:

$$A_v = 2\left[a + \frac{D_p}{2}(1 - cos\emptyset)\right]t \quad \textbf{(43)}$$

The shear plane locating angle for pin-connected plates is calculated is degrees from the following equation:

$$\emptyset = 55\frac{D_p}{D_h} \quad (44)$$

Where,

a = distance from the edge of the pinhole to the edge of the plate in the direction of the applied load

A.3.2 BEARING STRESS

This applies to locations where the load is resting on only a portion of the total cross-section.

Allowable bearing stress based on projected area of pin is calculated using the following equation:

$$F_p = \frac{1.25F_y}{N_d} \quad (45)$$

Allowable bearing stress for plate-pin connections that will rotate for many cycles is calculated using:

$$F_p = \frac{0.63F_y}{N_d} \quad (46)$$

A.3.3 PIN-TO-HOLE CLEARANCE

Pin-to-hole clearance in connections that will rotate under load or that will experience loading reversal in service for many load cycles shall be as required to permit proper function of the connection.

A.3.4 Pin Design

Shear forces and bending moments in the pin shall be computed based on the geometry of the connection. Distribution of the loads between the plates and the pin may be assumed to be uniform or may account of the effects of local deformations.

A.4 Welded Connections

The strength of groove welds subjected to tension or compression shall be equal to the effective area of the weld multiplied by the allowable stress of the base metal.

The design strength of fillet or partial-joint-penetration groove welds shall not be equal to the effective area of the weld multiplied by the allowable stress, F_v, given from Equation 47.

$$F_v = \frac{0.60E_{xx}}{1.20N_d} \tag{47}$$

Where,

E_{xx} = nominal tensile strength of the weld metal

The strength of the complete-joint-penetration groove welds subject to shear shall be based on the strength of the base metal.

If two of more of the general types of welds are combined in a single joint, the effective capacity of each shall be separately computed with reference to the axis of the group to determine the allowable capacity of the combination.

A.5 Fatigue

Refer to ASME BTH-1 section 3.4 Tables 3-4.4-1 and 3-4.3-1.

The codes discussed were used where applicable when optimizing our final design. This ensured all standards were met as well as the corresponding needs of Conviron.

Appendix B Concept Generation, Selection & Development

In Appendix B is a detailed look at the development of the concepts. The process starts by taking a look at the needs and developing specifications that the concepts need to meet. From the specifications, metrics to measure success are determined. The process of generation concepts, selecting the most promising concepts. As well as improving a select few of the concepts can be found in Appendix B.

Table of Contents

List of Figures

List of Tables

B.1 Target Specifications

Statements from key stakeholders were collected on attributes desired in a new lift design. The customer statements gathered from this meeting were compiled, translated into appropriate needs, and then edited and verified by the client. The needs were then organized based on client priority and other safety requirements the lift must meet, allowing us to compile a list of target specifications for the design. This section discusses the analysis and quantification of the needs and target specifications.

B.1.1 Customer Needs

During our meeting with Jonathan Li and his colleague Kevin Perris, it became clear that having a lift capable of operating in small, restricted spaces, especially those with low ceilings, is a critical need of the client's that is not met by current methods. For this reason, designing a lift with a compact footprint is a major focus for our team moving forward.

Conviron has customers in countries all over the world that do not always have access to the sort of amenities we are accustomed to in North America. This means our lift design must be completely self-contained; mechanically operated. The design will not use additional power sources or special tools whose accessibility is dependent on the type of work environment. ASME BTH-1 codes and standards were researched and determined where applicable on each individual design.

The unpredictable environments that Conviron operates in also means that the customers can be in locations not easily accessible by roads that can handle trailers used to haul equipment and tools. Conviron needs a lift that is easily portable, regardless of the terrain travelled to reach their destinations. Furthermore, because the client's installers must sometimes carry equipment long distances or up staircases to assemble the space saver unit, portability of the lift is critical.

After the meeting with Jonathan Li, the team compiled a list of needs which were then weighted based on importance to the client. The safety requirements of the lift were also considered when determining the customer needs. The customer needs can be found in TABLE XVII.

TABLE XVII. PRIORITIZED CUSTOMER NEEDS

Need #	Customer Need	Rating	Priority
8	Lift can operate in tight areas/low rooms	5	1
9	Lift can support load safely.	5	2
10	Lift is designed to meet ASME BTH-1 standards.	5	3
11	Lift is self-contained	5	4
17	Lift is portable	5	5
1	Lift's storage dimensions are small enough to fit in a pickup truck.	4	6
3	Lift is the only tool required to perform lift of machine top	4	7
4	Lift maintains shape during and after use.	4	8
6	Lift is stable on uneven solid surfaces.	4	9
7	Lift is secured in position prior to lifting	4	10
2	Lift is easily constructible and de-constructible	3	11
5	Lift maintains shape after many cycles.	3	12
12	Device is ergonomic	3	13
13	Lift is resistant to corrosion	3	14
14	Lift is simple to operate	3	15
15	Device should be operable by a (minimum of 1 person) maximum 2 people	3	16
16	Assembled lift is minimized in weight and footprint	3	17

This list of customer needs in TABLE XVII is ordered using a rating system from 1 to 5, with 1 being the least important and a rating of 5 being the most important. The column "Need #" is the order in which the needs were brought up during the discussion with Jonathan Li. These needs were then rearranged based off the rating system and ordered in terms of descending priority to help organize the most important customer needs.

B.1.2 Metrics

Based on the customer needs, metrics and units were created in TABLE XVII. The abbreviation "Imp" means importance. These metrics are ranked from 1 to 5 with 1 being the least important and 5 being the most important. A high ranking is given to a metric that satisfies customer needs with higher importance. The highlighted yellow rows in TABLE XVIIIshow the most important metrics that will be considered when designing the lift.

TABLE XVIII. METRICS AND IDEAL VALUES

Metric	Need #	Imp	Metric	Units	Marginal Value	Ideal Value
1	1,16,17	5	Maximum area of disassembled lift fits in standard ½ ton pick up truck	in^2	4936	<4936
2	2,3,14	1	Time to assemble/disassemble for installation process	min	15	<15
3	2	4	Additional tools required to operate/assemble/disassemble	unit	5	<=1
4	2,16,17	4	Maximum weight of each disassembled part	lb	32	<20
5	2,17	2	Number of disassembled parts	units	10	5
6	4,9,10	5	Maximum bending stress in a member	psi	22000	<10000
7	4,5,10	4	Fatigue	cycles	500000	2000000
8	6	2	Points of contact with the ground surface	#	5	3
9	8,16	5	Maximum height of assembled lift (inches below space saver height)	in	0	<=22
10	8	3	Maximum width assembled (with or without the load)	in	105	30
11	9,10	5	Minimum load capacity	lb	700	>700
12	8	5	Stress under load	psi	21000	<10000
13	8	2	Total mass of the lift	lb	300	200
14	4	2	Surface area of ground contact points	in^2	25	100
15	4,10	4	Shear stress in connectors	psi	11547	<9000
16	10,11,14	4	Bearing stress	psi	21000	<10000
17	12,14	5	Outsourced parts required to operate/assemble	#	1	0
18	12,14	4	Ease of use by operator	Subj.	80%	100%
19	12	2	Repetitive movement required to operate	Subj.	Low	Very Low
20	13	3	Corrosion Rate	Const.	Low	Very Low
21	14,15	5	Number of operators required	#	2	1
22	16	4	Base surface area when assembled	in^2	4158	<=4158
23	17	4	Size of individual assembly parts	Subj.	Manageable	Easily Manageable

TABLE XVIII also contains information regarding marginal and ideal values known as target specifications. The marginal and ideal values were generated based on the customer's needs and the Genie lift SLC-18. The sections that lack info will be determined in Phase III as they require complex equations found in ASME BTH-1 2017 standards. These metrics will only be determined if they meet the most important customer needs.

B.1.3 BENCHMARKING

TABLE XXI contains information on benchmarking with the forklift (Standard) and Genie SLC-18, where both the forklift and Genie lift are being used as existing methods for lifting the machine top.

