Manipulation and Transportation of Gas Turbine Discs

Final Progress Report

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Honor Statement:

By typing my name below and submitting this lab report electronically, we are agreeing to the following honor pledge, which is consistent with the rules described in the syllabus and in class:

We pledge that we have neither given nor received inappropriate aid in preparing this report.

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I. EXECUTIVE SUMMARY

Mitsubishi Hitachi Power Systems (MHPS) produces large turbines which consist of approximately twenty large and heavy discs. These discs require inspection, cleaning, and occasional repairs every ten years. This process requires lifting each disc by crane off of the rotor shaft and onto a pallet to be driven by forklift to the repair/cleaning station. The discs can only be examined and cleaned on one side at a time, so it must be flipped multiple times with cranes. It can take fifteen days for one disc to go through the whole cycle. MHPS would like to make this process more efficient by developing a manual mobile workstation that allows for faster transportation and manipulation of the disc. Prior art search was done into existing solutions such as barrel inverters patents for coil flippers. Codes and standards from NIOSH and OSHA, pertaining to mechanical device safeguards and allowable safe forces that workers can experience when operating a device were also followed. Customer requirements were compiled and correlated with engineering requirements. Engineering specifications were quantitatively determined such as geometric constraints of the workspace and the forces that the solution device would need to withstand. Market research was done to determine who the stakeholders are.

The main function for this project, transporting the discs, was broken down into simpler functions which were put into a morphological chart. The pictographic solutions from the chart were combined in various ways to make five unique designs. These designs were compared against a benchmark and then evaluated quantitatively to determine which would be chosen for further development. The chosen design features a customized pallet with roller wheels to interface with a cart, and shafts to interface with the disc which will result in a modular, scalable, and safe design that performs the desired functions. 3D-CAD models of the cart and the pallet from the chosen design were developed based on ergonomic factors. They were analyzed and adapted with an iterative "simulate and improvise" approach with FEA, optimizing cost and strength of the design until the proof of concept was achieved. A prototype was created based on the BOM and manufacturing processes (primarily welding) outlined in the fabrication package. The prototype was assessed in various ways such as societal and environmental impacts, safety and liability, and patent claims and commercialization. Future steps for this project include testing the prototype with an actual disc, continuing improvement on the prototype, and finally implementing the solution at MHPS.

II. NOMENCLATURE

CAD : Computer Aided Design

BOM : Bill of Materials

FEA : Finite Element Analysis

FOS : Factor of Safety

MHPS : Mitsubishi Hitachi Power Systems, the sponsor of this capstone project

NIOSH : National Institute for Occupational Health and Safety

OSHA : Occupational Health and Safety Administration

A : cross-sectional area for square tubing of the cart's frame

F : total distributed weight of the pallet and disk

I_x : cross-sectional moment of area for square tubing of the cart's frame

R : reaction forces exerted on each wheel of the cart

t : thickness of square tubing of the cart's frame

w : outer width of square tubing of the cart's

III. BODY

A. Introduction and Background

Turbines and compressors are mechanical devices that convert fluid flow into usable energy. They are often very large, and by consequence, very heavy and can consist of many components such as the shaft, blades, discs, etc. Manufacturing, repairing, or simply moving the individual components of these devices can be a task that requires powerful cranes, a lot of manual labor, safety procedures, and a lot of time. MHPS is a supplier of these turbine and compressor parts and would like to optimize this process. This project focuses on moving the discs which can weigh between 2,000 to 8,500 lbs. They must be moved around to various locations within the workspace. Currently, they utilize cranes and forklifts to move the discs, but it can take up to fifteen days to inspect one disc. Therefore, they would like to develop a new system that would free up the cranes and forklifts for other tasks.

The users of this solution will be the workers in the MHPS workspace. Desired product functions include transporting and manipulating the discs for cleaning, repairs, and inspections. Points of interaction include movement of the disc by the workers and inversion of the disc with a device such as a load inverter. This product will be very valuable to the main stakeholder, MHPS, as it will save them a lot of time and money.

Technical issues include mechanics involved with heavy weights, quality material selection with a feasible price, regulatory codes and procedures, and the time frame of one semester. Four preliminary designs were drafted and evaluated based on their ability to meet the specifications, the engineering and customer requirements, and their ability to accomplish their desired functions. A final design utilizing a cart-pallet system was then chosen based on the results of the evaluation. A detailed design of the cart and pallet followed which involved the generation of CAD models and assemblies of the cart and the pallet. Ergonomics were considered to allow comfortable and safe operation of the system. FEA simulations were used to determine the strength of the design which was then optimized through multiple iterations to achieve a lighter, cheaper, and stronger final product. After proof of concept was achieved, a prototype was manufactured according to a fabrication package and BOM given to MHPS. The prototype was assessed in various ways such as societal and environmental impacts, safety and liability, and patent claims and commercialization. Future steps for this project include testing the prototype with an actual disc, continuously improving the prototype, and finally implementing the solution at MHPS, resulting in large cost savings due to major process efficiency improvement.

B. Existing Products, Prior Art and Applicable Patents

In order to gain a better understanding of the design objective, a prior art search was performed to identify how similar problems have been solved in other situations. The first subject of the prior art search was to determine alternatives to moving heavy objects without the use of a forklift. Minimizing the use of forklifts in industrial environments is not uncommon, as operating a forklift can be dangerous and costly in terms of time and money. One common alternative to forklifts is using a simple cart to move objects. Depending on the weight of the load, how far it travels, and the frequency that it has to be moved, the cart can be pushed by hand; as long as the user can sustain a force that can overcome the frictional forces between the wheels and the surface of the floor, the weight of the load itself is not a problem. Carts can also be linked together in order to move multiple objects at once, but they lack the verticality of a forklift. Another alternative to forklifts is to implement a conveyor system to move the objects. Like carts, conveyors can either be powered by a motor or not powered at all, as with rolling conveyors found at airport security gates. Conveyors can move as many objects as can fit on the system, but the path which the object follows is limited to where there are conveyors built.

Additionally, MHPS also included a secondary objective identify a new way to invert the discs during maintenance. Currently, MHPS uses a tandem lift method to invert the discs, where two cranes are used simultaneously to manipulate the disc orientation until it is inverted. This method is both time and resource consuming, as it requires multiple workers to reorient the discs and control the cranes. On the market currently, there are load inverters that are able to invert items 180 degrees. Firstly, an object is placed inside the inverter, where it is hydraulically clamped in order to secure it during inversion. Next, a motor drives the inverter to rotate 180 degrees along with the object inside of it. Lastly, the hydraulics are released, allowing the object to be transported away. The inverter can be customized to fit any necessary specifications and is currently used for loads ranging from barrels to steel blanks. This device is appealing to us because it can easily interface with the disc and takes less resources to operate than the cranes.

A patent search was also performed to identify similar concepts to the one presented in the design objective. A patent was filed in 1977 by Morgan Construction Co. for a flipping mechanism used in inspecting metal coils formed from rolling mills. Patent US4013177A [1] describes the use of a motorized inverter to flip the metal coil such that both sides of the coil can be accessed and inspected. The concept for the device was similar to the load inverter, with a conveyor to feed the coils into the inverter where they could be flipped and later transported away. However, the patent expired in 1994, so designs and mechanism similar to the ones described in the patent can be used without the fear of patent infringement.

C. Codes and Standards

The main design aims to reduce the number of powered components required in the machinery by replacing such components with manual power supplied by the operator, such as pushing. While this reduces the complexity of operation and safety risks, there still remain some safety standards which must be followed. The process begins with cranes which will be used to load the discs onto the pallets. All cranes must have adjustable booms with boom angle indicators. A load rating chart should be provided in the cab of each crane for the operator [2]. The weight of the loads that the cranes will be moving reach several thousand pounds. Once on the pallet jack, these loads will be pushed around. While OSHA does not have a set limit for the maximum pushing/pulling force, they recommend no force greater than 50 lbs (about 222 N). When possible, the operator should push, not pull, the load. Pallet jacks with appropriate handles that can accommodate the entire hand are also needed. These handles should extend up to the power zone, which is the region of the body between mid-thighs and mid-chest [3]. The wheels of the pallet jack must be well-aligned and suitable for the environment. Pneumatic tires are better for uneven terrains. The operator must take care to not exceed the maximum supported limit of the pallet jack. This maximum limit must be clearly marked on the pallet jack [4]. It must also have brakes that allow for a quick stop in case of emergencies and to prevent pulling to stop by the operator. The inverter must have a safeguard against any rotating parts [5]. All possible contact points with any dangerous moving parts must be covered. The safeguard must not be easily tampered with and it should not create its own hazards. It should still allow easy operation of the machine to not encourage the operator to bypass it. Like the pallet jack, the maximum load that the machine can support should be clearly marked, and the operator must make sure to not exceed it. Warning signs must be visible so that the user can take caution during operation. The load must also be safely secured during the flipping stage. The operator should not have to apply more than 50 lbs. of force to rotate the load.

D. Customer Requirements and Engineering Design Specifications

It is important to define which entities have the most interest and power in this project. There are four main groups as depicted in the stakeholder matrix seen in Figure 1. Team *Rotordynamics* has the most power because they can change anything in the design and the most interest because they are being evaluated as engineers. MHPS management has the most influence because Team *Rotordynamics* is designing the project to benefit their daily operations. The workers can also be considered stakeholders because they will use the chosen concept when completed and it could impact the number of workers needed to perform various tasks. Finally, the material suppliers have very small power or interest, but they are still stakeholders because the design will be influenced by available standardized parts and they will make a profit off the building of the design.

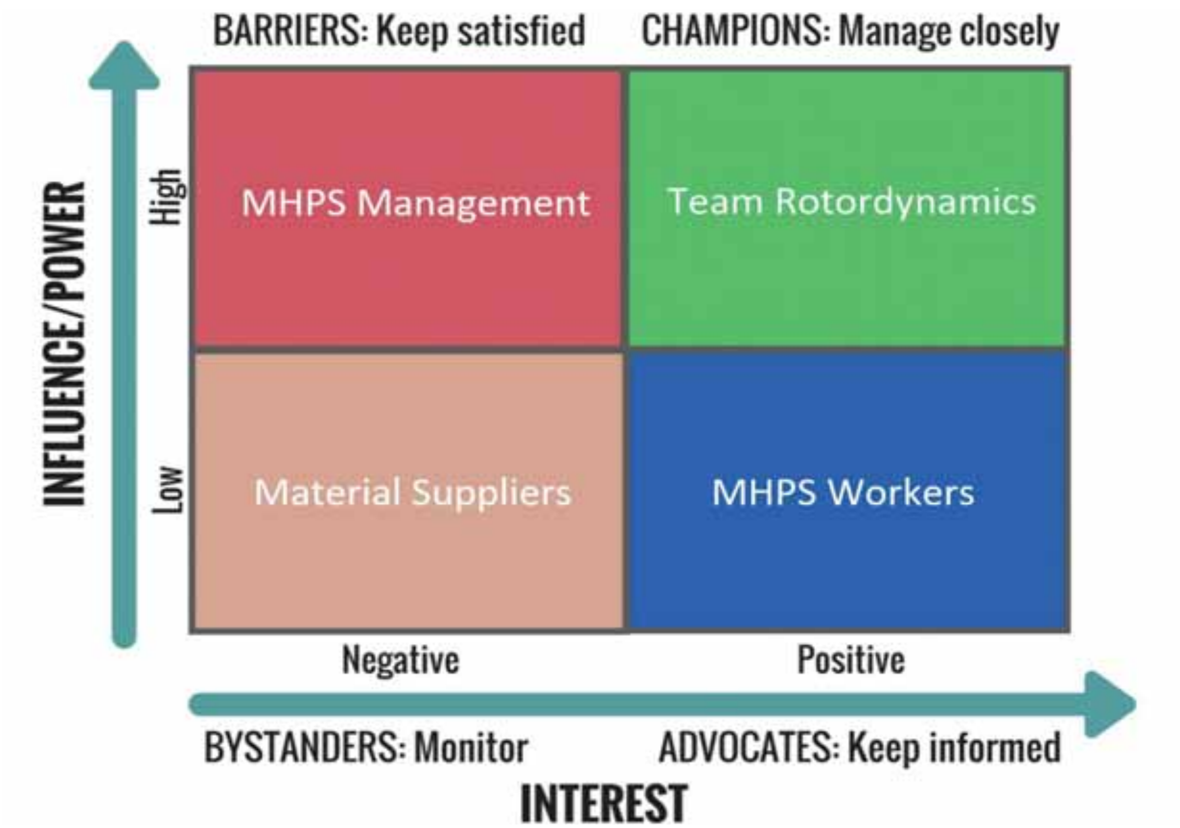


Figure 1. 2x2 Stakeholder Matrix

Because MHPS is the primary stakeholder other than Team *Rotordynamics*, requirements and specifications were compiled to satisfy their needs. For any future design to be considered worthwhile, it must conform to these constraints and must beat the original method of disc manipulation. The constraints are compiled and summarized in Table 1. Specifications such as material strength, force capability, and successful transportation will require the most attention as they are fundamental to producing a product that will satisfy the customer's specifications. A successful design will need to incorporate material that can maintain 99% stiffness after 1000 cycles, be capable of producing enough force to manipulate 3833 kg of mass and be able to transport product around the facility while traversing floor gaps up to 2" in width. With these metrics, the design team has a better way to judge design alternatives during the ideation process.

Table 1. Specification sheet showing the constraints of the product

D/W	Requirement	Responsibility	Source
D	Transport and manipulate compressor and turbine discs ranging from 946 to 3833 kg without use of crane or forklift	Design Team	MHPS
	Geometry		
D	Height of loaded cart < 3.5'	Design Team	Standard
D	Width < 10''	Design Team	MHPS
	Energy		
W	Consume 0 watts of electrical energy (I.E. manual operation)	Design Team	MHPS
	Safety		
D	Machine guard >1' from machine nip points and rotating parts	Design Team	OSHA
	Operation		
D	Transportation device can be pushed and steered by 1 person	Design Team	MHPS
W	Flipping device can be hand-operated by 1-2 people	Design Team	MHPS
D	Cycle length < 15 days	Design Team	MHPS
	Kinematics		

D	Movement speed under 4 km/h	Design Team	Standard
D	Flipping speed < 3 deg/s	Design Team	Standard
	Materials		
D	99% Stiffness after 1000 cycles	Design Team	Standard
	Ergonomics		
W	Comfortable to operate for >12hr	Design Team	Standard
	Assembly		
D	Assemble-able in MHPS SMW facilities	Design Team	MHPS
	Schedule		
D	Assembly completed before December 2nd	Design Team	Capstone
	Forces		
D	Manipulate payloads: 946 kg - 3833 kg	Design Team	MHPS
	Signals		
D	Signals visible or audible from >10'	Design Team	OSHA
	Maintenance		
W	Survive >1000 cycles	Design Team	Standard
D	Prevent ingress of 100 µm particles	Design Team	Standard
	Transport		
D	Traverse floor gaps of depth 1.5" and width 2"	Design Team	MHPS

The customer requirements of MHPS and the engineering requirements to accomplish the task were put into a House of Quality, which can be seen in Figure 2. The most important customer requirements in red, as per the given weights in the left column, were transportation of turbine and compressor discs without cranes/forklifts, accommodation of ‘F’ and ‘G’ class rotors, scalability, and NIOSH compliancy. Weak and strong correlations were determined between the customer and engineering requirements to decide what should be focused on the most while making the design. For example, transportation of the disc was determined to have a strong correlation with the number of functional subsystems in column 3. Accommodation of ‘F’ and ‘G’ class discs was determined to have a moderate correlation with energy management. Scalability was determined to have a weak correlation with programming and controls, and NIOSH compliancy was determined to have a strong correlation with safety indicators. The relative weights of importance for the engineering requirements in the bottom row can show that energy management, assembly time, and frictional losses were of key consideration in this design process.