TABLE XIX. BENCHMARKING CUSTOMER NEEDS

Need #	Customer Need	Rating	Fork Lift (Std)	Genie Lift (SLC-18)
1	Lift's storage dimensions are small enough to fit in a pickup truck.	4	X	XXXX
2	Lift can be easily constructible and de-constructible	3	X	XXX
3	Lift's is the only tool required to perform lift of machine top.	4	XXX	XXX
4	Lift maintains shape during and after use.	4	XXXXX	XXXXX
5	Lift maintains shape after many cycles.	3	XXXXX	XXXXX
6	Lift is stable on uneven solid surfaces.	4	XXXX	XXXX
7	Lift is secured in position prior to lifting	4	XXXXX	XX
8	Lift can operate in tight areas/low rooms	5	X	XXXX
9	Lift can support load safely.	5	XXXXX	XXX
10	Lift is designed to meet ASME BTH-1 standards.	5	XXXXX	XXXXX
11	Lift is self-contained	5	XX	XX
12	Device is ergonomic	3	XXXXX	XXX
13	Lift is resistant to corrosion.	3	XXX	XXX
14	Lift is simple to operate	3	XX	XXXX
15	Device should be operable by (ideally by a minimum of 1 person and) maximum 2 people	3	XXXX	XXXX
16	Assembled lift is minimized in weight and footprint	3	X	XX
17	Lift is portable	5	X	XX

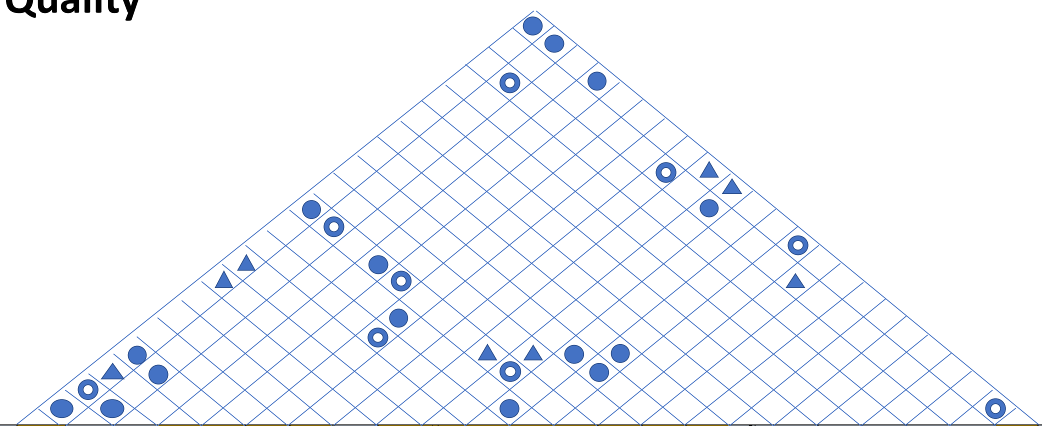
The number of x's show whether a product is competitive. The more x's a competitor received, the better the product was at achieving the corresponding customer need. The forklift and genie lift were compared to define which one was the most successful in terms of meeting customer needs, and as a result allowed the team to define which lift would be useful as a reference for screening the teams design concepts. The rating column is the importance value that was determined in TABLE XIX.

B.1.4 HOUSE OF QUALITY

The House of Quality in TABLE XX is a tool that correlates the customer needs, metrics, benchmarking and target specifications. The top section of the chart presents the relationship between the different metrics to show whether they affect each other positively or negatively. The information in the House of Quality will highlight important target specifications based off the customer needs. The yellow highlighted areas show the prioritized customer needs in TABLE XVII. The orange highlighted areas show the metric and target specification that will be used to aid the concept screening and concept scoring analysis. The blue circles in the middle matrix area, show the number of metrics that can meet the customer needs.

TABLE XX. HOUSE OF QUALITY

House of Quality



● Very Strong Relationship
◎ Strong Relationship
▲ Weak Relationship

Need #	Customer Needs	Maximum area of disassembled lift fits in 1/2 ton pick-up truck	Time to assemble/disassemble for installation process	Additional tools required to operate/assemble/disassemble	Maximum weight of each disassembled part	Number of disassembled parts	Maximum bending stress in a member	Fatigue	Points of contact with the ground surface	Maximum height of assembled lift (inches below space saver height)	Maximum width assembled (with or without the load)	Minimum load capacity	Stress under load	Total mass of the lift	Surface area of ground contact points	Shear stress in connectors	Bearing strength	Outsourced parts required to operate/assemble	Ease of use by operator	Repetitive movement required to operate	Corrosion resistant	Number of operators required	Base surface area when assembled	Size of individual assembly parts	Importance of Need	Genie Lift	Fork Lift
1	Lift's storage dimensions are small enough to fit in a pickup truck.	●																							4	xxxx	x
2	Lift can be easily constructible and deconstructible		●	●	●	●																			3	xxx	x
3	Lift's is the only tool required to perform lift of machine top		●																						4	xxx	xxx
4	Lift maintains shape during and after use.						●	●							●	●									3	xxxxx	xxxxx
5	Lift maintains shape after many cycles.							●																	4	xxxxx	xxxxx
6	Lift is stable on uneven solid surfaces.								●																4	xxxx	xxxx
7	Lift is secured in position prior to lifting																								5	xx	xxxxx
8	Lift can operate in tight areas/low rooms									●	●		●	●											5	xxxx	x
9	Lift can support load safely.						●					●													5	xxx	xxxxx
10	Lift is designed to meet ASME BTH-1 standards.						●	●				●				●	●								5	xxxxx	xxxxx
11	Lift is self-contained																●								3	xx	xx
12	Device is ergonomic																	●	●						3	xxx	xxxxx
13	Lift is resistant to corrosion.																			●					4	xxx	xxx
14	Lift is simple to operate		●														●	●	●			●			3	xxxx	xx
15	Device should be operable by (ideally by a minimum of 1 person and) maximum 2																								3	xxx	xxxx
16	Assembled lift is minimized in weight and footprint	●			●					●													●		3	xxx	x
17	Lift is portable	●			●	●																		●	5	xx	x
	Target Value (units)	in²	min	unit	lb	pieces	N/m²	cycles	points	in	in	lb	N/m²	lb	in²	N/m²	N/m²	parts	Subj.	Subj.	Subj.	worker	in²	Subj.			
	Target Value	4936	<15	<=1	<20	5	Lack info	2000000	3	<=22	30	>700	Lack info	200	100	Lack info	Lack info	0	100%	Low	Very Low	1	<=4158	Easily Manageable			

Benchmarking the Competition: xxxxx = Most Competitive; x = Least Competitive

B.2 Concept Generation

This section includes research on the lifting mechanisms, structure layout and applicable codes. Afterwards the preliminary lifting design concepts would be brainstormed individually so there is no bias created from the first idea presented. The preliminary designs contain a sketch of the apparatus and a summary explaining details of the operation.

B.2.1 Lift Mechanisms

Various lift mechanisms that could be incorporated into our designs are discussed in this section. Since our design must only be mechanically operated, the two primary lift mechanisms that this report discusses are based on pulley systems and hydraulics.

B.2.1.1 Block and Tackle Pulley System

The first lift mechanism brainstormed was a block and tackle pulley system and was inspired from a vertical boat lift pulley system concept. In this type of pulley system, pulleys are assembled together to form blocks, where one block is fixed in position while the other block moves with the load as it is being lifted. There are several different types of block and tackle pulley systems such as a gun tackle, luff or watch tackle, double tackle, gun tackle, and three-fold purchase pulley system. These different pulley systems can be seen in Figure B-11.

Figure B-1.Block and tackle pulley systems (Block and Tackle, n.d.)

The advantages of a block and tackle pulley system are realized from using the same cable multiple time to support the same load. In the gun tackle pulley system (Figure B-1), a single cable is first attached to the fixed block. The cable then wraps around the free block that has a hook attached to support the load it is meant to lift. It then wraps around the fixed block pulley where the free end can either be pulled or attached to some type of winch system to lift the load. Figure B-2 shows how the tensions within a single cable are distributed if a gun tackle pulley system was used to support a 100N load.

Figure B-2. Gun tackle pulley system tension distribution [9]

The advantages of a block and tackle pulley system can be seen in Figure B-2, where since the cable is supporting the 100N load twice (once from where the cable is attached to the fixed block, and once where the cable wraps around the fixed pulley in the block), there is only 50N of tension in each section of the cable, therefore reducing the total force needed to lift this 100N block by 50%. The disadvantages of this type of system are seen at the point where the block is fixed. At this point the additional 50N of load is redistributed from the tension in the cable to the fixed point of the block, forcing this point to support an additional 50N of force than the load being lifted. The more a cable is wrapped around the blocks in this pulley system, the more the tension in the cable will be reduced, but this will also increase the stress exerted at the point where the fixed block is secured.

B.2.1.2 Telescoping Pulley System

The second type of pulley system our team looked at was inspired by our benchmarked lift, the Genie SLC-18. This type of pulley systems consists of 2 or more sections that are raised by one or more cables depending on the load being lifted, and each section of the lift raises the next section up after it. A diagram of a telescoping lift system utilizing a 2-cable system can be seen in Figure B-3.

Figure B-3. Telescoping lift (phase 1) [10]

In Figure B-3, the top section (purple) of the lift is raised to the point where its stops have contacted the stops on the yellow section of the lift. At this point the purple section will now begin to lift the yellow section up with it as the winch pulls the cables in further.

Figure B-4. Telescoping lift (phase 2) [10]

Figure B-4 now shows the second section of the lift (yellow) has been raised up by the stops on the purple section. The yellow sections' stops have now reached the blue sections' stops and can now lift the blue section even further until the blue stops hit the final stops that are fastened to the beige base section.

As many sections can be used as deemed necessary to reach the desired height you are trying to achieve with this design, and the geometry of the sections can be changed however you choose if required standards are still met for the design. It should be noted that you can also use hydraulics to lift this type of system as well which will be covered later in Section B.2.1.3

B.2.1.3 Hand Pump Hydraulic System

A hydraulic lift system is extremely useful for lifting heavy loads easily. It utilizes pascals principle, which says that pressure is equal to the force divided by the cross-sectional area on which it acts [11]. Hydraulics use this principle to lift heavy loads by forcing liquids from a pipe of small cross-sectional area into pipes with a larger cross-sectional area to create a high force from a relatively low force. A simple schematic of this concept can be seen in Figure B-5.

Figure B-5. Principle of hydraulics [11]

Due to Conviron's need to have a mechanically operated lift, a hydraulic hand pump will only be considered for this project.

A hydraulic hand pump, shown in Figure B-6, operates by sucking fluid into the small piston area (B) from a reservoir. This fluid is then forced into the larger piston area by pushing down the jack handle which increases the pressure in the larger piston chamber and forces the piston (A) to rise. Fluid within the pump is controlled using stops at positions C and D, where stop C is used to allow fluid to flow into B when a negative pressure is created when raising the pump handle, but stops the fluid from going back into the reservoir when the fluid is being forced into the larger piston chamber. The stop at position D is to allow fluid to enter the large piston chamber when the pump handle is pushed down but not allow any fluid out of the large chamber when the pump handle is raised.

Figure B-6. Hydraulic hand jack [12]

Advantages of using a hydraulic system to act as our lift mechanism are that it allows for ease and simplicity of lifting the machine top onto the lower cabinet, which are both needs of Conviron. There are some significant disadvantages that come with a hydraulic system as well. A hydraulic lift is very heavy and cannot be disassembled easily to make it lighter so it will not be easy to transport relative to other methods mentioned in this report. It also offers a relatively significant maintenance challenge if a mechanical issue arose.

After discussion with Mr. Li and Brian Mamrocha, it was decided that disadvantages of hydraulic systems outweigh the advantages that they offer and no design concepts will be generated based on this type of lift mechanism. This section is included because it was heavily discussed as a potential lifting mechanism up until this point.

B.2.2 STRUCTURE LAYOUT

The structure referred to in this section describes where the lift is situated around the lower cabinet. The purpose of the structure is to resist forces and moments that arrive with the different lifting configurations. The structure must be stable under loading, as tipping or shifting of loads could be dangerous. The structure also needs to be lightweight and portable when disassembled. Since most framework can be designed and modified to disassemble into smaller sections, portability is not an issue for the structure concept generation. There are three main structures that were investigated.

B.2.2.1 FRAME

The first structure concept idea was based upon building a frame around the lower cabinet on three sides. A figure of the frame can be seen in Figure B-7. This would be composed mainly of square tubes with welded joints. This design will need a cross over brace along the lengthwise section to prevent movement of the top-left or top-right members relative to the base of the lift. Braces may also be required on the sides, but these can be much smaller, in the form of gussets.

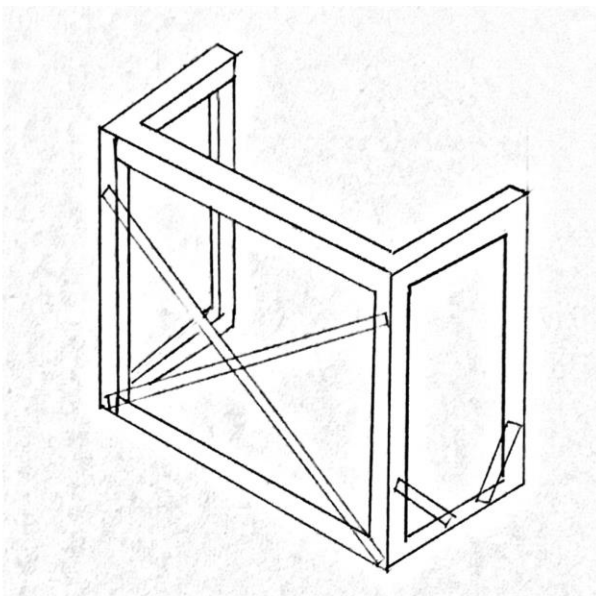


Figure B-7. Frame structure

This design would provide a high level of stability due to the base having a large surface area and the lift point located at a central point over said base. As a result of the large base it does have a larger footprint. With the structure surrounding the lower cabinet, the members must be stretched long distances, potentially resulting in increased the weight. If the structure supports the load efficiently however, the added material may not be significant. Since such a long distance is spanned, the lengthwise sections must to be disconnected for transport meaning the frame needs to be built in a modular fashion to increase portability and ease of assembly.

B.2.2.2 Forward Low-Profile Legs

There is a 3” gap of available space between the lower cabinet and the floor, leading to a possibility of having two legs that extend underneath the cabinet for stability. The structure would be narrower than the unit that it is lifting, consisting of matching left and right legs that would connect near the rear of the structure. The two sides are connected with horizontal square tubes. The design is shown in Figure B-8.

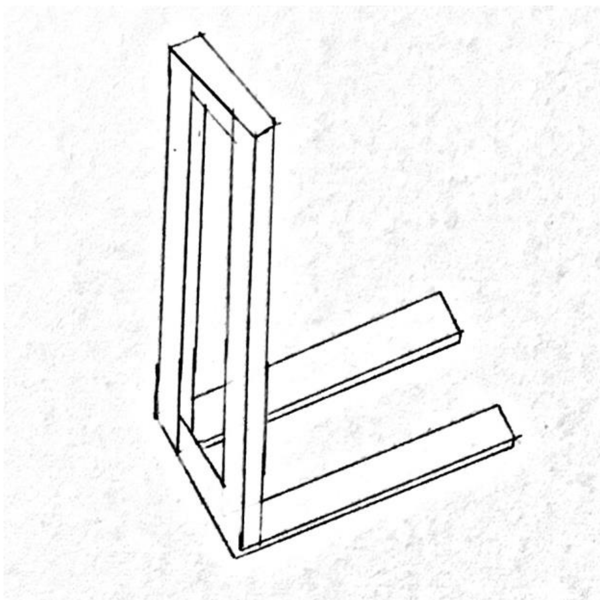


Figure B-8. Forward low-profile legs structure

This structure has a smaller footprint. Since the lifting points are behind the center of mass of the machine top, a moment will result. Therefore, the lift system must be designed to withstand the resulting stresses and the legs must also be designed to have the desired stiffness to keep the lift stable. The weight of the structure will increase because of the lifts requirements to handle the moments and stresses that the layout will present. However, the smaller footprint means less linear length in the members, reducing material use and weight. This may not offset the weight increase due to its stability. The structure is small and can be taken apart into several pieces, this makes portability relatively good. The structure will have fewer pieces than the frame design, adding to the ease of portability as well as assembly and disassembly. The structure will be composed of square tubes wherever possible and will be welded together, making it easy to manufacture.