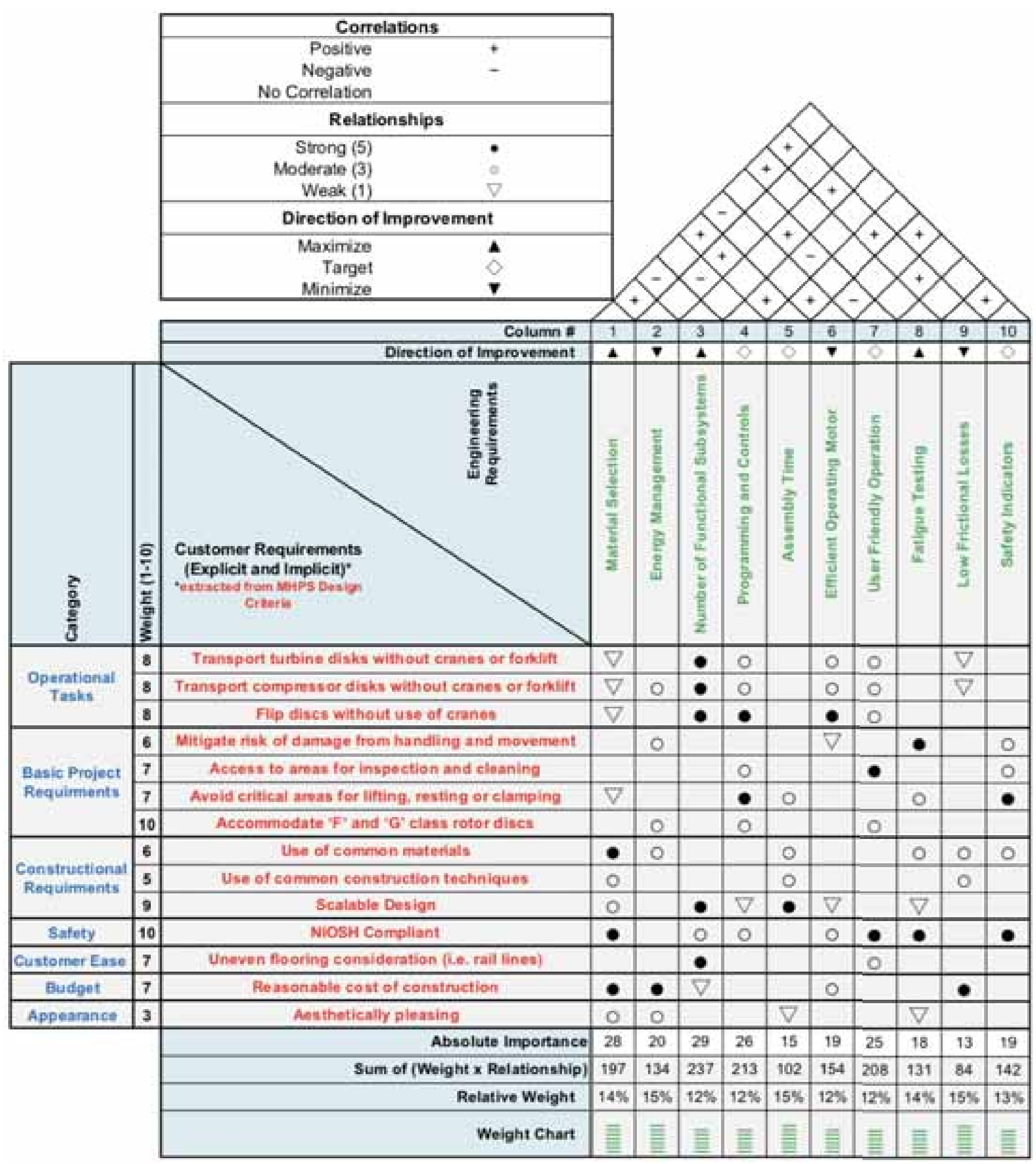


Figure 2. House of Quality

E. Market Research

As the proposed design has been created to solve a company-specific problem, the marketing of this exact product is not completely feasible. In general, the concept of transporting and manipulating large disc-like objects may be useful for various manufacturing industries. Manufacturers specializing in products such as mattresses, aerospace wing components (i.e. ailerons, edge slats, etc.), or competitor turbine rotors may find benefits of this elected design within their daily operations; however, in order for this design to be accommodating to other products, constraints such as critical dimensions, material selection, and level of operator expertise would have to be considered and likely re-evaluated. The specificity associated with this elected design significantly reduces the scope of compatible products, and as an alternative means of manipulating and transporting similar generic products currently exist on the market, the investment of overhauling the design for the sake of being more versatile does not prove worthwhile. Furthermore, MHPS has elected to keep proprietary rights of this design and does not intend to replicate variations for alternative industries or competitor usage. Based on these considerations and identification of the sole customer of this product, market research beyond the preliminary design phase should not be required.

F. Design Concept Ideation

After developing a full scope of the project's specifications and requirements, a function to form design analysis took place. Transporting the discs was determined to be the main function of the system and is seen on the far-left side of Figure 3. This general function was broken into sub-functions which would prove necessary to accomplish the overall task. It was decided that manipulating the disc, moving the disc, interfacing with an operator, and managing the power of some mechanism yet to be defined would be vital. These sub-functions, although more specific, had yet to convey what the most basic functionality of the mechanism would be. Therefore, they were broken down further into sub-sub-functionalities: flip disc, control orientation, lift disc, move disc on to cart, drive through factory, grab disc, control driving, control disc manipulation, charge battery, and power components.

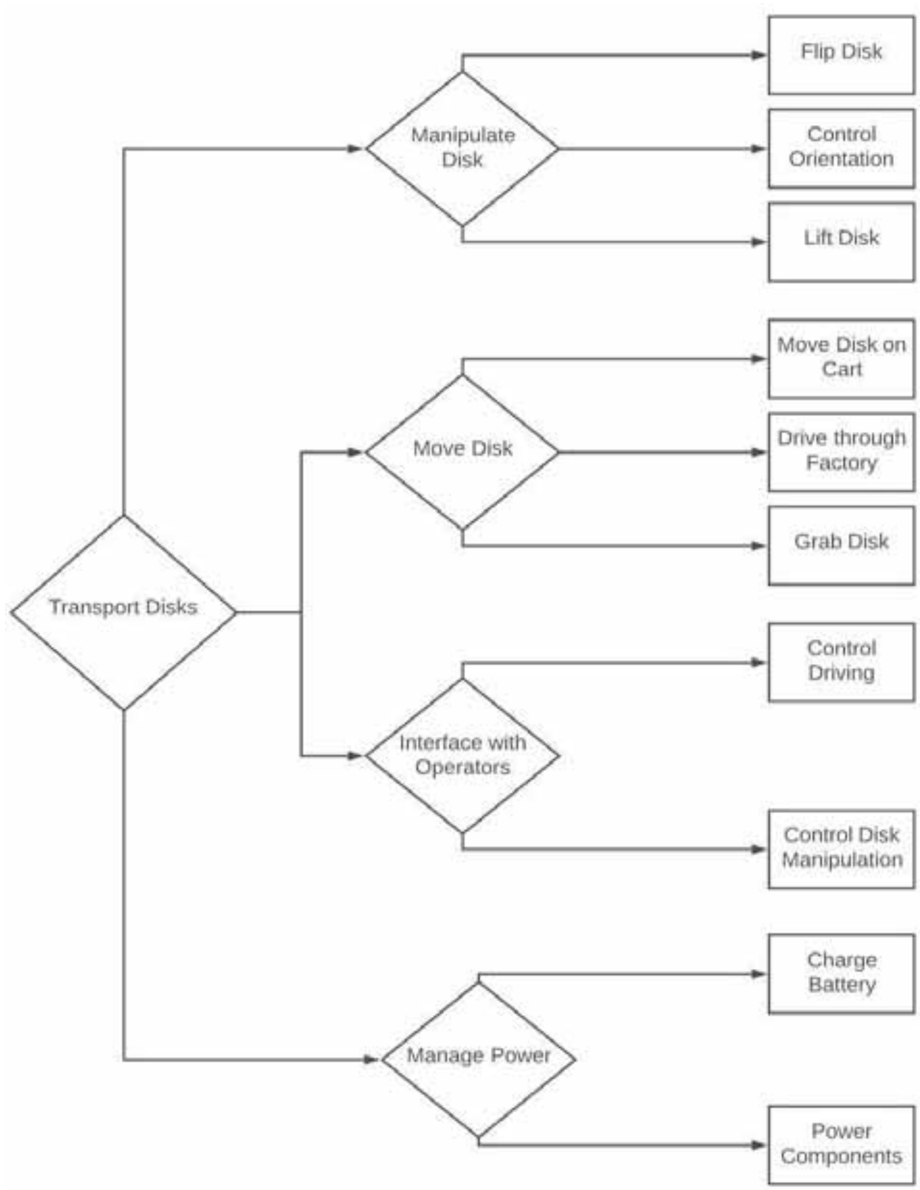


Figure 3. Function tree for the main functions of the system

After determining the most basic functions, a morphological chart was made, shown in Figure 4. This chart shows different ways to achieve the desired functionalities with simple pictographic symbols. For example, control orientation could be accomplished with a DC motor, and drive through factory could be accomplished with a control stick, etc. After brainstorming ways of accomplishing simple functions, these ideas were formed together into actual preliminary designs. The morphological chart's cells will be referenced by row (m) and column (n) from now as Figure 4 (m,n) to explain how the designs were made.

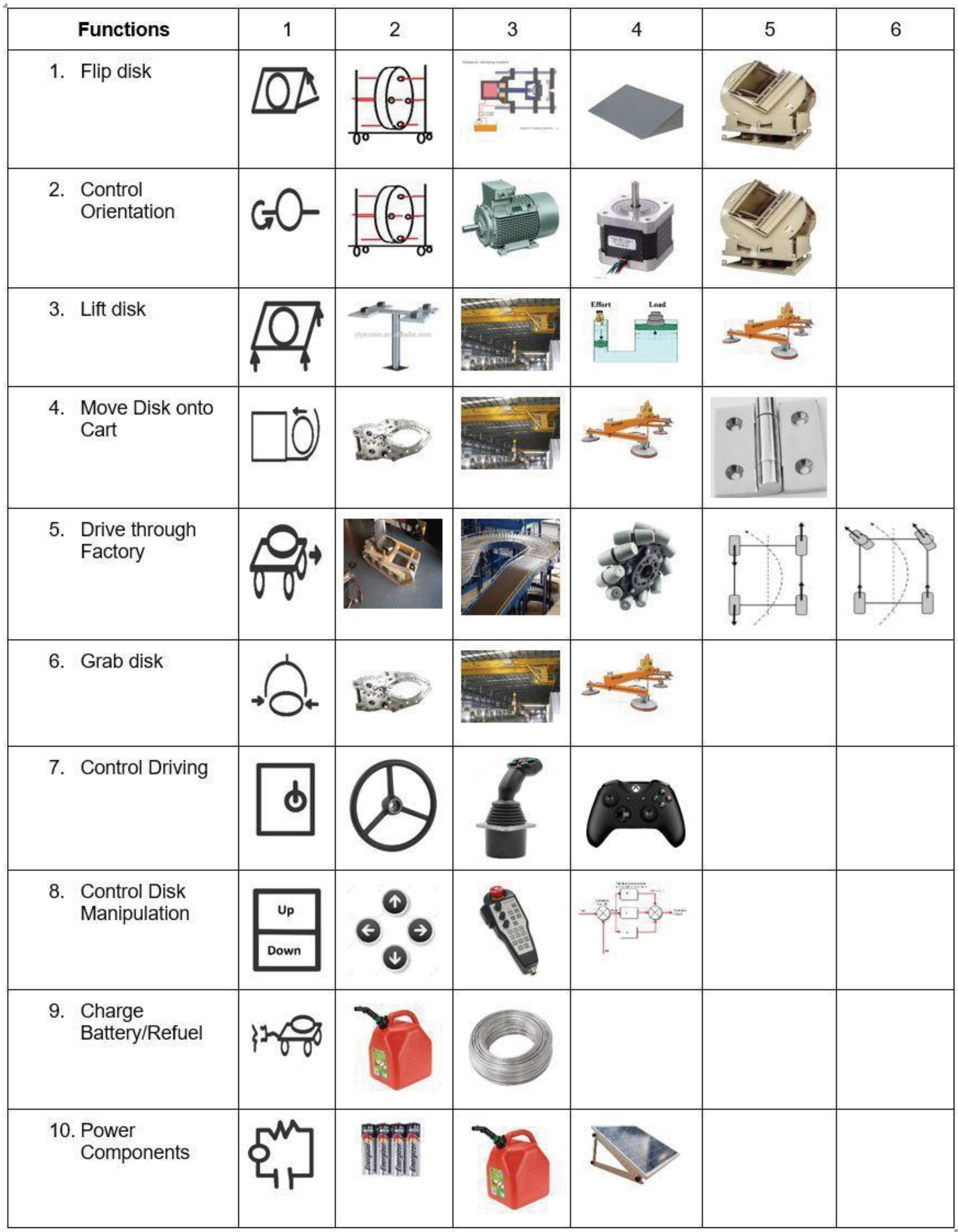


Figure 4. Morphological chart

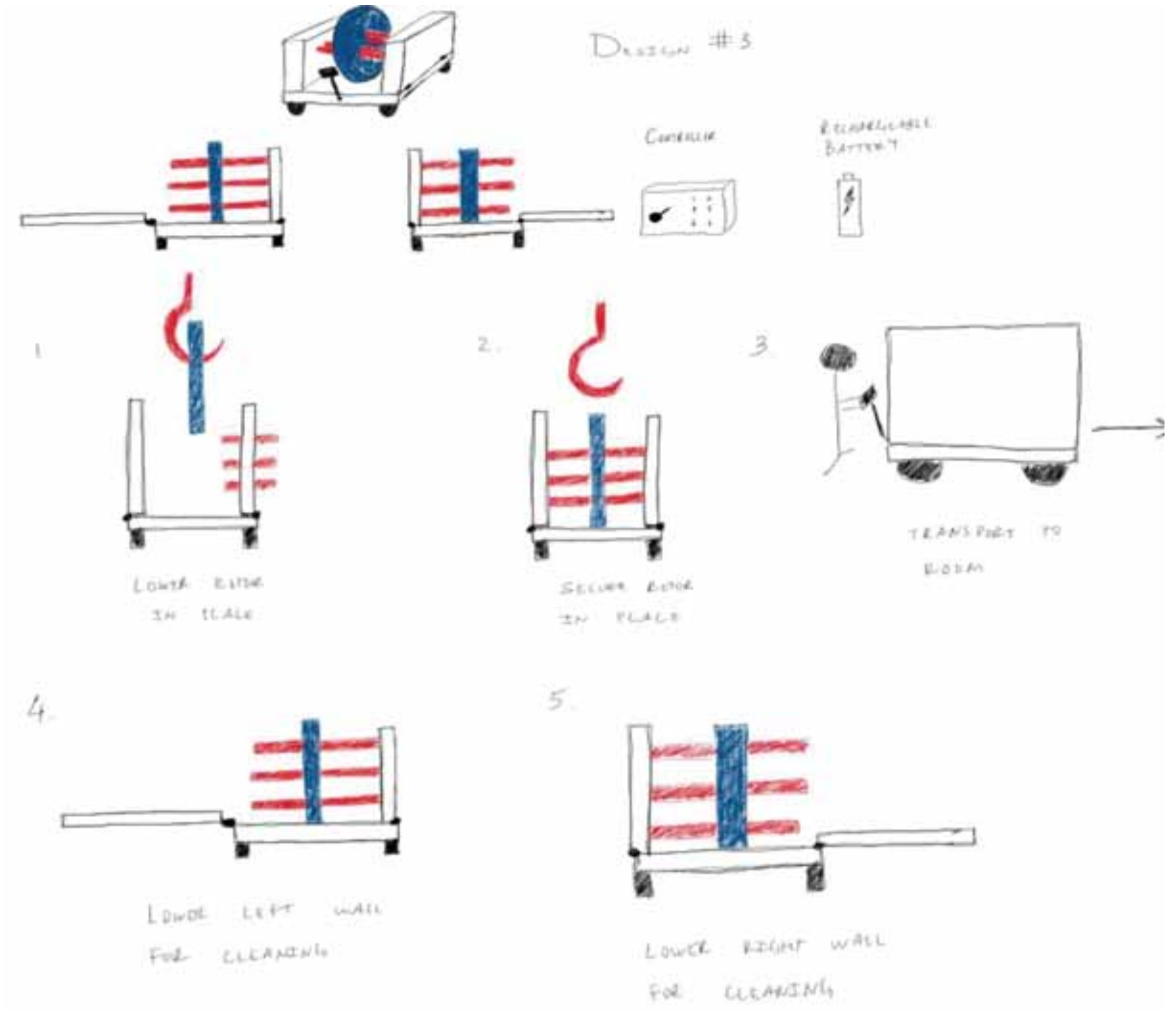


Figure 5. First conceptual design

First conceptual design, featured in Figure 5, is a dedicated cart system which uses hinges to lower the panels on the side to allow the disc to be moved onto the cart (Figure 4 (4,5)). It also uses a crane end piece to grab and lower the disc to the cart (Figure 4 (6,2)) along with cylindrical holders that go through the spindle bolt holes to enable control of orientation (Figure 4 (2,2)). It also features a controller interface to manually control the device (Figure 4 (7,1)). The main benefit of this design is that the disc can be worked on from both sides thanks to the panels, and the drawback is that the cylindrical holders could be difficult to adjust to varying sizes of discs.