B.2.2.3 REARWARD LEGS COUNTER BALANCED

Another alternative for the structure is to have it narrower than the width of the machine top, with a counter-balance behind the lifting mast. The unit will be in front of the mast, and the counter balance at some distance behind the mast to offset the moment created by the machine top. This structure will have a left and right side, connected with square beams for rigidity. The design will require a substantial amount of weight, or the weight must be a sufficient distance behind the mast in order to effectively counter-balance the lift when lifting the machine top. An example of this design of structure is available in Figure B-9.

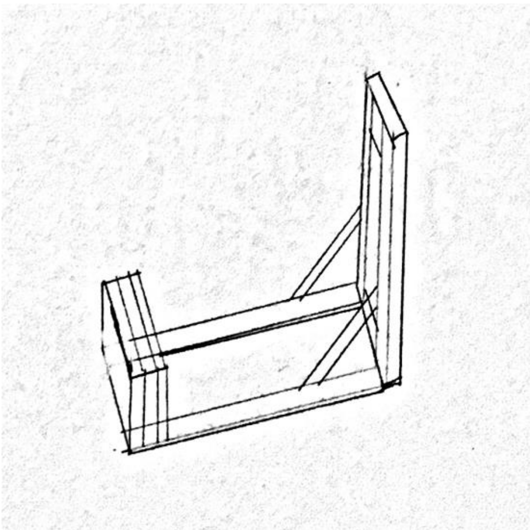


Figure B-9. Rearward facing legs, counter-weighted structure

The footprint of this structure can be relatively small if a large amount of counter weight is used, however additional weight is not desirable. A smaller amount of weight can be used if it is extended further out behind the load, increasing the footprint, material used, and overall lengths of beams. The structure would have large bending moments through it, as the machine top tries to tip it forward and the counter-weight keeps it grounded. This design could be disassembled into many pieces for ease of transportation but, depending on the weights, there may be many beams that would make portability of the design low. The structure would be easy to manufacture because, like the other alternatives, it can be made from square tubing and welded together.

B.2.3 Attachments

In this project, we must consider how the machine top is attached to the lift with the existing lifting points. These are the three main concepts that were suggested by the team; the cable connection, the fork connection and the screw in connector method.

Based on the project needs, the lift must be able to lift 700 lbs. from ground level up to approximately 100 inches, and use the current lifting points. The current machine top has 4 holes on both sides as the lifting points, and the current process of lifting the machine top is to connect the lifting jig to the machine top with eight bolts.

B.2.3.1 Cable Connection

The cable connection was one of the concepts brought out by the team. The cable has the advantage of being easy to manually operate. Cables come in a range of lengths and can be long lasting and maintenance friendly. The cable can also be easily inspected, and manufactured with safety and reliability in mind. The metal cables are widely used in many industries as a lifting element, such as on Genie lifts and crane lifts. In our concept, the cable connection uses one metal cable to connect two or four lifting points from each side of the machine top. Figure B-10 shows an example of a typical wire cable.

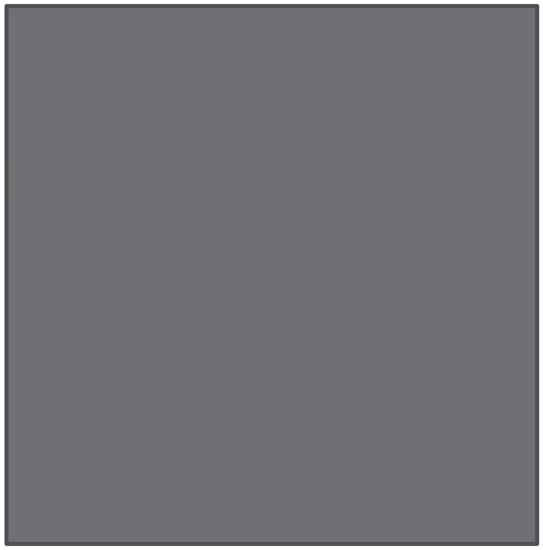


Figure B-10. Example of wire cable [5]

The cable concept still would require using bolts to connect to the machine top, where the bolts can be easily removed or replaced. The only concern of the cable concept is the stability of the machine top when it is being lifted to the desired height, since the cable connection only uses one contact point at each side of the machine top.

Based on Figure B-11, the cable for our design concept would require a ¼ inch diameter bright wire uncoated steel (IPS) where the safe load is 1300 lb.

Figure B-11. Wire cable example with 1300 lbs loading capacity [6]

B.2.3.2 Fork Attachment

The fork attachment concept is a custom designed fork used for lifting the machine top with the current lifting points as shown in Figure B-13. The fork attachment concept is based on a variety of forklift's and genie lift's fork attachments, where the attachments are designed to hold specific objects with special holding locations such as examples shown in Figure B-12.

Figure B-12. Examples of different type of attachment for forklift [7]

The fork will attach to the modified genie lift concept design. The fork attachment has the advantages of custom fitting which the load would be stable during the operation compare with cable attachment concept.

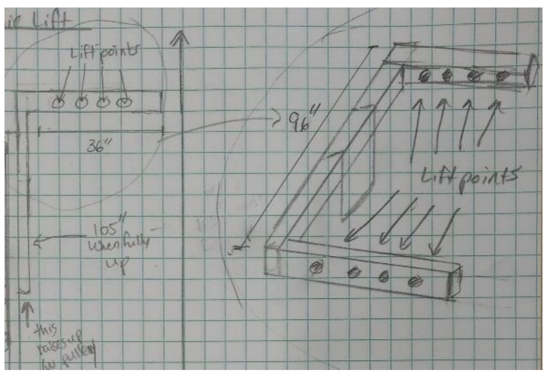


Figure B-13. Fork attachment design concept

B.2.3.3 SCREW IN CONNECTOR

Both cable and fork attachment concepts utilize a screw in connection since the lifting points of the machine top could not be changed under the current scope. The screw in connectors act as the attachment points where the cables or forks hook onto the machine top. These screw in connectors are in the shapes of door knobs, with the stems of the connectors containing screw grooves to allow them to screw directly into the lift points on the machine top. These connectors can then have cables loop around them to lift the machine top. In the forklift connection concept, the holes in the forklift would latch onto these connectors to lift the machine top. Figure B-14 shows how cables would utilize this screw-in connector concept.

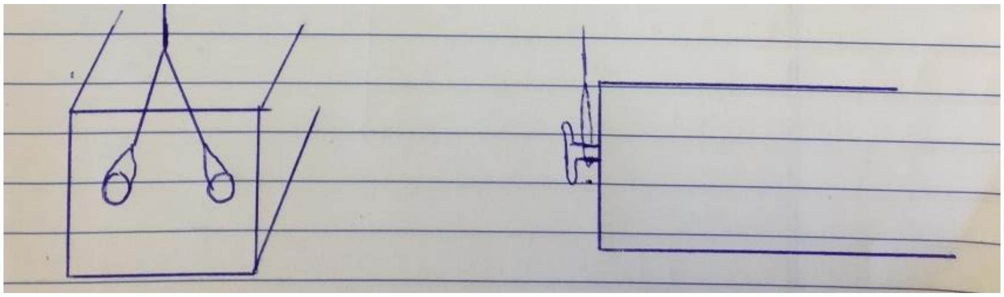


Figure B-14. Lifting the machine top with cable connection and screw in connectors

B.2.4 Design Concept Summaries

The following section will describe the different ideas that were developed individually. Each idea will include a sketch, along with an explanation on how the device works.

B.2.4.1 Box Frame Concept Summary

Below in Figure B-15 is a fixed frame concept idea, where the frame of the lift is constructed around the lower cabinet and the machine top that will initially be sitting on the ground in front of the lower cabinet. The lift will utilize two independent block and tackle pulley systems; one that will raise and lower the machine top vertically, and a second system that will slide the machine top horizontally into position over top of the lower cabinet.

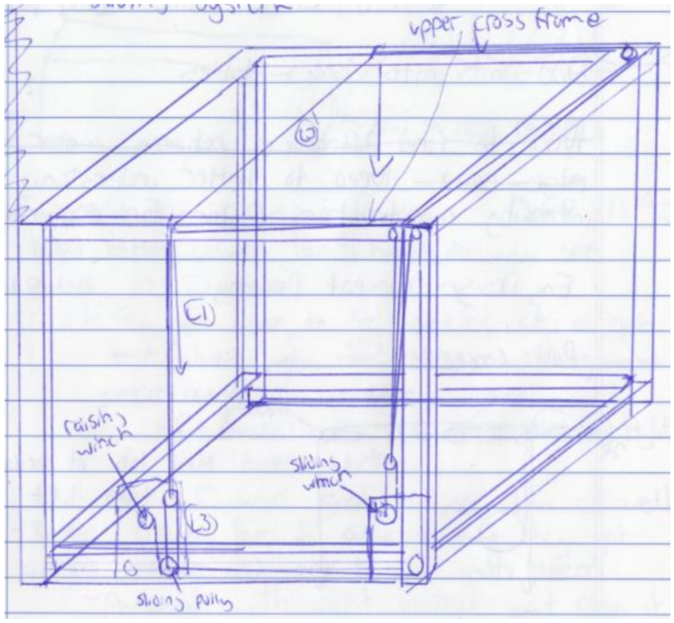


Figure B-15. Box frame concept

The block and tackle pulley system responsible for lifting the machine top could be any of the types mentioned in Section B.2.1.1 depending on the strength of the cables and fixed supports used. It will consist of a fixed block at the base of the lift, a free block, and a winch. A cable will first run from the winch, down and around the fixed block pulley, and then up around the free block pulley, before being secured to the fixed block. Two cables will then be attached to the free block and wrap around each of the top horizontal frame members, before finally looping on to the drill-in hook receivers attached to the machine top. Once attached to the machine top, the pulley system will then lift the machine top vertically until it reaches a height slightly higher than the lower cabinet.

The second pulley system, consisting of the same block and tackle pulley system, will have three cables fastened to the free block. Each of these cables will run horizontally to the points in which the cables, winch, and fixed block of the lift system are attached to the frame. Each of these points are on sliders that allow free movement in the horizontal direction. The winch of the sliding pulley system can then be used to move the machine top into position over the lower cabinet before it is lowered onto it.

Advantages that come with this concept are an extremely stable lift when operating, and simplicity to operate, as it only requires the use of two winches and there are not any physical movements of the lift required to lift the machine top into position. Disadvantages include the fact that it will be relatively difficult to assemble and disassemble as there will be many members required to construct it and the overall footprint of the lift will be significant as well.

B.2.4.2 ¾ FRAME CONCEPT

The ¾ frame design has two steel loops on either side, with the loops bolted onto the mounting points. On both sides, there are triangle cables with an attachment point at the peak. The lift has a hook that attaches onto the peak of the cable. The lift cable has a pulley at the top of the frame where the cable is looped around. The cable traverses through the pulley system to a winch. There are two winches one on each side for simplicities sake. The lift is four post system. Each post is extendable to double its initial height, and held in place with pins. The two posts on the same side will be joined by square tubing with castor wheels on the bottom. The two posts on the same side will also be joined by a square tube on the top for added strength. To prevent each side from falling inward under load, there is an extendable square tube along the bottom for support. An x-frame is added that joins the top of a post on one side, to the bottom of a post on the other. The front of the lift is open so when the machine top is at height; the lift can be rolled forward until the unit is over top of the lower cabinet at which point the sides of the lift will be parallel to the sides of the lower cabinet. The design will be modular so it can be disassembled for transportation. Each side, or even post can be independently detached for transportation. The X-frame and lower beam can be detached and can either be collapsible or foldable for transportation. A sketch of the design can be seen below in Figure B-16.

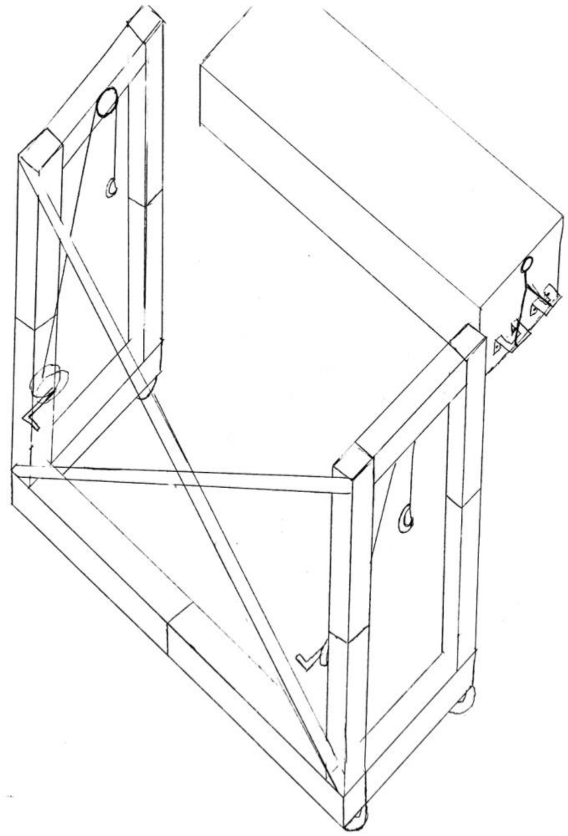


Figure B-16. 3/4 frame with pulley system concept

An advantage of the ¾ frame design is its stability, which is inherent due to its wide base. Since the design pulls from the top, most of the force will be transmitted in the form of compression. Minimal bending moments are present to provide additional stress to the structure. Therefore, the square tubes need not be as thick as other designs, saving weight and increasing portability. To reach around the length of the lower cabinet, long lengths of material are required, this may add some additional weight. To aid with assembly and disassembly, the design will be modular with quick connections.

B.2.4.3 Screw Jack Concept

The screw jack has a D-box that mounts to either side of the machine top. The machine top must be at least 1ft off the ground before lifting. The lift extends as low as the bottom square tube. The lift has two forks that slide into the D-boxes. A crank with a gear reduction turns a screw to lift the unit up. The spine of the lift is the full extended height that it must lift and has a c-channel to hold the slider in place. The frame of the lift is slightly wider than the lower cabinet to provide more stability and allow the lift to roll around the lower cabinet. The lift is on wheels, so once the unit is in the air it can be rolled forward, positioning the machine top over top of the lower cabinet before it is lowered. Since the wheels are positioned wider than the lower cabinet, there is no interference and the load is maintained close to the spine of the lift until the machine top is lowered into its final resting position. The screw jack design can be seen below in Figure B-17.

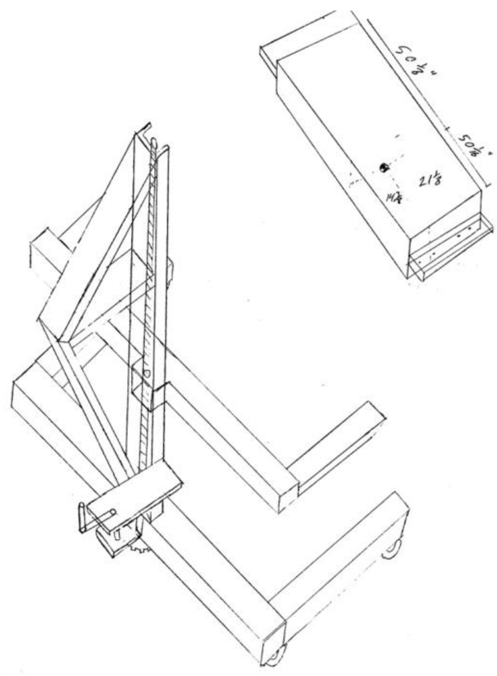


Figure B-17. Screw jack with legs extended around lower cabinet and forks that sliding into D-box lift point mounted on the machine top

An advantage of this design is that screw provides a solid connection to the load, with no possibility of the load swinging. The wide base of the design provides a high degree of stability for the lift. With the legs going around the lower cabinet, the load can remain close to the mast, resulting in a reduced moment effect. The added material required to extend the lower structure around the lower cabinet may add some additional weight, as well as increase the size of the footprint. The mast of the design needs to support a great amount of weight and stabilize the entire machine top. To accomplish this, it needs to be reinforced and will be heavy. Another disadvantage is the screw cannot be disassembled, reducing portability greatly. The remainder of the design can be broken down for transportation.