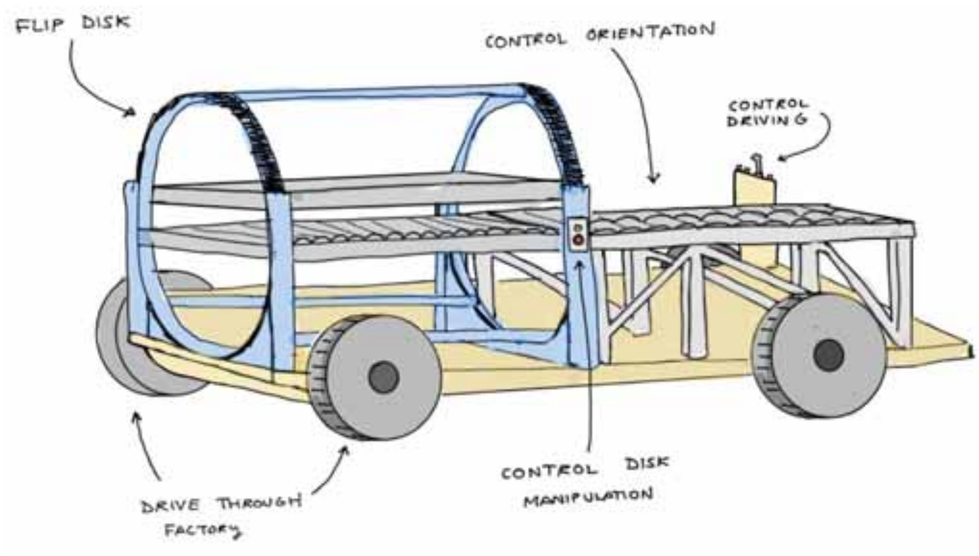


Figure 6. Second conceptual design

Second conceptual design, featured in Figure 6, is a dedicated cart system which uses a barrel inverter to flip the discs, (Figure 4 (1,5)). This cart also uses skid steering functionality to drive through the workspace (Figure 4 (5,6)) which allows the cart to turn its wheels independently from the driving forward. It also features an ergonomic green, red button system based on (Figure 4 (8,1)) to manipulate the position of the disc as well as a control stick (Figure 4 (7,3)) to drive the device. The main benefit of this design is that appears light weight, yet it has all the functionality tightly blended together. The drawback is that with everything so compact, it might be difficult to use for an operator especially moving from place to place within the factory.

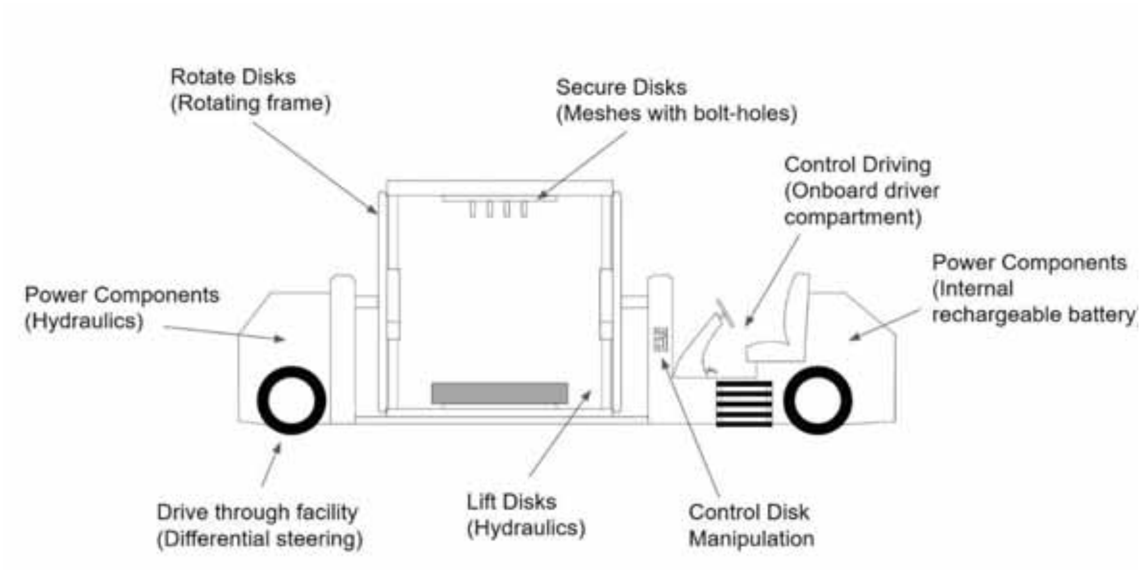


Figure 7. Third conceptual design

Third conceptual design, featured in Figure 7, is a variation of a forklift that uses prongs from (Figure 4 (1,2)) to insert into the spindle bolt holes of the disc and flip the disc within the chamber in the center. While concurrently using hydraulics from (Figure 4 (3,1)) to lift the disc. This device would be powered internally with rechargeable batteries (Figure 4 (10,2)) and it would use Differential steering to drive through the factory safely (Figure 4 (5,5)). The benefit to this design is that it seems high tech and robust. The drawback is that bringing the disc within the center area blocks off a lot of the disc from being cleaned.

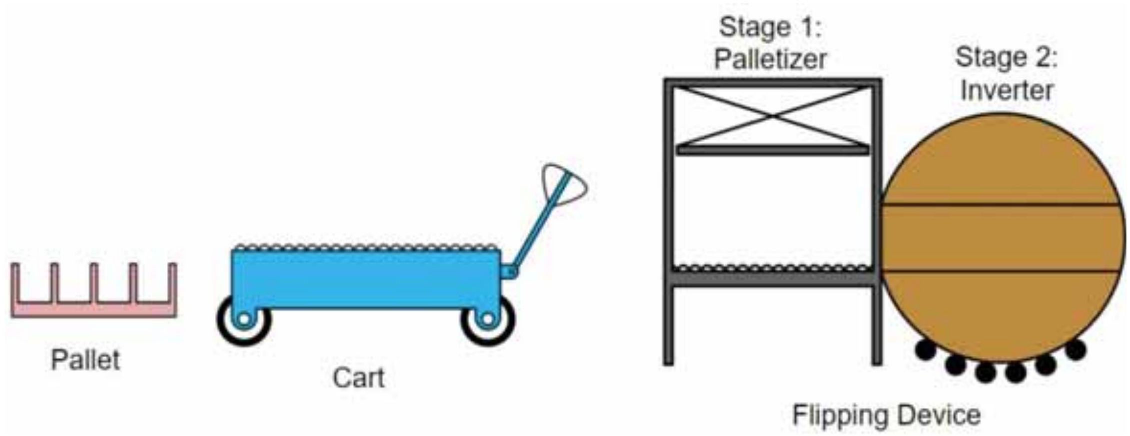
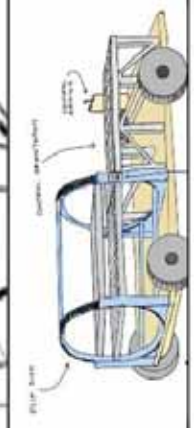
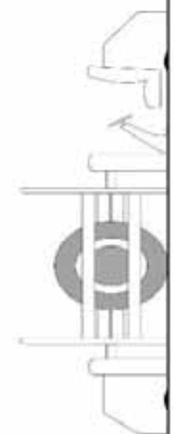
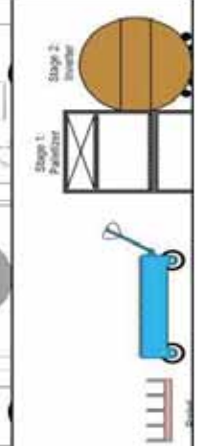


Figure 8. Fourth conceptual design

Lastly, fourth conceptual design, featured in Figure 8, takes on a slightly different approach in that it separates the functions into more independent mechanisms. The pallet uses shafts to enable the disc to be oriented (Figure 4 (2,2)). The pallet, with a disc, is then placed on the cart by crane and pushed through the factory (Figure 4 (5,1)). Inspection and repairs can be made. Then it uses rollers on top of the cart to slide the pallet into a stage one palletizer where another top pallet is placed on-top. This is necessary to grab the disc from both sides inside the inverter (Figure 4 (1,5)) where the disc is flipped by using a control switch (Figure 4 (8,3)). The main benefit of this design is that while one disc is being flipped, the cart can be used to carry another disc over. The drawback of this design is that there are many steps involved.

G. Preliminary Concept Selection and Justification

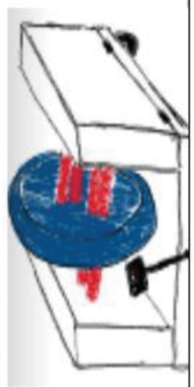
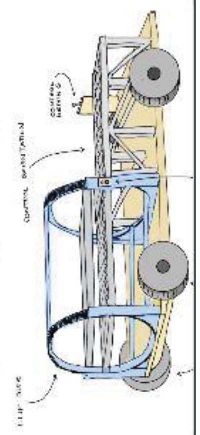
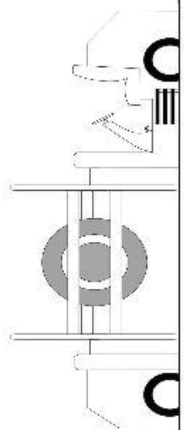
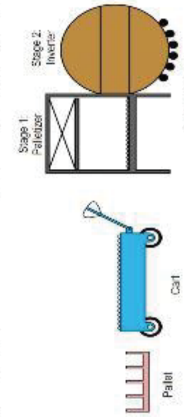
The designs resulting from the morphological chart were evaluated and compared. The four designs were compared to a benchmark using the comparison matrix in Figure 9. The benchmark pictured represents the current process being used by MHPS which is done solely by cranes and forklifts. The other three designs were given either a "+", "-", or "s", to show that it was decided that it was either better, worse, or the same as the benchmark in a particular category. For example, all the designs were considered better at manipulating and moving the discs, because they were designed with those requirements in mind. Design one (column 2) was determined to be worse ergonomically because it would require the operator to walk around with the cart to operate it and the controls are not as user friendly as the benchmark. In contrast, design three (column 4) was determined to be more ergonomic than the benchmark because the operator can sit in a comfortable chair and not have to change from forklift to crane while still being able to do all the desired functions. Assembly time is also a huge requirement because the project must be complete before December 2nd. Design two (column 3) could be built easily because all the parts are easy to see, and it is not overly technically complicated compared to the benchmark. In contrast, design three (column 4) would be difficult to build with a full computer operating system that would be more complicated to use compared to the benchmark, because it is essentially the controls for a forklift and a crane all at once. Another requirement is power management as MHPS would ideally like to move away from motorized vehicles. Design 4 (column 5) is much better than the benchmark at power management because it has no motors and is operated by hand. In comparison, design 3 (column 4) has to have its battery charged frequently.

Concepts	1	2	3	4	5
					
Manipulates Disk	B	+	+	+	+
Moves Disk	E	+	+	+	+
Ergonomics	N	-	s	+	-
Manage Power	C	+	s	-	+
Safety Assurance	H	-	s	+	s
Assembly Time	M	+	+	-	+
Price Value Ratio	A	+	+	s	+
Maintenance	R	-	+	s	+
Throughput	K	+	+	+	+

Key: + = Better than Datum, - = Worse than Datum, s = Same as Datum

Figure 9. Comparison matrix of conceptual designs against benchmark

The first comparison matrix brought up some major considerations about the complexity of designs and pointed toward the fourth design (column 5) as being possibly better than the rest. Therefore, a secondary comparison matrix, seen in Figure 10, was made to compare the four designs quantitatively and ultimately come to a conclusion. The numbering system used is defined as 4 being very good and 1 being just barely tolerable. For example, design four (column 5) had a 4 in managing power because only the inverter might need to be powered for being able to grab the disc with hydraulics to flip it. The fourth design's assembly time would also be better than most others giving it a 3 because it is simple components that would need to be built. The throughput category is where design 4 is simply the best because this design has different separated components. This allows for the disc to be moved by the cart, and then while the disc is being inverted, the cart can be utilized to move another disc or be used for a different task elsewhere. The results from this matrix calculated a relative total higher for design four (column 1) which led us to choose the fourth conceptual design as the primary design for the project.

Concepts	1	2	3	4	5
					
Manipulates Disk	2	4	4	4	4
Moves Disk	2	4	4	4	4
Ergonomics	4	2	3	4	3
Manage Power	2	4	3	1	4
Safety Assurance	4	2	2	3	3
Assembly Time	2	2	3	1	3
Price Value Ratio	2	2	3	2	4
Maintenance	2	2	3	3	4
Throughput	2	3	3	3	4
Total	22	25	28	25	33
Relative Total	.17	.19	.21	.19	.24

Key: 4 = Very Good, 3 = Good, 2 = Satisfactory, 1 = Tolerable

Figure 10. Comparison matrix for the four conceptual designs

However, despite the fourth conceptual design being chosen as the best solution, there still remain some foreseeable problems that have to be considered in further analysis. The first is the use of the cart for other operations for which it is not intended. MHPS wants this product to be solely for the transportation and manipulation of turbine discs, so the design should prevent it from being moved to other parts of the factory for unintended uses. Another issue is the weight of the loads. These discs can reach up to 8000 lbs., and this is not an easy weight for a worker to push. The design must lessen the effect of the load on the worker. A third potential problem is human error. The design must be very user-friendly so as to prevent any mistakes by the workers, such as misaligning the disc in the inverter which might damage it. It should be very clear how the disc should be aligned on the pallet, how the pallet should be placed on the cart, how the cart should be operated, etc.

Upon a detailed discussion with the main stakeholder, MHPS, it was decided to narrow the scope of the design project to the cart and the pallet, which was more appropriate for a 15-week semester. Concept 4 would remain the same, but the inverter would not be designed as commercial ones are readily available. Upon conducting research about feasible inverters in the market, a commercial inverter by Bushman Equipment Inc. was found suitable. The details of this inverter are summarized in Appendix C. The cart and pallet, however, would be designed while keeping in mind that the system may need to interface with an inverter in the future. After this was settled, detailed 3D CAD design of concept 4 was generated.

Figure 11 shows the CAD of the pallet. It features eight Delrin oil and abrasion resistant hard rubber pad for the discs to rest on without damaging the pallet or the disc. There are two shafts which go through the spindle bolt holes of the disc to support it during inversion as well as to keep it aligned on the pallet. The pallet has V-groove wheels which allow for self-alignment on its corresponding tracks due to gravity. The universal contact point for all discs in the scope of the project is shown in red. There are ergonomic decals for workers to interface properly, intuitively, and safely with the pallet.

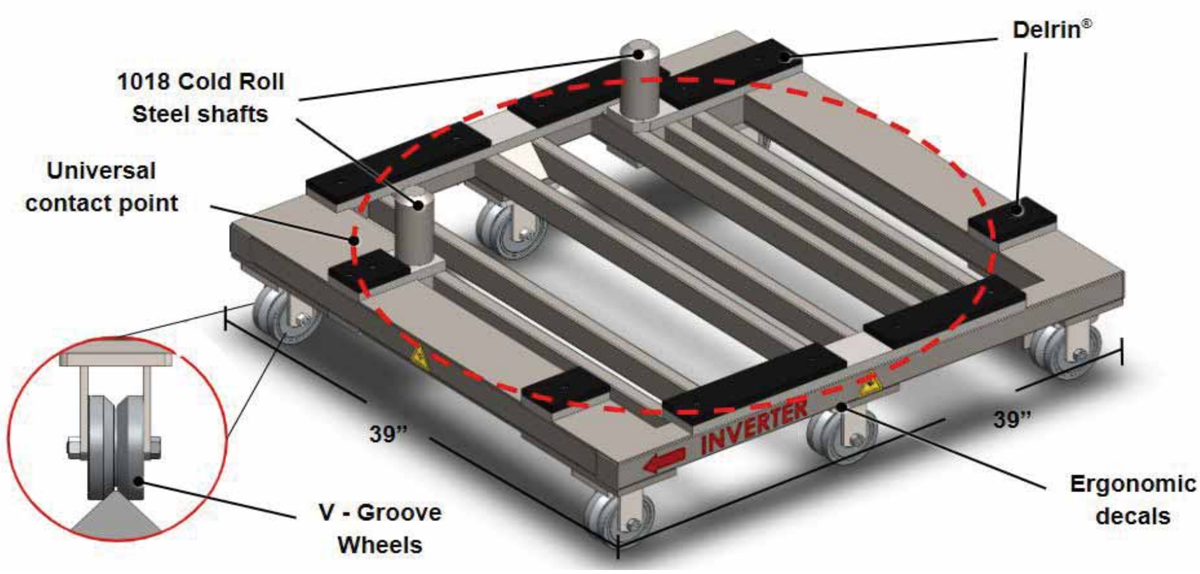


Figure 11. Pallet

Figure 12 shows what it will look like when a disc is lowered onto the pallet and then put into the inverter. The inverter will lower another pallet down into essentially a disc sandwich. It will be locked into place and flipped over its central axis.

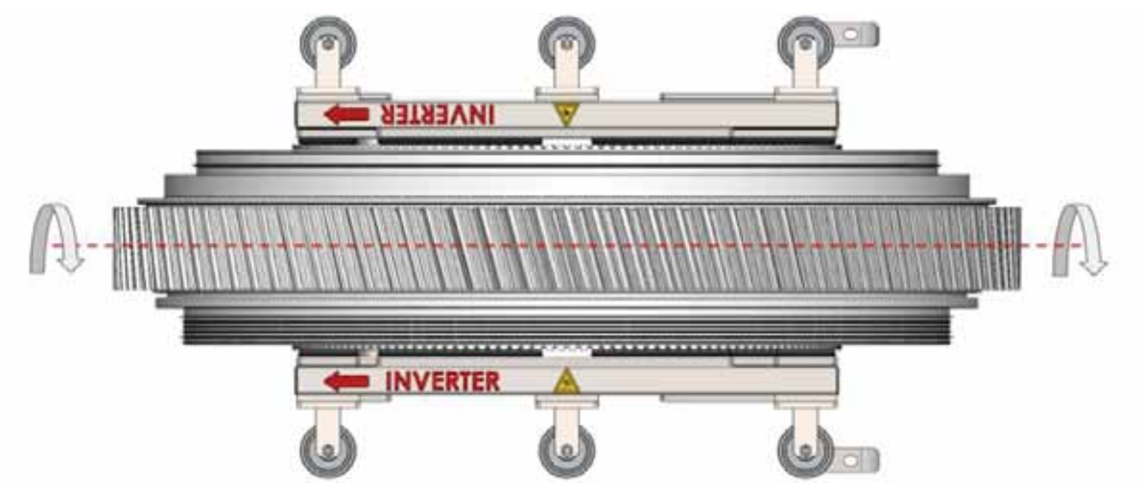


Figure 12. Disc sandwiched for inverter

The structure of the pallet in Figure 13 is made of steel in a way that will hold all the various sizes of discs in the horizontal position as well as the vertical during inversion.

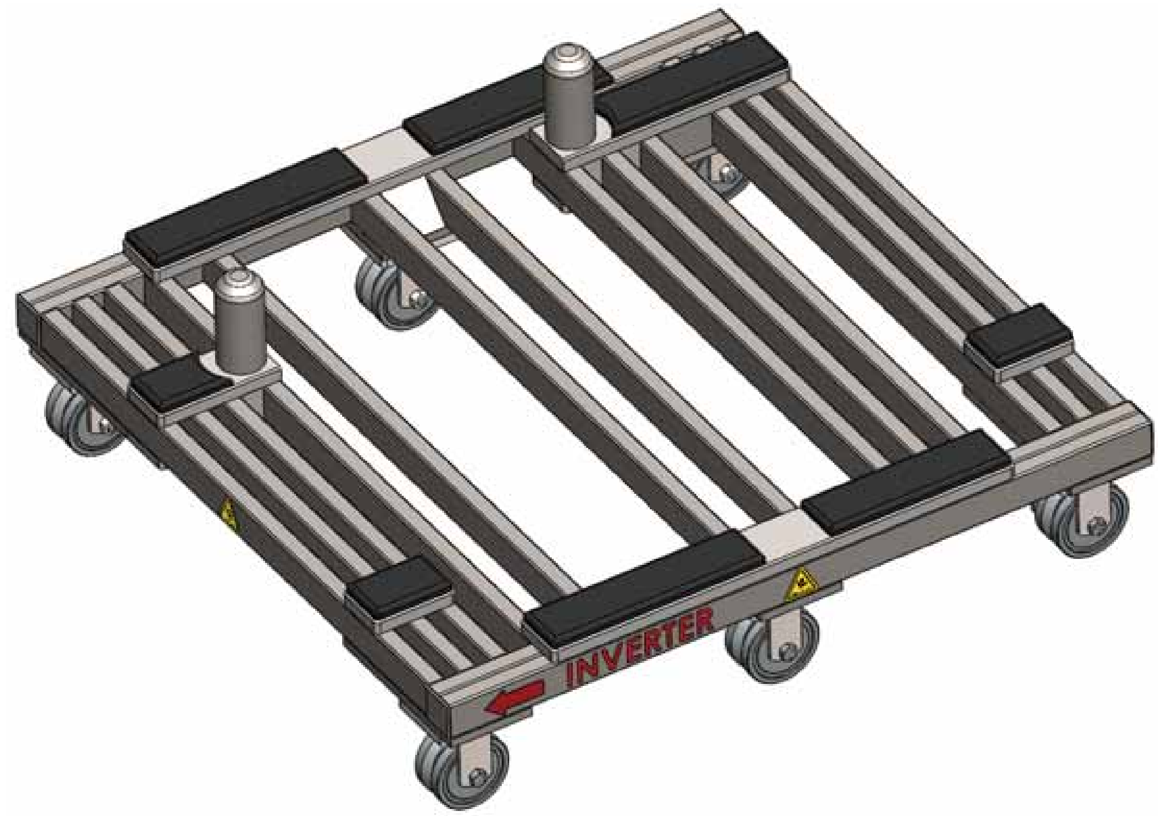


Figure 13. Pallet structure

The V-groove rollers interface with the cart (Figure 14), which allows the grit to flow off the sides instead of building up during the cleaning process of grit blasting.

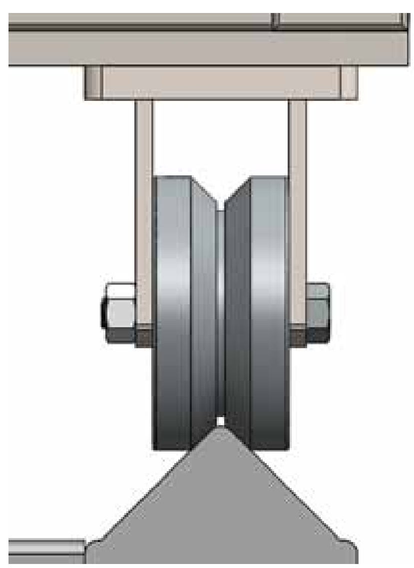


Figure 14. Pallet v-groove rollers

The cart, seen in Figure 15, can be broken into two significant assemblies: the frame and the steering mechanism. The frame is composed of rectangular low-carbon steel tubes that are welded together at the seams. Two rails run along the length of the frame. The majority of the surface of the cart is left open, which helps to prevent the cart from being used for anything other than transporting the pallets and discs. Efforts were taken to minimize the number of interior corners, since these are places where grit can collect. All interior corners are easily accessible, so that any accumulated grit can be air-blasted out. Also, all of the bearings in the cart are permanently lubricated and sealed to prevent grit ingress. The cart also features a pallet jack handle connected to a fifth wheel steering subassembly with a spring return feature.

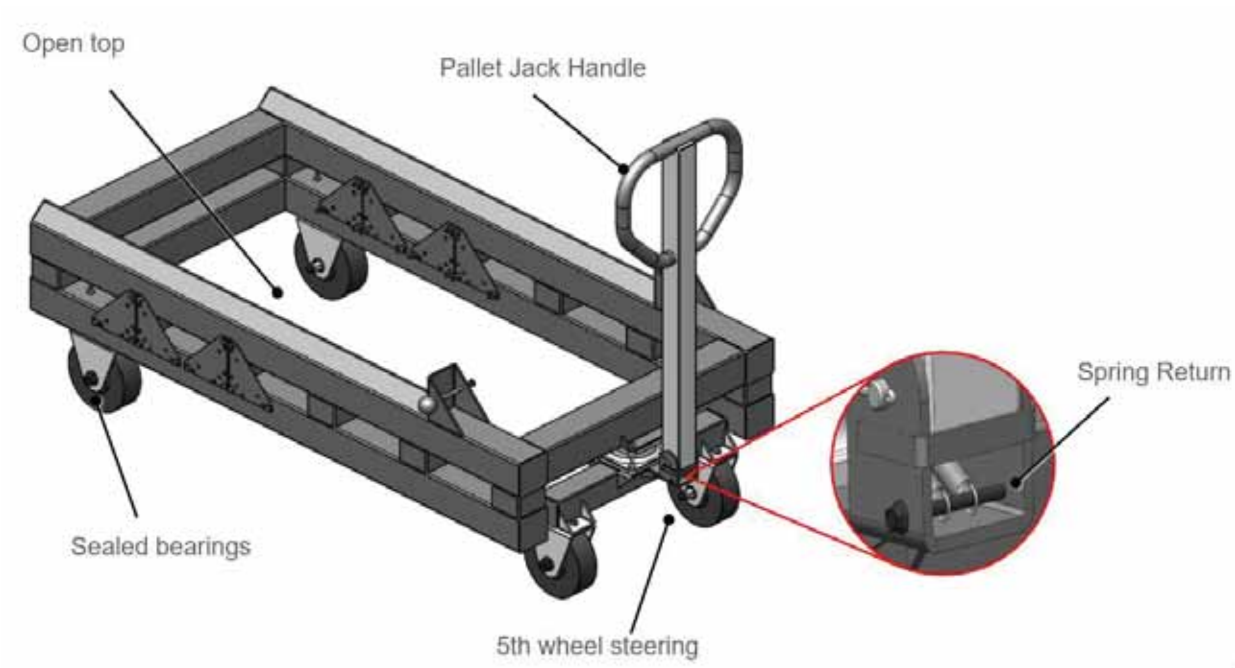


Figure 15. Cart

The steering mechanism subassembly (Figure 16) handle can rotate between upright and 45-degree positions, allowing for the user to use their preferred stance when pushing or pulling the cart. The extension spring located at the base of the handle that helps it return to an upright position when released by the user, and the high-capacity nylon wheels are lighter than traditional iron or steel wheels, while still maintaining abrasion resistance and high traction.

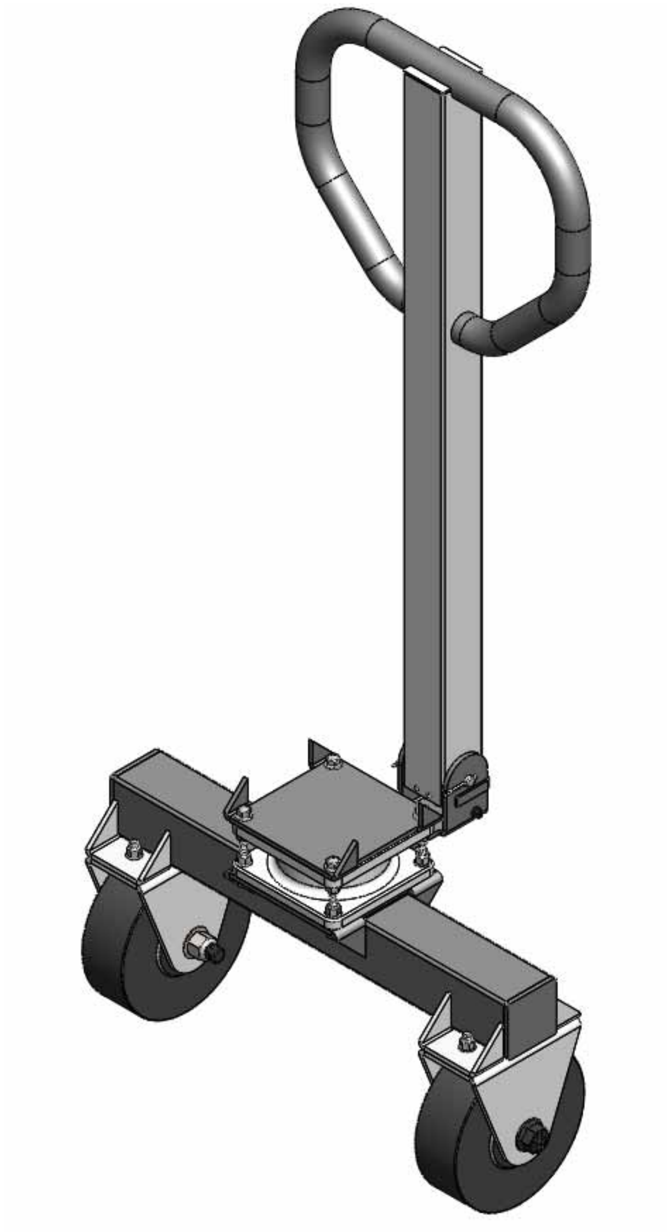


Figure 16. Cart steering handle

Figures 17 and 18 show the final assembly without and with a disc, respectively.