B.2.4.4 Modified Genie Lift

The modified Genie lift is a design based off the Genie lift, with different external features that allow the design to lift the machine top effectively. The features include uniquely sized fork for this application, and legs that only extend rearward due to the design being required to move the machine top above the lower cabinet. The design maintains a single mast like the genie lift and uses pulleys with wire cables attached to a winch to lift the fork system vertically.

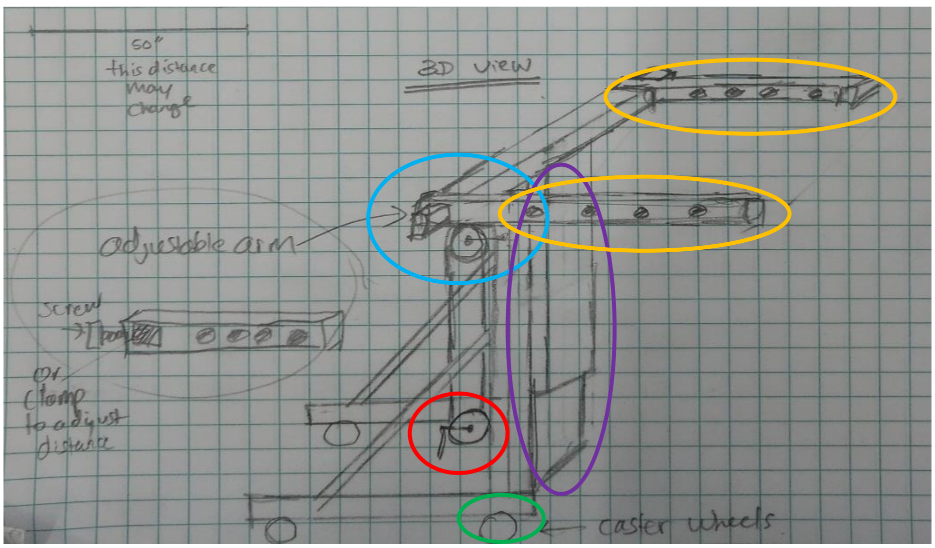


Figure B-18. Modified Genie lift in 3D

The blue circle shows an adjustable arm for the fork to account for any changes in width from the machine top. The red circle shows a winch that controls the height of the fork. The green circle shows caster wheels that allow the modified Genie lift to maneuver while placing the machine top over the lower cabinet. Each of the caster wheels will have locks as a safety measure. The purple circle shows the single mast assembly extends the fork attached using a telescoping pulley system. The orange circle shows the holes where the fork will attach to the lifting points of the machine top.

Since the design is required to be portable and easy to disassemble, the fork be broken down into three pieces. Figure B-19 shows the fork in three pieces; one piece on each side and then another middle piece that can attach to the lifting apparatus' single mast.

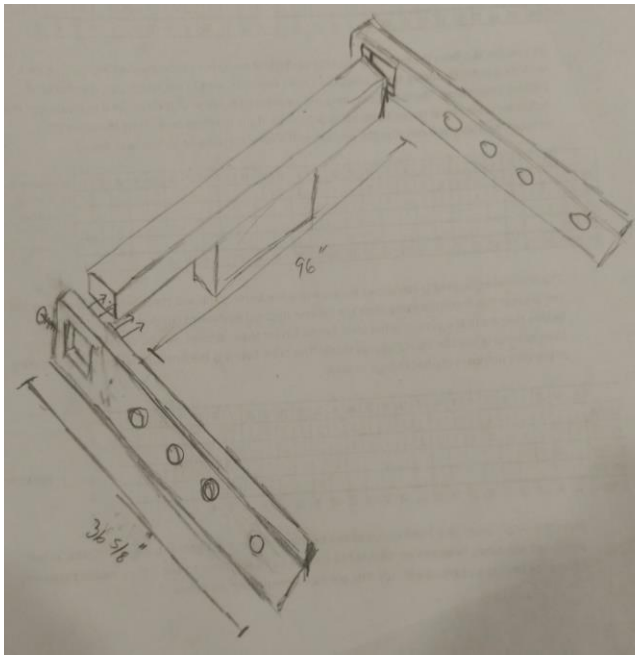


Figure B-19. Three piece fork assembly

The fork along with the weight of the machine top might place the centre of gravity in an undesirable location. By placing supports and weight on the opposing side, the design can offset any stability issues. The weights and supports will increase the weight of the overall design. The stability of the design is a concern and should be modified further to become safer. Precise calculations proving the safe use of the design are required. The design idea is inspired by the genie lift, therefore applicable patents were researched. This research concluded that genie lift's patents did not conflict with the design. Since the client does not look to make a profit on the sale of the lift design, the team decided not to spend too much time finding the specific patents that may or may not apply.

B.2.4.5 Modified Sliding Genie Lift

The modified sliding Genie lift design is based on Genie lift, using the lower mast support to lift the machine top as shown in Figure B-20. The lifting component connects the machine top at the lifting points using blots. The lift will raise the machine top to the desire height using a pulley system. The lower mast support needs to be up against the lower cabinet as a support, since there is no counter weight. The design uses the lower cabinet as a support during the entire lifting process, allowing for a light weight and more compact design.

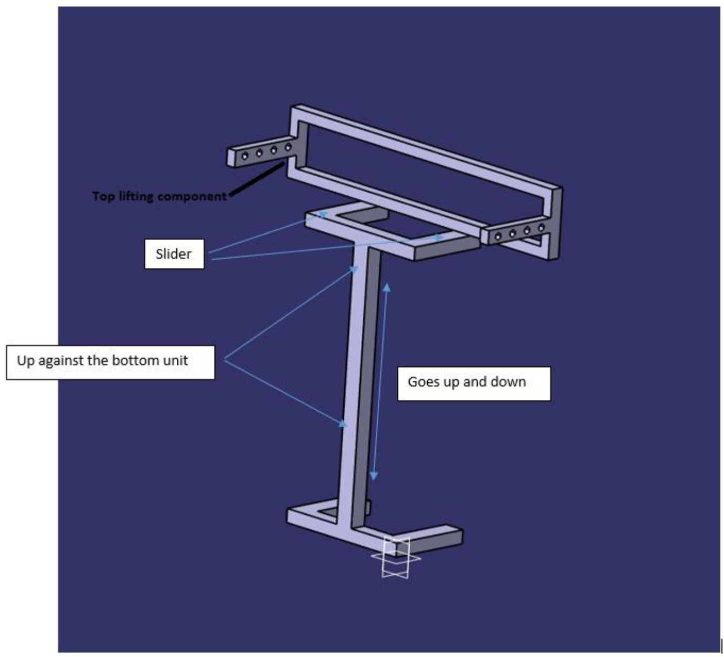


Figure B-20. Modified sliding Genie lift in 3D

An advantage of the sliding modified Genie lift is the reduced weight, minimal material is needed to construct the design due to the lift using the lower cabinet as a support. This design is relatively simple use. The compact design allows for easy assembly and disassembly as well as a high degree of portability. A disadvantage of this design is the added stress placed on the lower cabinet. The lower cabinet is a light component of the Space Saver, designed to handle the load of the machine top directly down on it. Using the lower cabinet as support would change the loading characteristics that might result in shifting or failure of the lower cabinet structure.