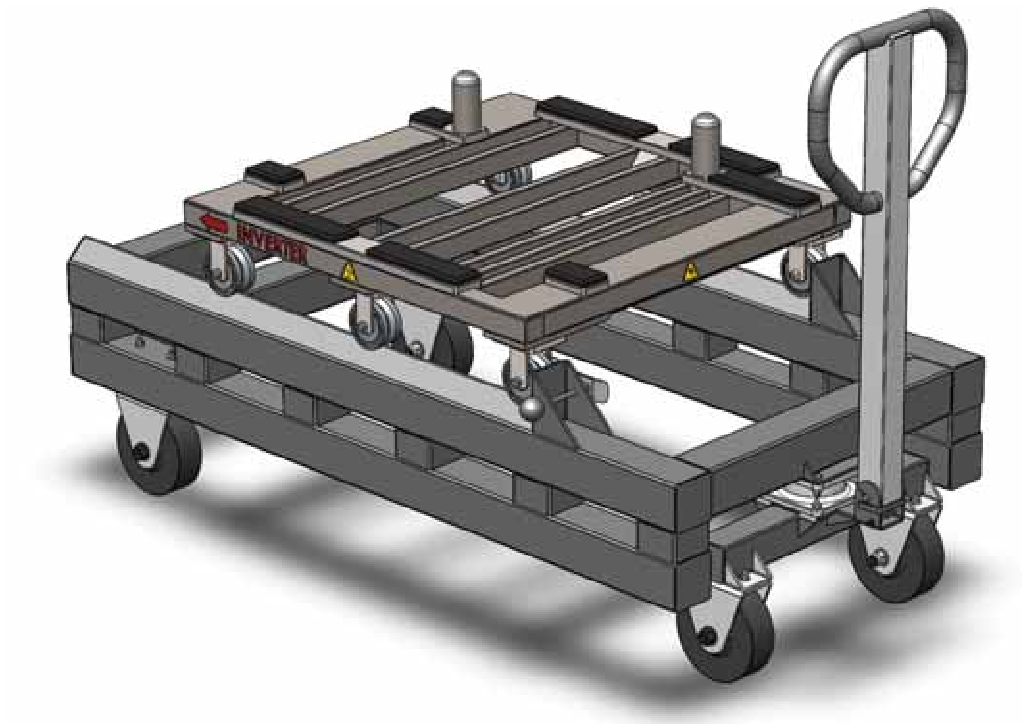


Figure 17. Pallet and Cart together

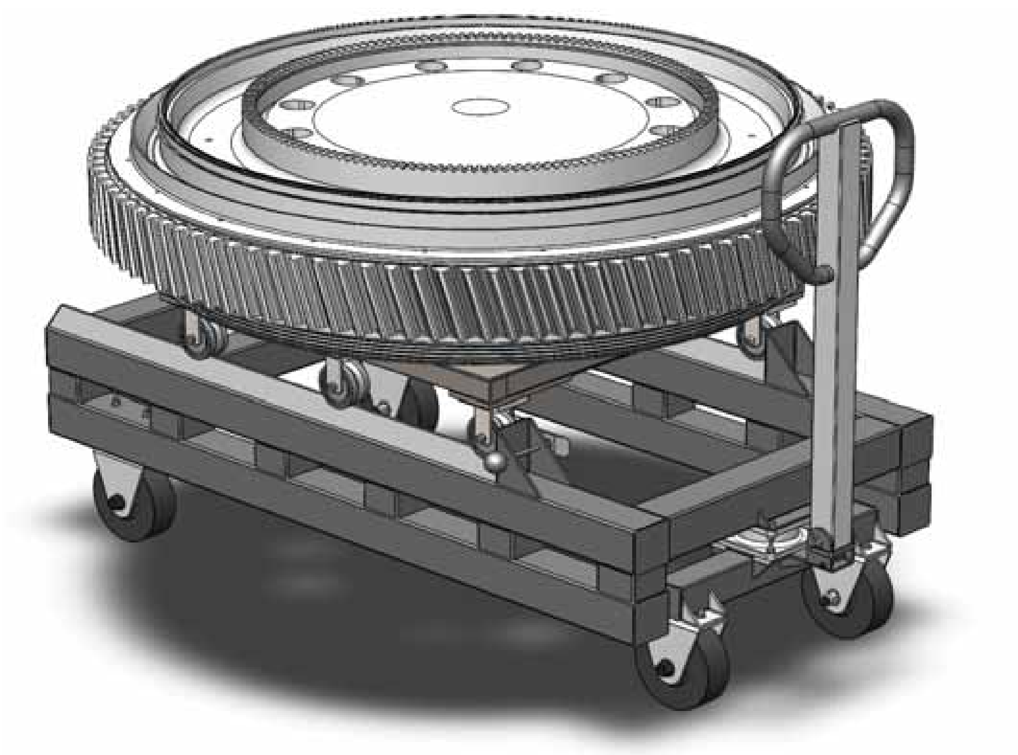


Figure 18. Pallet and Cart carrying a disc

H. Industrial Design

When developing the details of the design, it was important to incorporate industrial design principles into the design such that it can be easily operated. Firstly, ergonomics was important to this design since the discs are so heavy, it is important to minimize the strain that the operators will experience while transporting the disc. For example, the height of the cart handle, seen in Figure 19, will be adjustable between the heights of 48 and 40 inches such that any operator can push the cart comfortably. When the cart is unused, a spring will keep the handle upright so that it does not tip over and pose a safety risk (trip hazard). When the pallet and disc are mounted on the cart, the surface of the disc is at an average height of 42 inches. A comfortable height at which to inspect and grip blast the disc as seen in Figure 20.

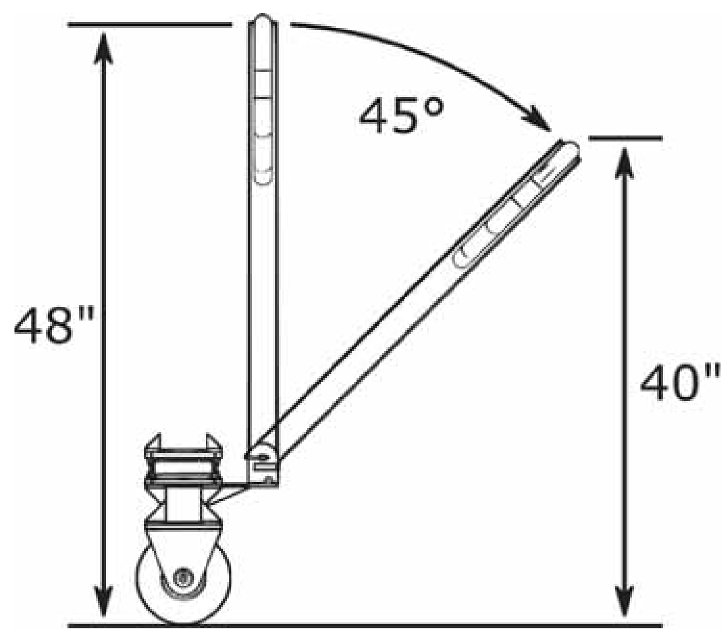


Figure 19. Spring-loaded handle range of motion

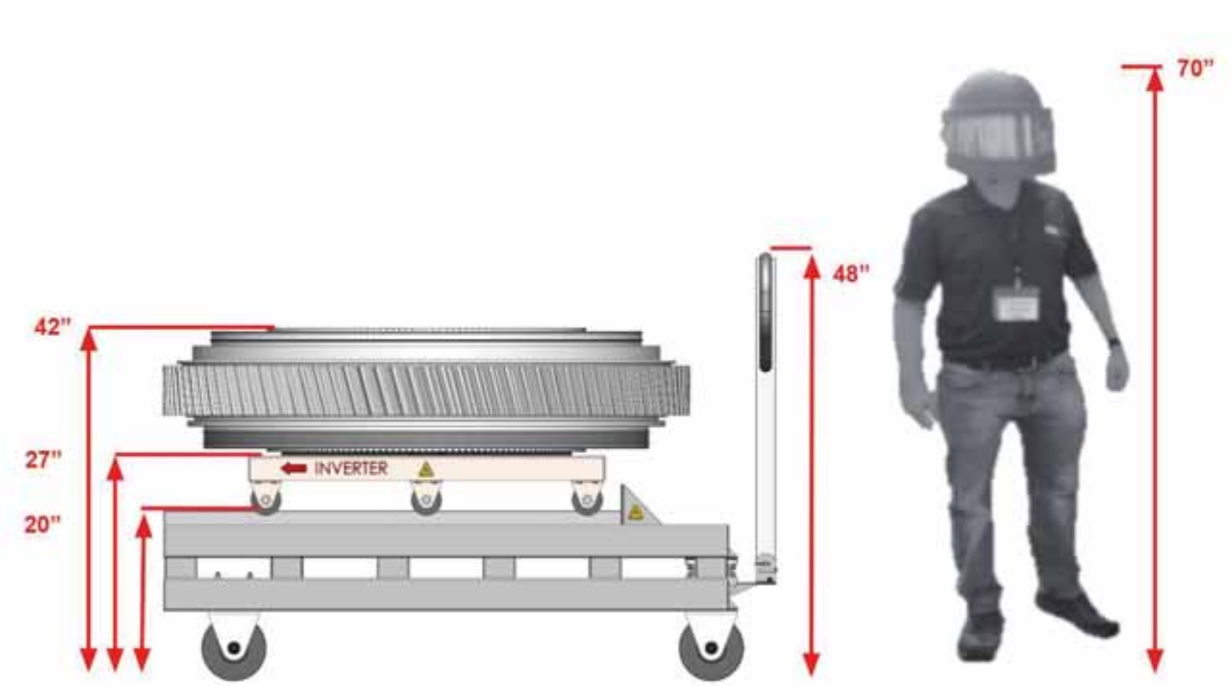


Figure 20. Ergonomic working height

Visual language is also implemented in this design to communicate crucial information to the operator. Firstly, the top platform of the cart is hollow when there is no pallet on it. This is an intentional design choice such that the cart can only interface with the disc and not be used for other purposes; this was requested by MHPS such that the cart will not be used for an unintended purpose and will always be available to transport discs. Also, the design uses color to communicate visual information and make the process of transporting the discs more intuitive. For example, the bulk of the pallet will be painted gray, but the top rails will be painted red to signify their importance in interfacing with the disc pallet. In addition, a red arrow will be painted on each pallet to indicate the direction that the pallet is supposed to enter the inverter, since the pallets are square it may be difficult to determine the orientation of the pallet by simply looking at it. The color choice of red and gray were chosen since they are the main colors in the MHPS logo and branding, and red is a high contrast color that is easily visible and contrasts well to a muted color like gray. Lastly, decals will be added onto the pallet to indicate the location of pinch points when the disc is loaded onto a pallet.

I. Engineering Analyses and Experiments

The Engineering Analyses and Experiments were split in three sections:

1. The Shafts
2. The Pallet
3. The Cart

The Shafts

The iterative design process began with the design of the pallet as this would be the main component used at all steps in the process. The shafts of the pallet were critical points since they would be supporting the majority of the loads. A MATLAB script, found in the Appendix B, was used to determine the minimum pallet shaft diameter needed to maintain a factor of safety of at least 2.0 given a static loading condition. The load was assumed to be the weight of the heaviest disc divided by two since two shafts would support it. This came out to be about 18801 N. The length of the shaft was set to be the thickness of the thinnest disc since this would save material and reduce the effect of bending moments. A36 steel was assumed to be shaft material. The shaft itself was modeled as a cantilever beam with the entire load acting as a point load at the end of the beam (worst-case scenario), though the load was actually distributed across it, as seen in the free-body diagram in Figure 21:

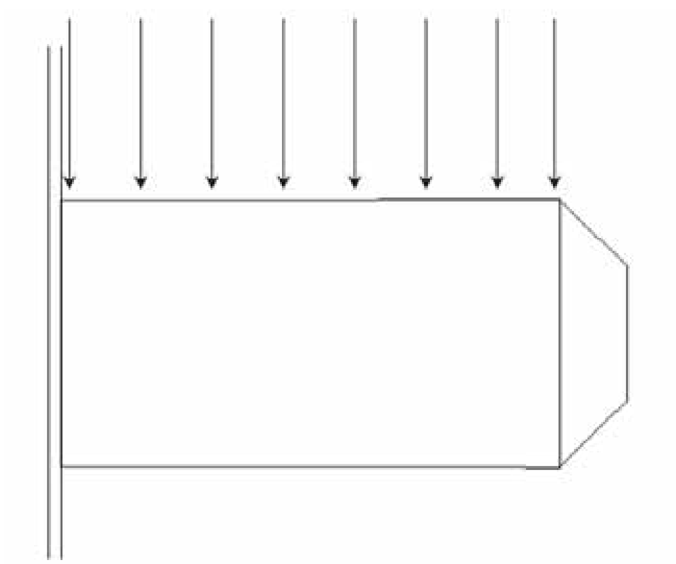


Figure 21. Free-body diagram of the shaft

Given a factor of safety of 2.0, the output of the MATLAB script, from Appendix B, is seen in Figure 22:

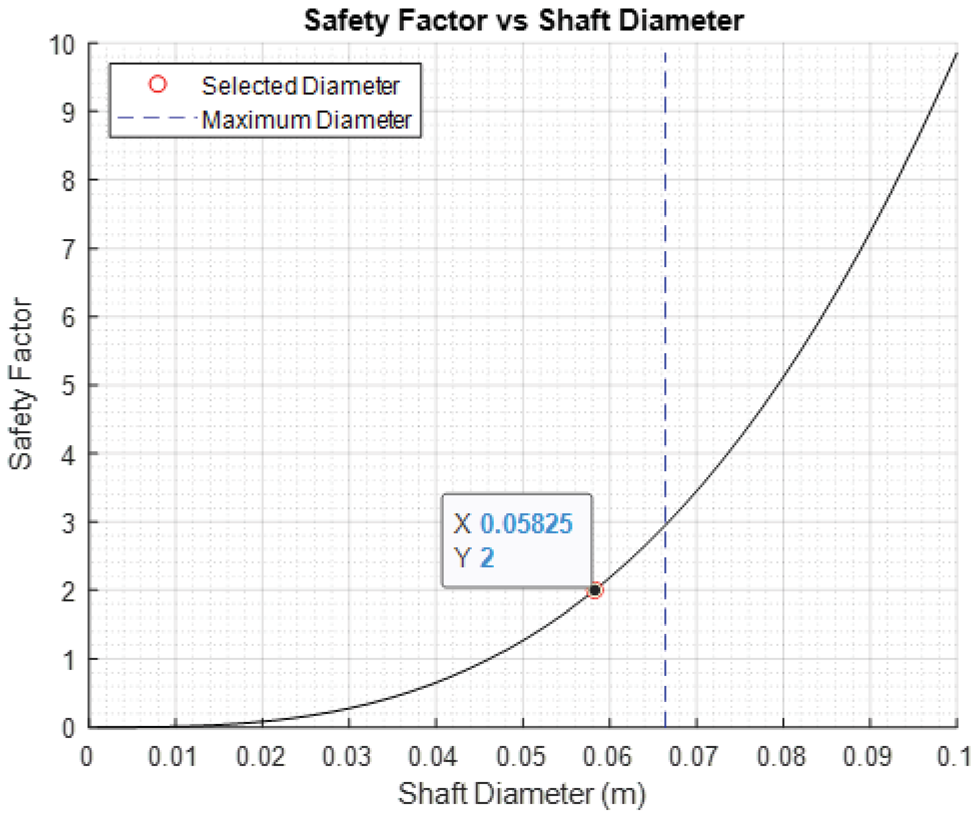


Figure 22. Minimum shaft diameter needed for a safety factor of 2.0

According to the plot, a minimum diameter of at least 58.25 mm was required for the pallet shafts given the above assumptions. This size was also smaller than the smallest spindle hole diameter on the discs which meant that the shaft could be used for all of the discs. Using nominal sizes, the shaft was designed with a diameter of 60.33 mm. An FEA was then done on it to confirm our results, and the results are seen in Figure 23:

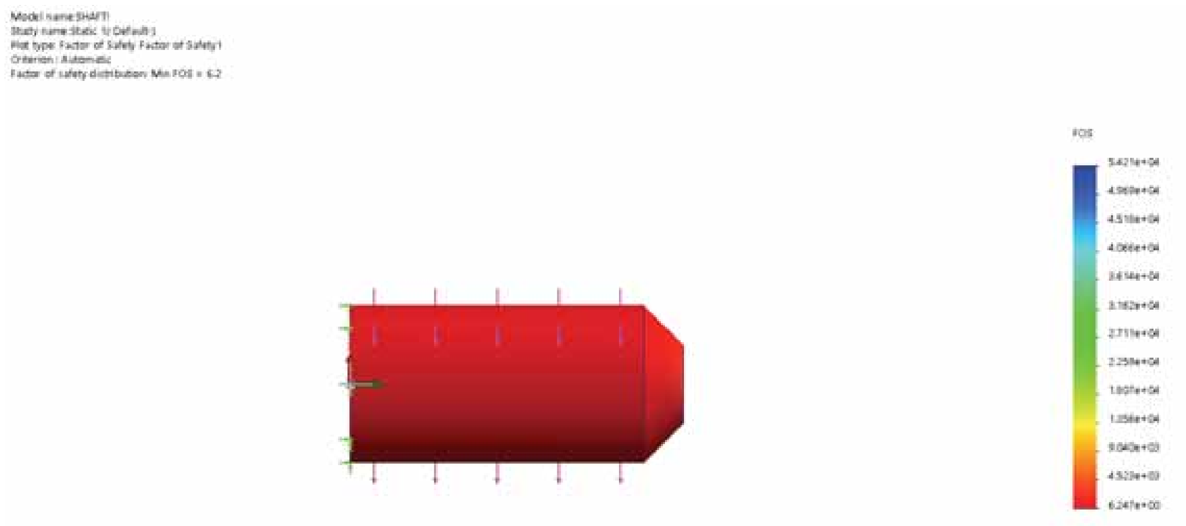


Figure 23. FEA for static loading on the shaft

The FEA output a minimum factor of safety of around 6.2 across the entire shaft which was well above our standards. A fatigue analysis, seen in Figure 24, also showed good results with a guaranteed life of 1,000,000 cycles:

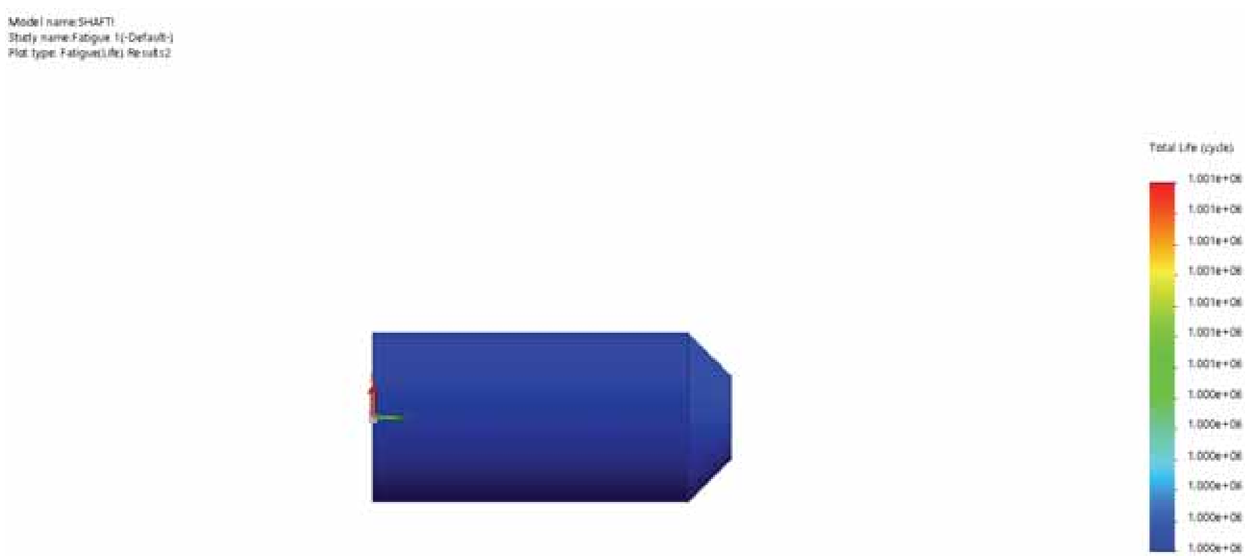


Figure 24. FEA for cyclic loading on the shaft

The design of the complete pallet then followed.

The Pallet

The pallet was designed to support all the varying disc sizes. It underwent several iterations before the final design was reached. Four iterations were done, and each underwent an FEA simulation to verify its structural integrity. The first pallet iteration is shown in Figure 25.

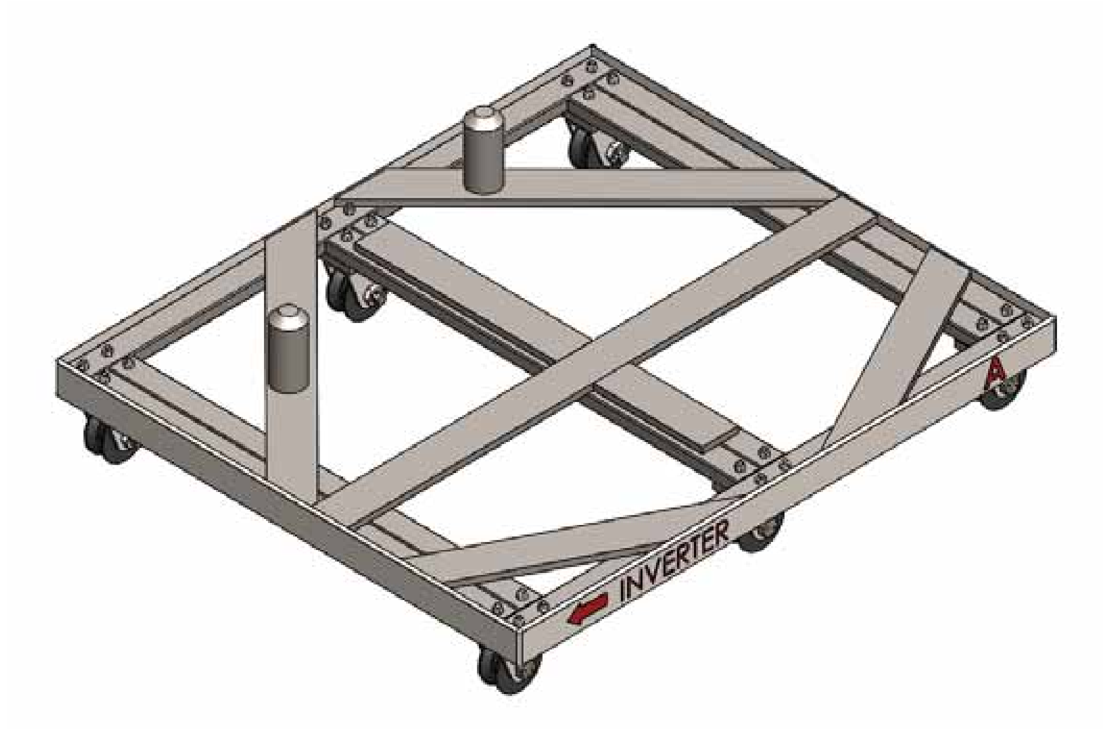


Figure 25. Pallet iteration 1

The pallet has six roller wheels and therefore six fixed geometries on which it rests. The largest disc lined up to make contact with the frame of the pallet in four locations. The weight of the disc, approximately 40 kN, was divided with larger surface contact supporting more of the weight. It can be seen in Figure 26 that there was a spike in stress in the base of the steel frame at 3.66 MPa.

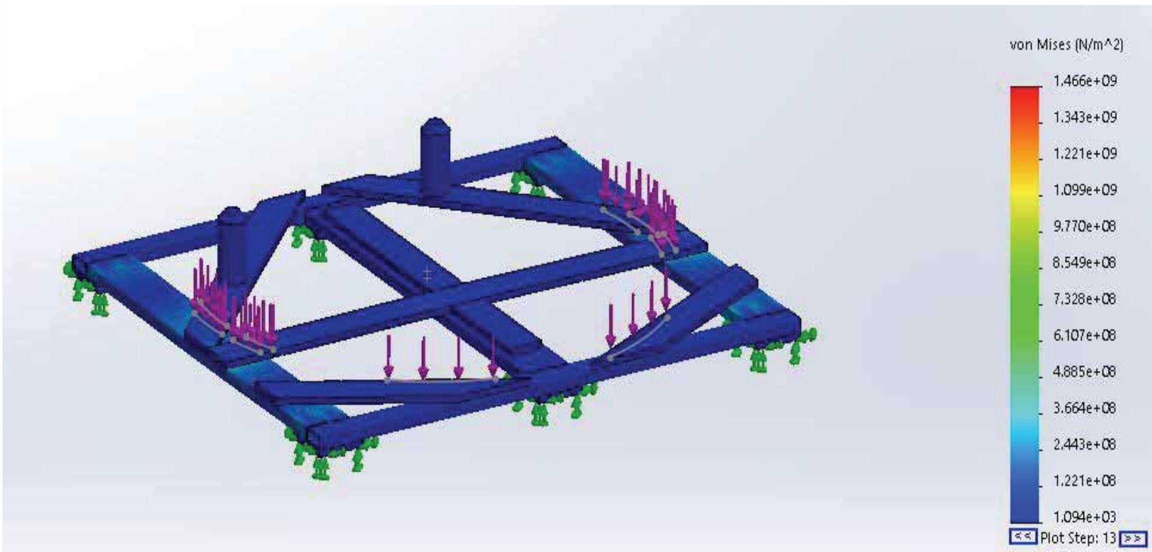


Figure 26. FEA of the pallet stresses

This resulted in some deformation, seen in the displacement results in Figure 27, which was slightly troubling because the frame deformed by 3 mm in the center outside area which corresponds to the open middle section of the cart. This brought to light that the frame needed more support in the center because it was supported by two rails on the outer sides.

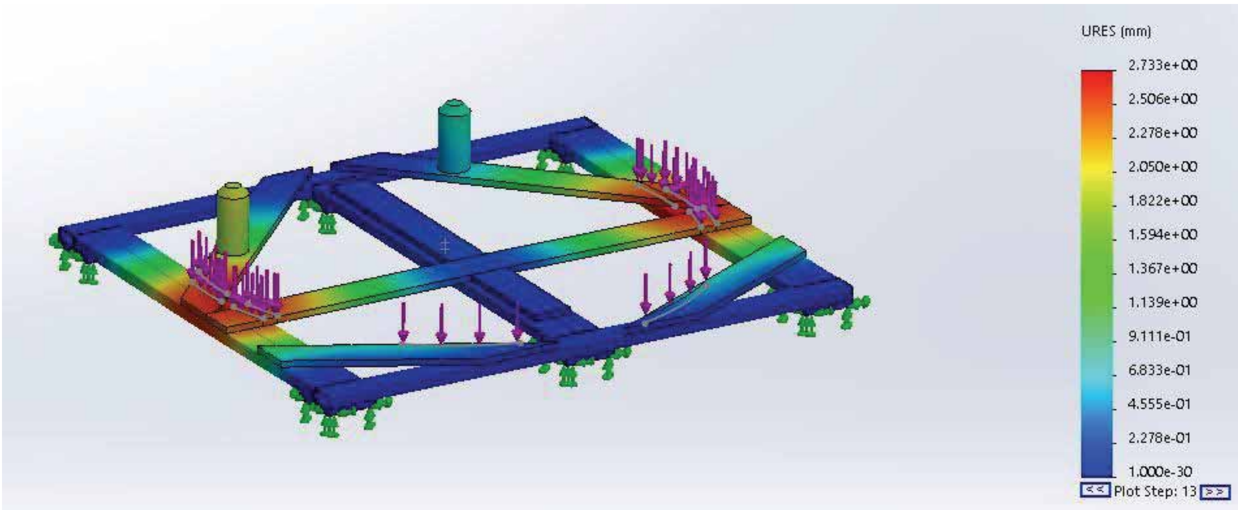


Figure 27. FEA of the pallet deformation

Next, FEA was done with the pallet in the vertical position to simulate the loads it would experience during its inversion. The results are seen in Figure 28. A hint of light blue, corresponding to a stress of 9.16 MPa, occurred on the top right outer beam under where the shaft is attached due to the force pulling downwards.

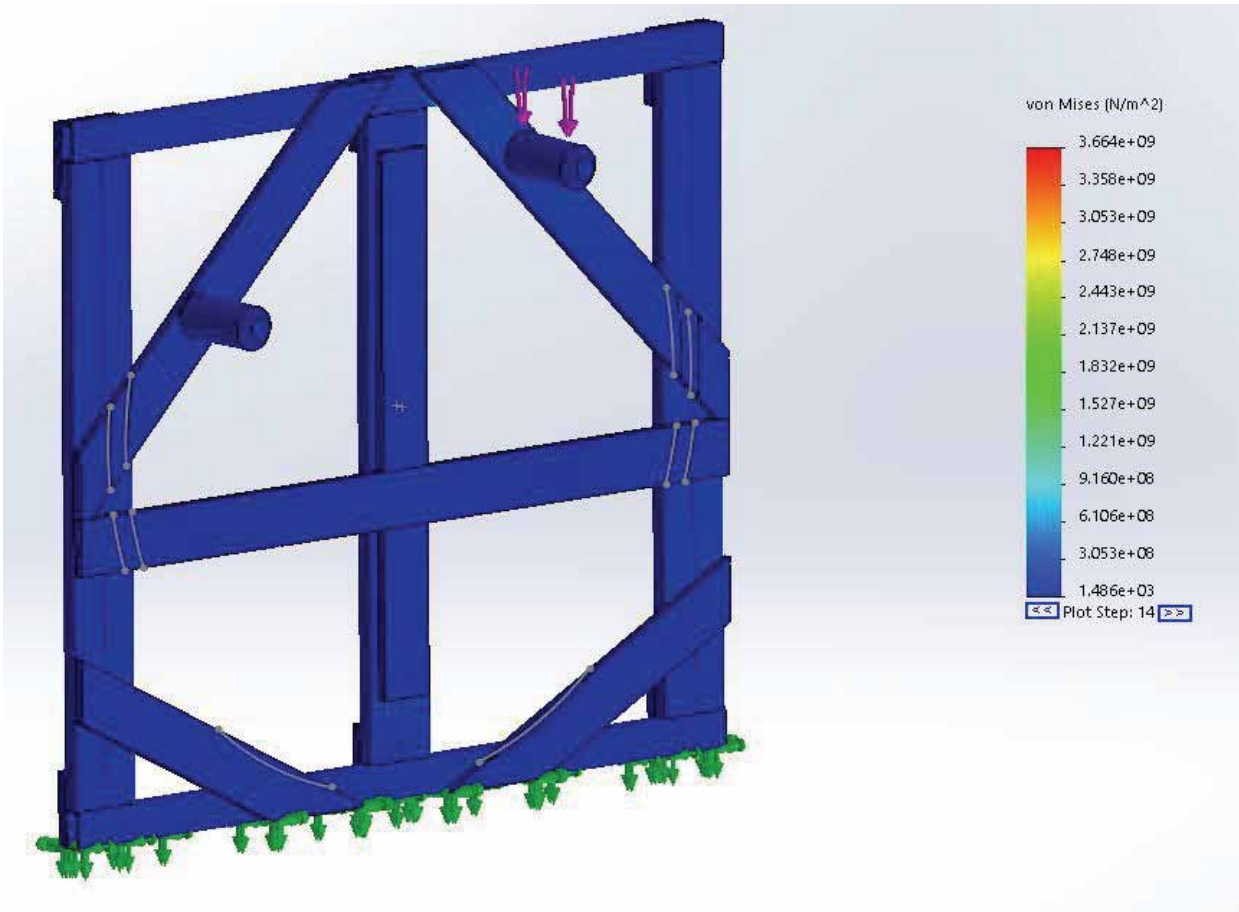


Figure 28. FEA of the pallet stresses in the vertical position

This caused very large deformations, seen in Figure 29, of up to about 15 mm which were proved to be unusable.

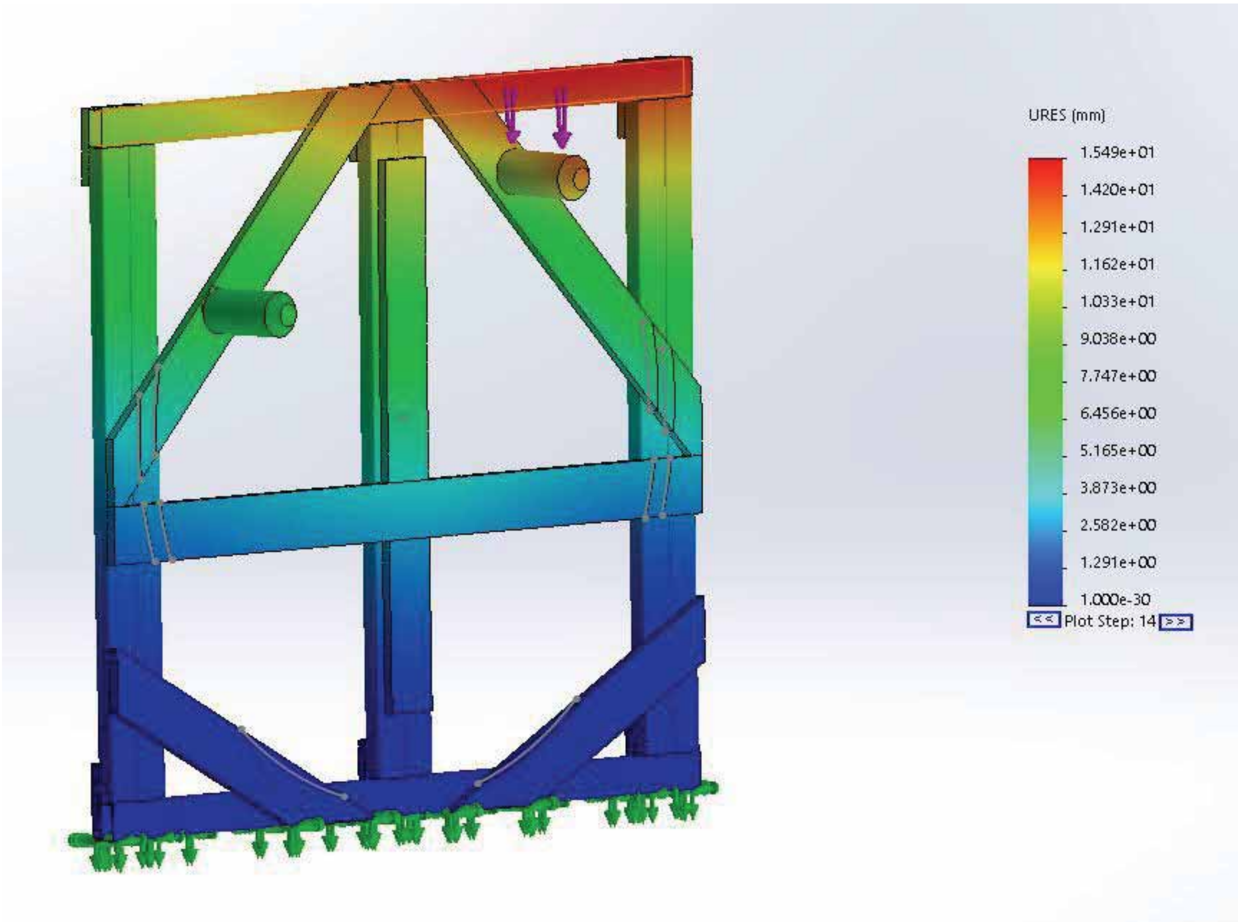


Figure 29. FEA of the pallet deformation in the vertical position

Therefore, a new pallet iteration was made with some reinforcements. The left shaft was also moved to split the weight of the disc between both shafts and distribute the load across the frame more evenly. The results are seen in Figure 30. The large displacement in the previous iteration was cut in half.

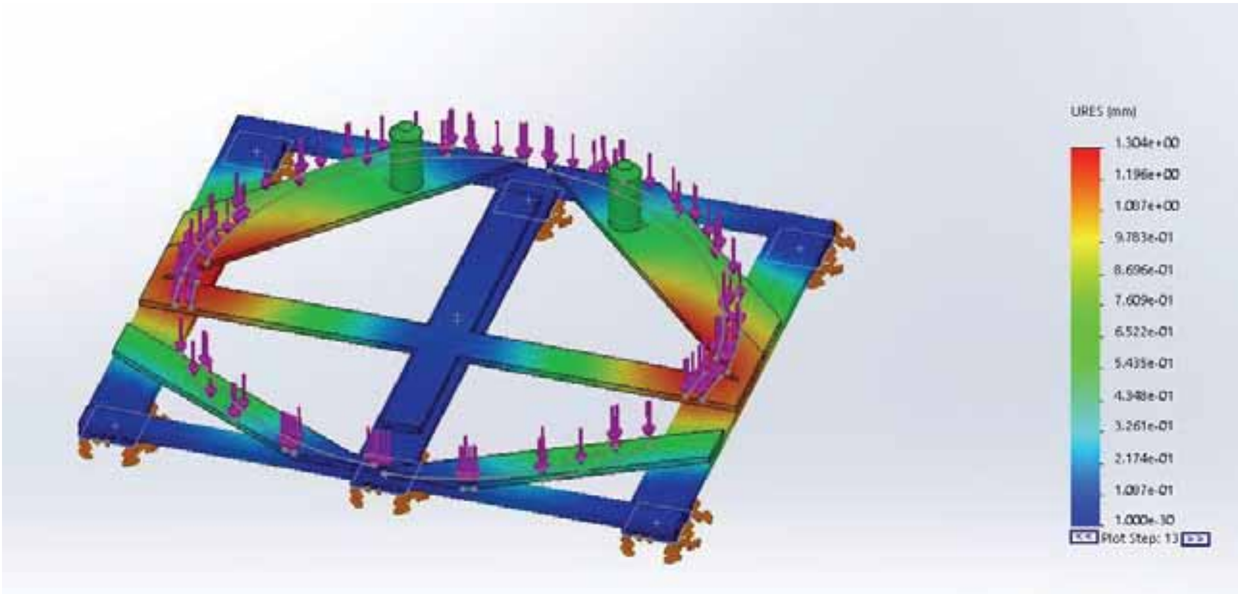


Figure 30. FEA deformation of iteration 2

But the pallet was still experiencing stresses on the base (Figure 31).

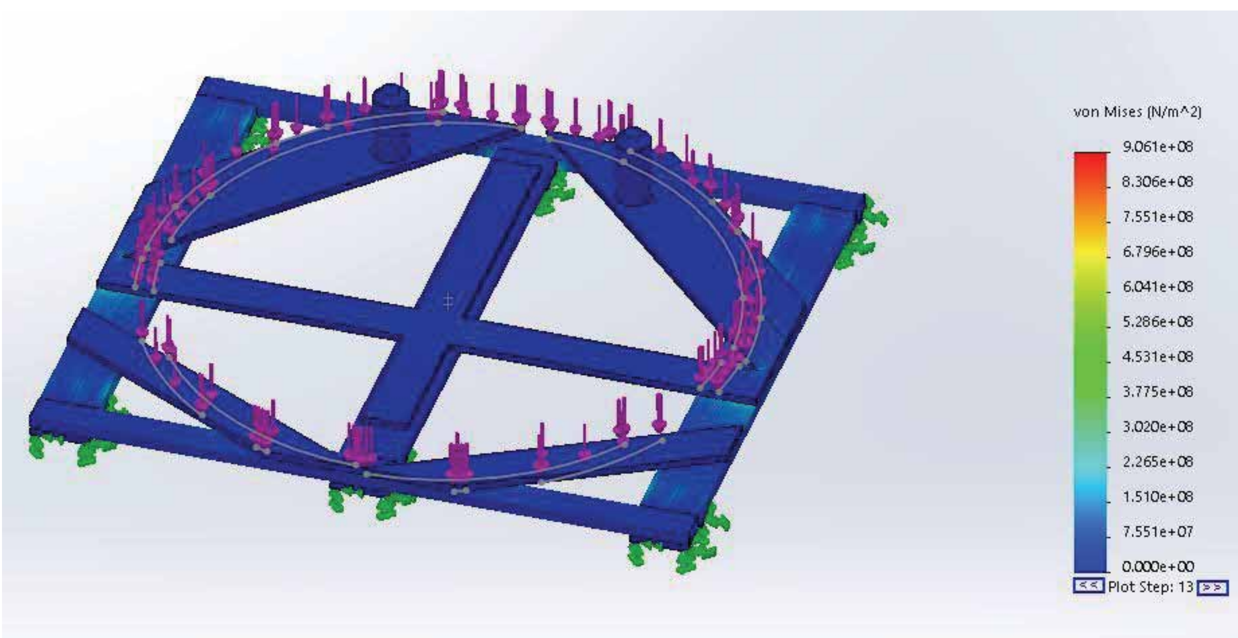


Figure 31. FEA stresses of iteration 2

The pallet was once again tested in the vertical position (Figure 32). This still did not yield promising results as the maximum displacement was nearly 13 mm.

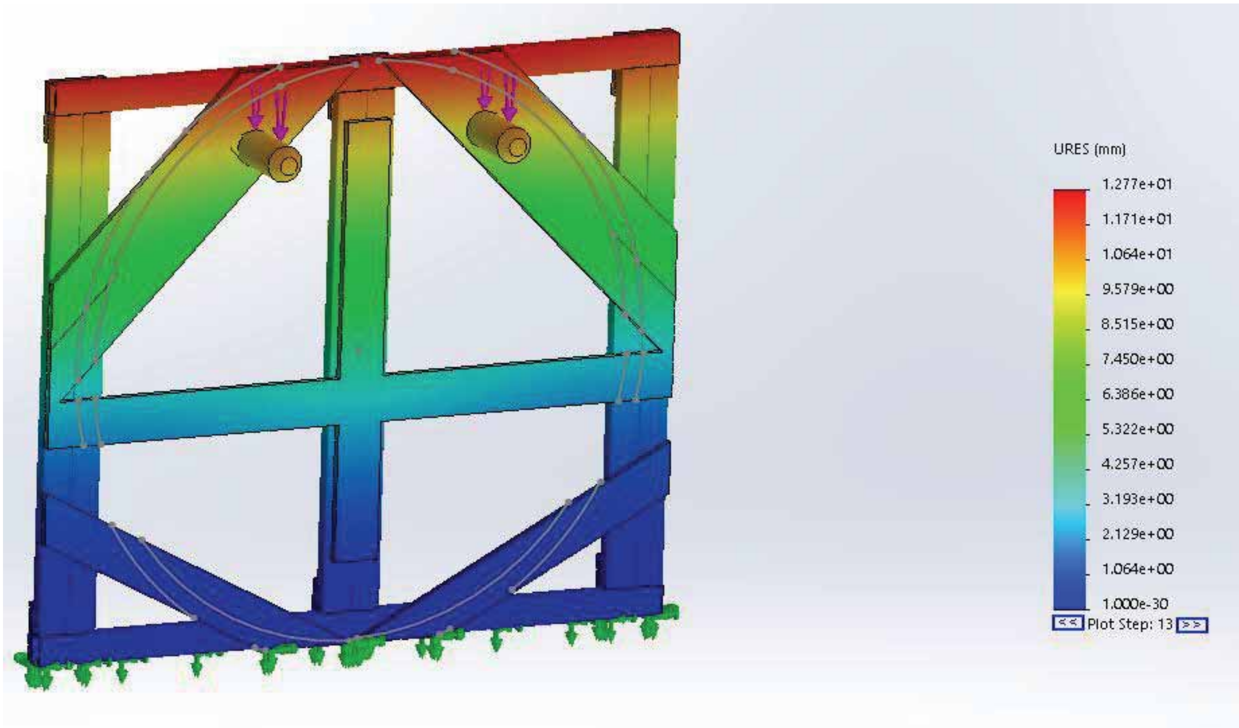


Figure 32. FEA deformation of iteration 2 in the vertical position

The strength of the pallet was significantly increase in a third iteration. The thickness was increased from one inch to two inches, and four steel bars were lined up on each side. The material was also changed from a mix of different steels with varying yield strengths to a uniform AISI 4340 normalized steel with a yield strength of 102.9 ksi. This improved the deformation drastically and proved the design to be more stable, shown in Figure 33. One issue with the FEA was that the fixed geometry where the roller wheels were mounted were not allowed to move based on how they were defined. As a result, deformation occurred in the middle section which actually had no forces applied to it. Overall, outer regions had negligible deformation, which was good, but the modifications had to be made so that the middle section did not experience such large deformations.

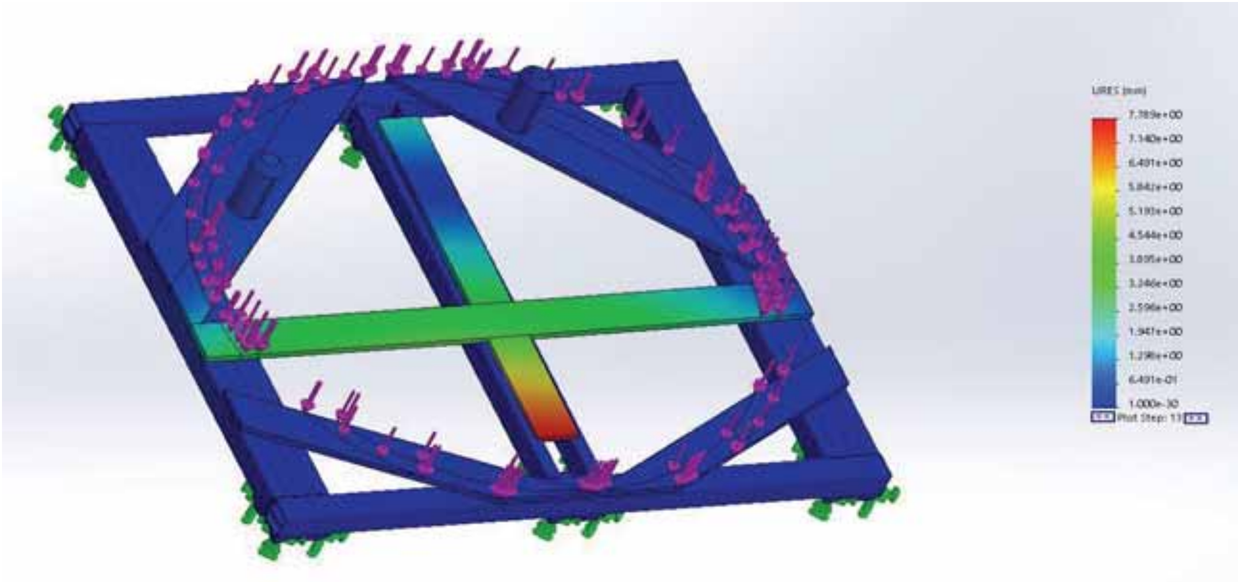


Figure 33. FEA deformation of iteration 3

The stresses in the base of the pallet have also been removed by the use of the additional steel in Figure 34.