B.3 CONCEPT ANALYSIS AND SELECTION

In this section, each design is taken through a process of ranking against a set of design selection criteria to evaluate them. The goal is to find a design that is superior. To gauge what selection criteria should be used and how the selection criteria applies to the customer's needs, a selection criteria justification matrix was composed. TABLE XXI is the justification for the selection criteria used.

Selection Criteria	Description	Needs Met
Portability	The ability of the design to be transported between different job sites practically and easily	1, 18
Manufacturability	Ability to manufacture the different components of design quickly and easily	3,15
Ease of Assembly	The process of assembling individual components of design is simple and can be completed efficiently	2
Simplicity to Operate	All processes of operating lift, including lifting, maneuvering, lowering, and placing machine top on top of lower cabinet are simple for instiallers to perform	3,11,12,15,16
Weight	Low weight of individual assembly parts as well as overall weight of design	2,17
Footprint	Small area and height is required to operate lift	17
Stability	Lift is stable when operating an maneuvering into position	6,7,9
Cost	Cost of design in terms of purchasing and manufacturing parts	17
Reliability	Lift will remain in service for a long period of time, with minimum maintenance required	4,5,9,13,

TABLE XXI. SELECTION CRITERIA JUSTIFICATION MATRIX

TABLE XXI shows the selection criteria that were chosen are portability, manufacturability, ease of assembly, simplicity to operate, weight, footprint, stability, cost, and reliability. The table shows a description of each selection criteria and the corresponding customer needs from TABLE XVII.

B.3.1 CONCEPT SCREENING

Each preliminary design concepts were screened against the Genie SLC-18 lift, meaning the Genie SLC-18 was given a zero rating in each of the categories for the selection criteria to represent the baseline. If a design was considered favorable over the Genie lift in any selection criteria category it was given a plus rating. If the any of the design concepts were considered inferior to the Genie lift in any given selection criteria category it was then given a minus rating. The total scores were tallied for each design concept and compared. The results from the design concept screening can be found in TABLE XXII.

TABLE XXII. DESIGN CONCEPT SCREENING

	Concepts				
Selection Criteria	3/4 Frame	Screw Jack	Modified Genie Lift	Box Frame	Modified Sliding Genie Lift
Portability	+	-	0	+	+
Manufacturability	+	-	0	+	0
Ease of Assembly	0	-	+	0	0
Simplicity to Operate	+	+	+	+	-
Weight	-	-	0	-	0
Footprint	-	-	0	-	+
Stability	0	0	0	+	-
Cost	+	-	+	-	0
Reliability	+	0	0	+	-
Pluses	5	1	3	5	2
Zeros	2	2	6	1	4
Minuses	2	6	0	3	3
Total	3	-5	3	2	-1

From TABLE XXII, the ¾ frame design concept and the modified genie lift concepts both tied for the highest rank. The ¾ frame concept had two more pluses than the pallet jack support concept, however it also had two extra minus ratings as well. The modified genie lift on the other hand scored 4 more zero ratings, meaning that it was considered comparable to the Genie lift in 6 of the 9 categories.

From the design concept screening, it was determined that the ¾ frame design and the modified genie lift design were chosen for further analysis and comparison while the other three design concepts were dropped out of consideration and deemed as unfeasible designs.

B.3.2 Concept Improvements

Improvements were made to each design after meeting with Mr. Li and Mr. Mamrocha. They gave the team advice on the preliminary designs moving forward and pointed out weaknesses that should be considered. The weaknesses are highlighted at the beginning of each improved design.

After the discussion with the client and the advisor, the team generated ideas to tackle these issues. Once the concepts were improved, they were re-sketched and filtered through concept scoring matrix to determine the final concept recommendation.

B.3.2.1 THE IMPROVED MODIFIED GENIE LIFT

This idea was based off a vertical material lift known as the Genie lift. The weaknesses addressed for the modified Genie lift were that there may be stability issues due to the single mast design along with the problem that a commercial Genie lift had legs in the front to stabilize it during lifting, but the new design removed them.

During this phase, additional information was discovered, making it viable to keep the legs at the front of the modified genie lift. According to the drawings of the lower cabinet given to the team by Conviron, there is a 2 ¾" gap at the bottom. This gap does not allow for the commercial Genie lift to fit under, but in the design for the modified Genie lift it could be implemented. Since the team can control the thickness of the legs, a pallet-jack type setup was approached. Figure B-21 shows a 3D sketch of the improved design.

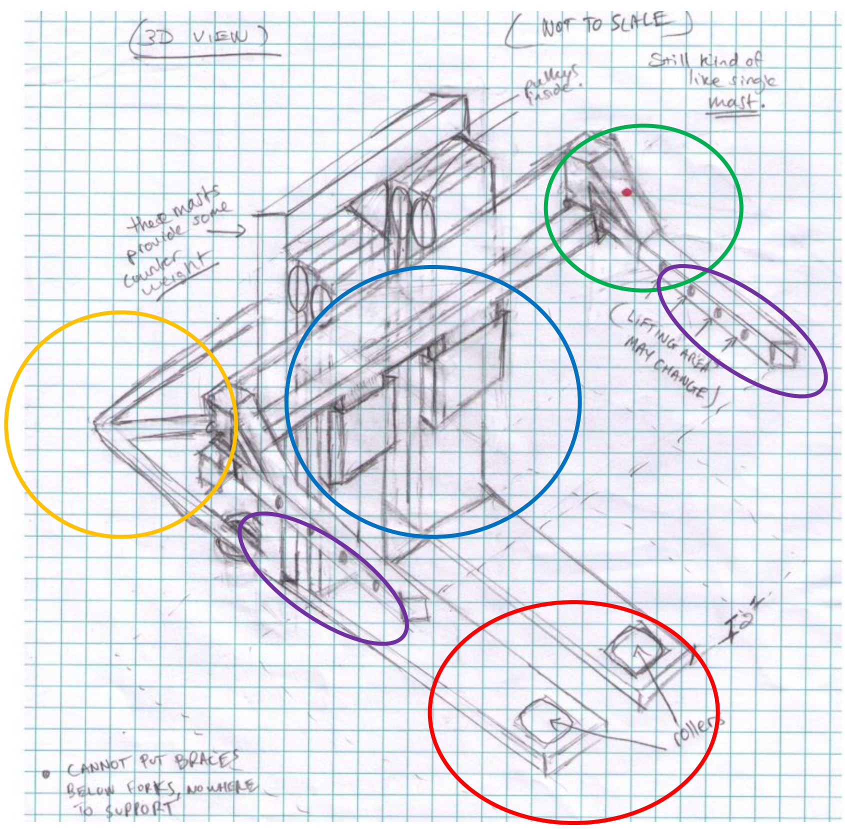


Figure B-21. Modified Genie-lift improved for maximum stability

The red circle shows the location of new legs that are 2 inches thick, with thin rollers so that it can slide under the lower cabinet like a pallet jack. These legs are only for stability and will not lift from this location. The blue circle highlights a double mast design and two easy pockets to hold the fork assembly. The green circle shows a brace built into the corners of the fork to ease the stress concentrated at the corners. The orange circle shows a lighter frame support design on the back due to the higher stability from the front legs. The lifting mechanism uses a telescoping pulley mechanism with a winch to crank it. The purple circle shows the locations of the holes where the fork can connect to the machine top's lifting points.

B.3.2.2 ¾ FRAME IMPROVEMENTS

To improve upon the design the pulley system was revised. To improve stability, the post will have C channels with a slider to prevent lateral movement. A cable is connected to the slider and the cable extends to the top cross bar where it then travels along the frame tubes, turning corners with pulleys. One of the posts is used as a mount for the winch. The cable from the winch is attached to a pulley, where both cables from the sides are connected and wrapped around this pulley. This provides a mechanical advantage for the lift system. The system needs to have 18" of height adjustment to accommodate low ceiling heights. Height adjustability is accomplished with slip-in, 18 inch inserts on the four posts. To improve stability, an x-frame is added on the back, and multiple holes on the post allow for the height inserts be attached with the x-frame. Gussets on the sides across the top or bottom angles were added to increase rigidity. The design will be modular to aid in assembly and portability. The connections will be made is logical locations so that they have a one-way fit. The revised design is illustrated below in Figure B-22.

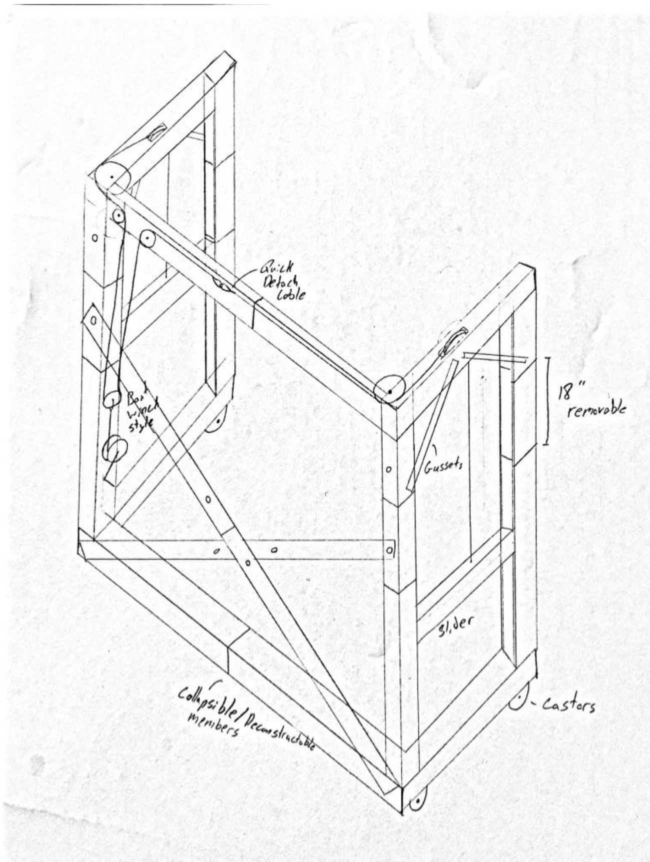


Figure B-22. Revised 3/4 frame

B.3.3 COST ANALYSIS

Our team consulted with a professional tool designer regarding the cost of the top two concepts outline in Section B.3.2. The preliminary cost analysis was conducted based on the information shown in TABLE XXIII.

TABLE XXIII. COST ANALYSIS SUMMARY

#	Cost Criteria	3/4 Frame	Modified Genie
1	Manufacturability	Low cost	High cost
2	Number of the parts that require additional machining	Few parts	More parts
3	Assembly complexity level	Low Complexity	High Complexity
4	Cost Criteria	3/4 Frame	Modified Genie

As shown in TABLE XXIII, the ¾ frame concept will have a lower cost compared to the modified Genie concept. This is since the ¾ frame could use square tubing for the structure which is commonly found in most of the metal supplier. The modified genie uses uncommon materials such as a custom machined mast, shown in Figure B-23, and many other components as well.

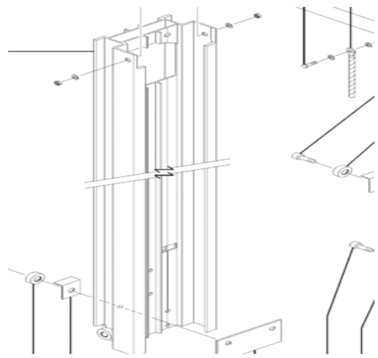


Figure B-23. Custom machined modified Genie parts

The number of custom machined parts indicate that the ¾ frame concept has a lower cost than the modified genie, indicated by the 2nd cost criteria in Table X. Our team also considered the complexity level when the lift is being assembled at the job site based on the need; ease of assembly. The ¾ frame concept has lower cost than the modified genie once again, as the ¾ frame is less complex during the assembly process, which saves the cost of labor during installation of the machine top. In conclusion, the preliminary cost analysis shows that the ¾ frame design concept has lower cost than the modified genie lift design concept.

B.3.4 Concept Scoring

The revised designs were scored to determine which is the most promising and should continue through to the development phase. The scoring criteria was the same as the screening with each criterion having a specific weight associated with it. The categories were weight, manufacturability, portability, ease of assembly/disassembly, simplicity of use, footprint, cost, and reliability. Each design was ranked in each category. The goal of the scoring process was to find the design that was superior, so it can be pursued further and improved.

The scoring process weights each category depending on its importance. To determine each categories importance a weighting matrix was used, where each category was compared one by one to each other. Each is rated based on whether option 1 or 2 is more important. The results are organized in TABLE XXIV, with the amount of hits added up and divided by the number of comparisons to determine the weight of each category.

TABLE XXIV. CRITERIA WEIGHTING MATRIX

	Criteria	Weight A	Manufacturability B	Portability C	Ease of Assembly/Disassebly D	Simplicity of use E	Footprint F	Stability G	Cost H	Reliability I
A	Weight		A	C	D	E	A	G	A	I
B	Manufacturability			C	D	E	B	G	B	I
C	Portability				C	D	C	G	C	I
D	Ease of Assembly/Disassebly					E	D	G	D	I
E	Simplicity of use						E	G	E	I
F	Footprint							G	F	I
G	Stability								G	G
H	Cost									I
I	Reliability									
	Total Hits	3	1	5	5	5	1	8	1	7
	Weightings	0.083	0.028	0.139	0.139	0.139	0.028	0.222	0.028	0.194
	Adjusted weightings	0.08	0.03	0.14	0.15	0.14	0.03	0.2	0.03	0.2
	Total	1								

As it can be seen in TABLE XXV, the selection criteria are in the far-left column while the weightings that were determined in TABLE XXIV are to the right of the selection criteria column. The Genie was included for a reference to see how our top two designs compared to it. If a design rated worse than the Genie, then pursuing that design further would be impractical. The designs were then rated from 1 to 5 with 1 being the lowest rating and 5 being the highest. The rating is multiplied by the weight to determine the weighted score.

The score is totalled, and the highest score is the best design and the candidate for further development. In TABLE XXV the scores of each design are shown.

TABLE XXV. CONCEPT SCORING MATRIX

		A-Genie lift (reference)		B -3/4 frame		C - Modified Genie lift	
Selection Criteria	**Weight**	Rating	Weighted score	Rating	Weighted score	Rating	Weighted score
Weight	0.08	4	0.32	3	0.24	3	0.24
Manufacturability	0.03	3	0.09	5	0.15	3	0.09
Portability	0.14	3	0.42	4	0.56	3	0.42
Ease of Assembly + Disassembly	0.15	4	0.6	3	0.45	4	0.6
Simplicity of use	0.14	2	0.28	5	0.7	5	0.7
Footprint	0.03	5	0.15	3	0.09	4	0.12
Stability	0.2	3	0.6	5	1	4	0.8
Cost	0.03	2	0.06	5	0.15	4	0.12
Reliability	0.2	3	0.6	5	1	4	0.8
	Net	3.12		4.34		3.89	
	Rank	3		1		2	
	Continue?	No		Yes		No	

From TABLE XXV, the 3/4 frame is the superior design with a score of 4.34. The modified Genie lift came in second with a score and 3.89. Lastly the Genie lift scored a 3.12 as a benchmark value.

B.4 FINAL RECOMMENDATIONS

The goal of this project is to design a lifting system that can lift the machine top onto the lower cabinet on site for Conviron. The primary goals are to have the system fit in the back of a pickup truck for transportation, assembly without difficulty, and lift the machine top safely and effectively. The final deliverables for the client are a 3-dimensional model with preliminary technical drawings, a bill of materials, preliminary FEA analysis and a final design report.

From the concepts generated, the most promising design concept has been selected. Various aspects of the design went through an idea generation process and different ideas were brought together to form complete lifting system designs that would best suit the client's needs. All the designs were run through a screening and scoring process, with well-defined criteria based on the client's needs. Select designs that showed advantages were improved upon using information gathering while talking with the client and advisors. A preliminary cost analysis was then performed on these designs concepts and based on our research and analysis, the most promising design is the ¾ frame. It showed great manufacturability, portability, stability of use, and reliability. It also is the most cost-effective solution.

Appendix C Technical Drawings

Technical drawing of all specifically designed parts are located in Appendix C.