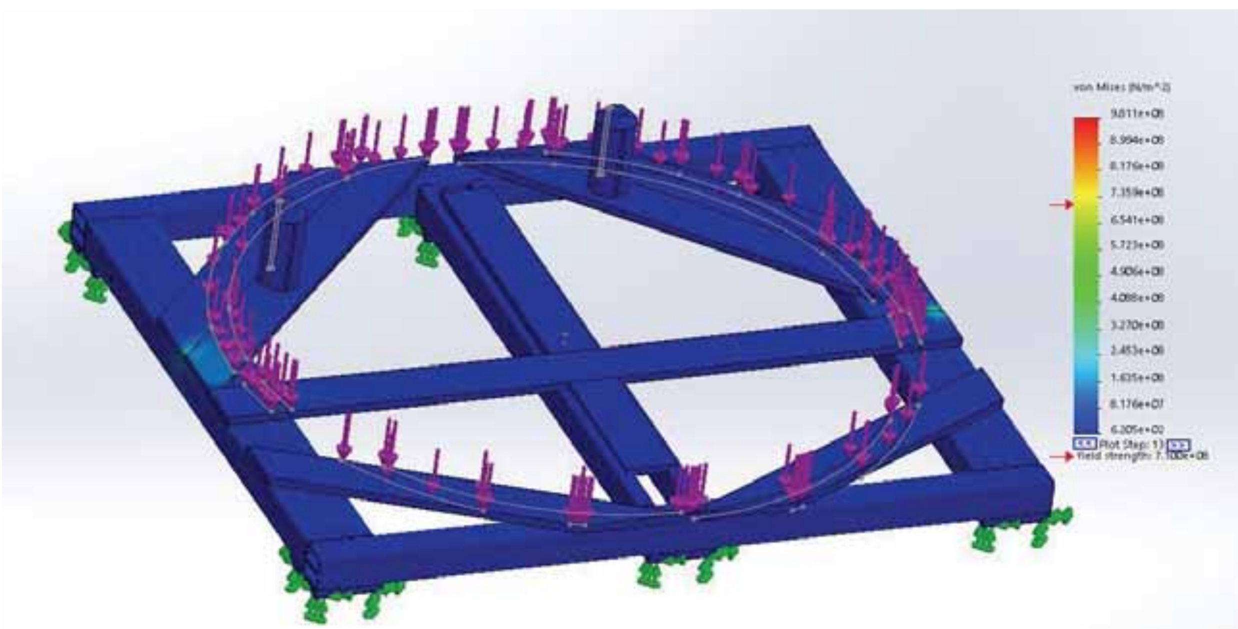


Figure 34. FEA stresses of iteration 3

Iteration 3 was then tested in the vertical position (Figure 35). The fixed geometries were also modified from previous tests to better simulate the pallet inside the inverter being clamped in with the disc. The frame held up well with only half a millimeter of deformation at the very end of the right shaft.

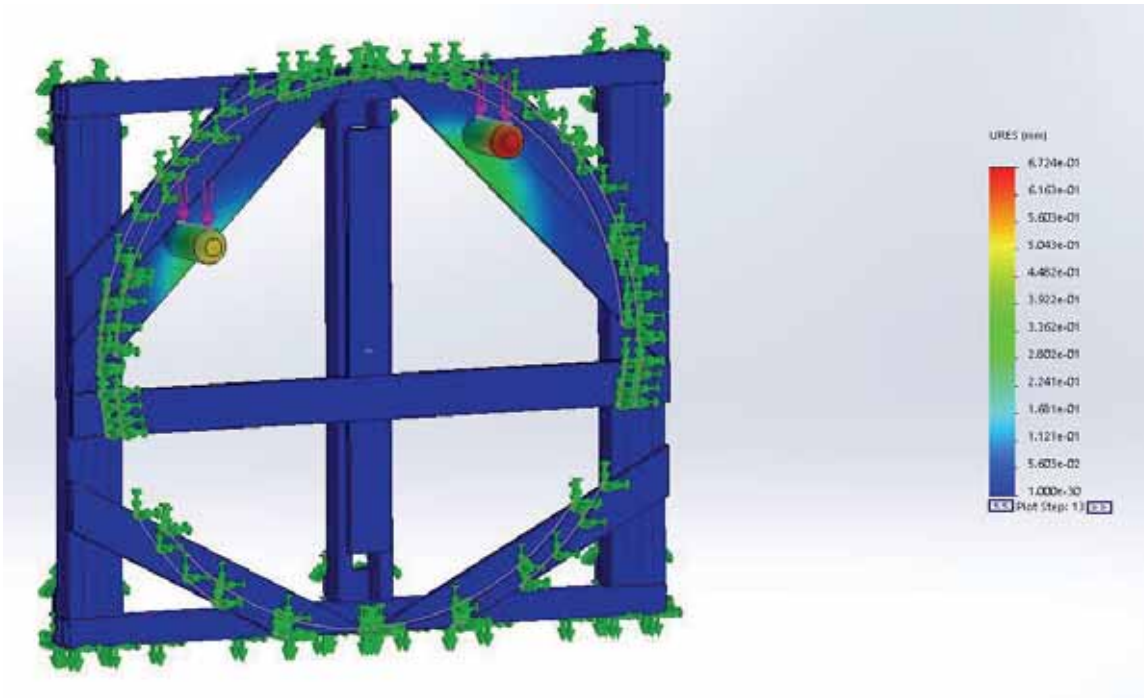


Figure 35. FEA deformation of iteration 3 in the vertical position

In Figure 36, the stresses are concentrated around the shafts but are at a manageable amount.

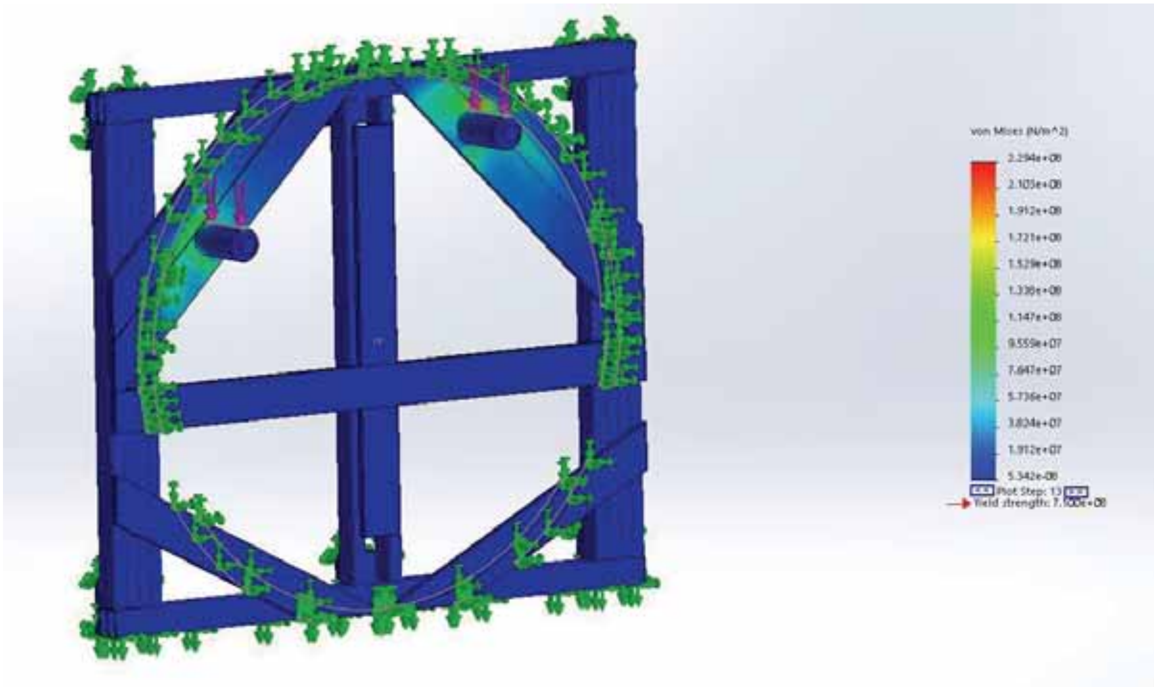


Figure 36. FEA stresses of iteration 3 in the vertical position

A fourth iteration was made. Now that a strong structure had been achieved, this iteration sought to lower the weight by spreading out the beams so that less beams would be necessary, therefore lowering cost as well as seen in Figure 37.

Figure 37. Fourth iteration of the pallet structure

FEA results on this iteration were promising. In Figure 39a, the maximum deformation is at 0.5 mm. In addition, Figure 39b shows an acceptable FOS all across the pallet except in one area, where it is about 0.8, implying failure. This point occurs where the load folds the beam over on the roller base platforms, seen in zoomed version as Figure 40.

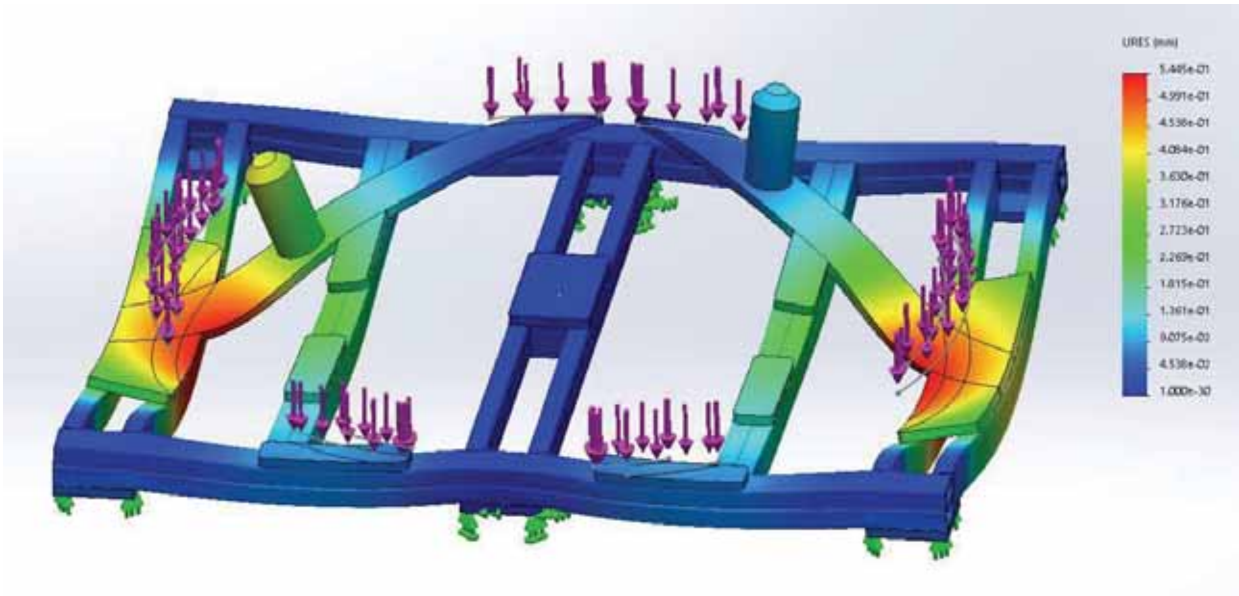


Figure 39a. Current iteration FEA deformation of the pallet structure

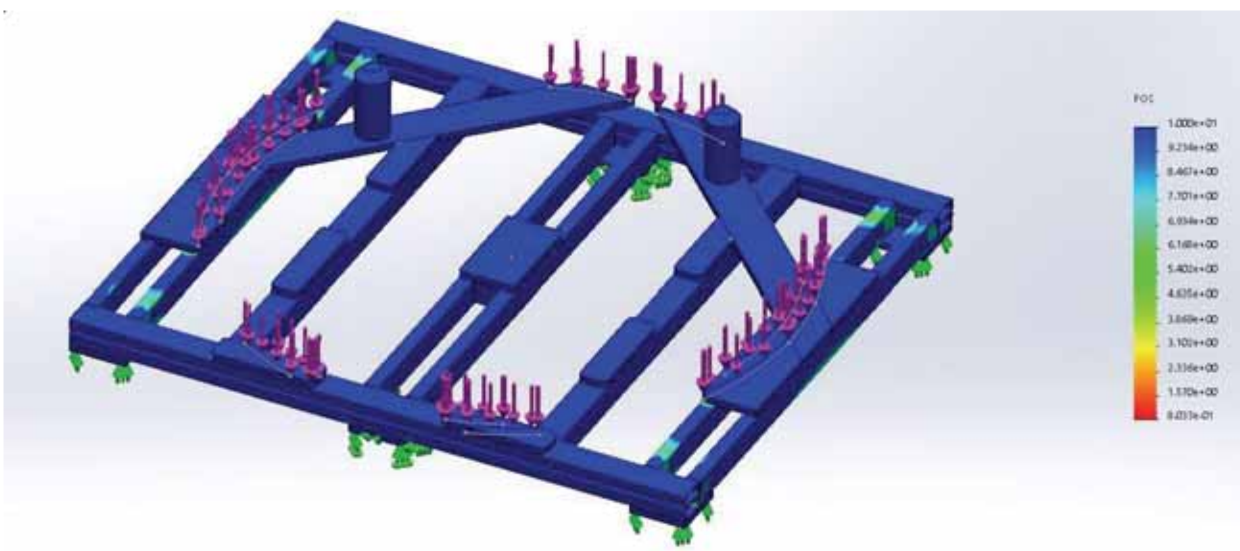


Figure 39b. Current iteration FEA FOS of the pallet structure

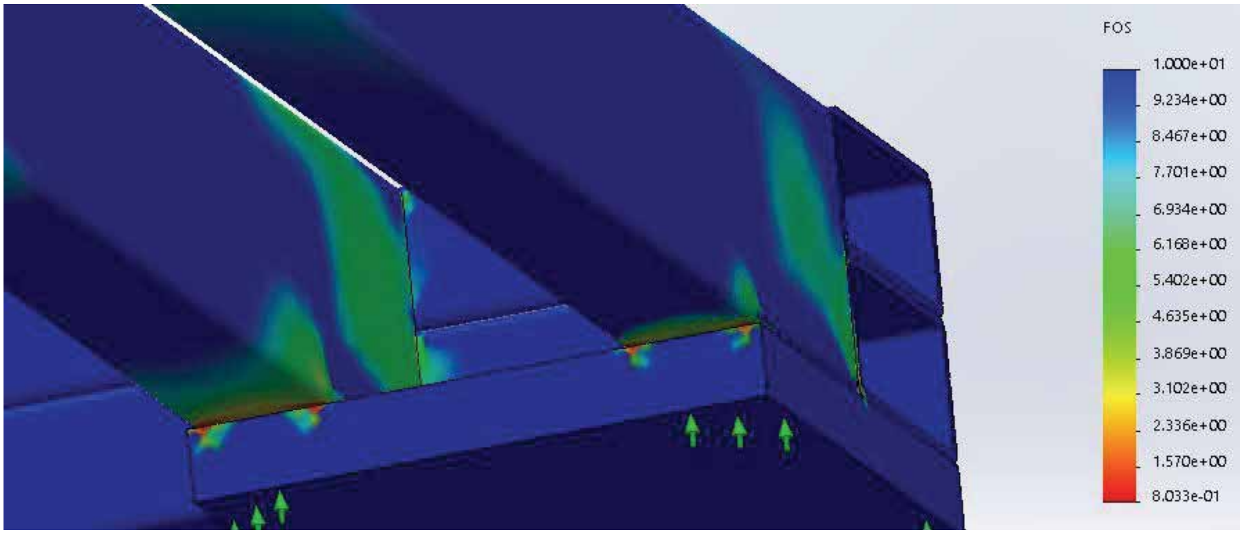


Figure 40. Zoomed in on problematic point in FEA FOS

FEA was done in the vertical position again which showed about 1.4 mm of deformation as seen in Figure 41.

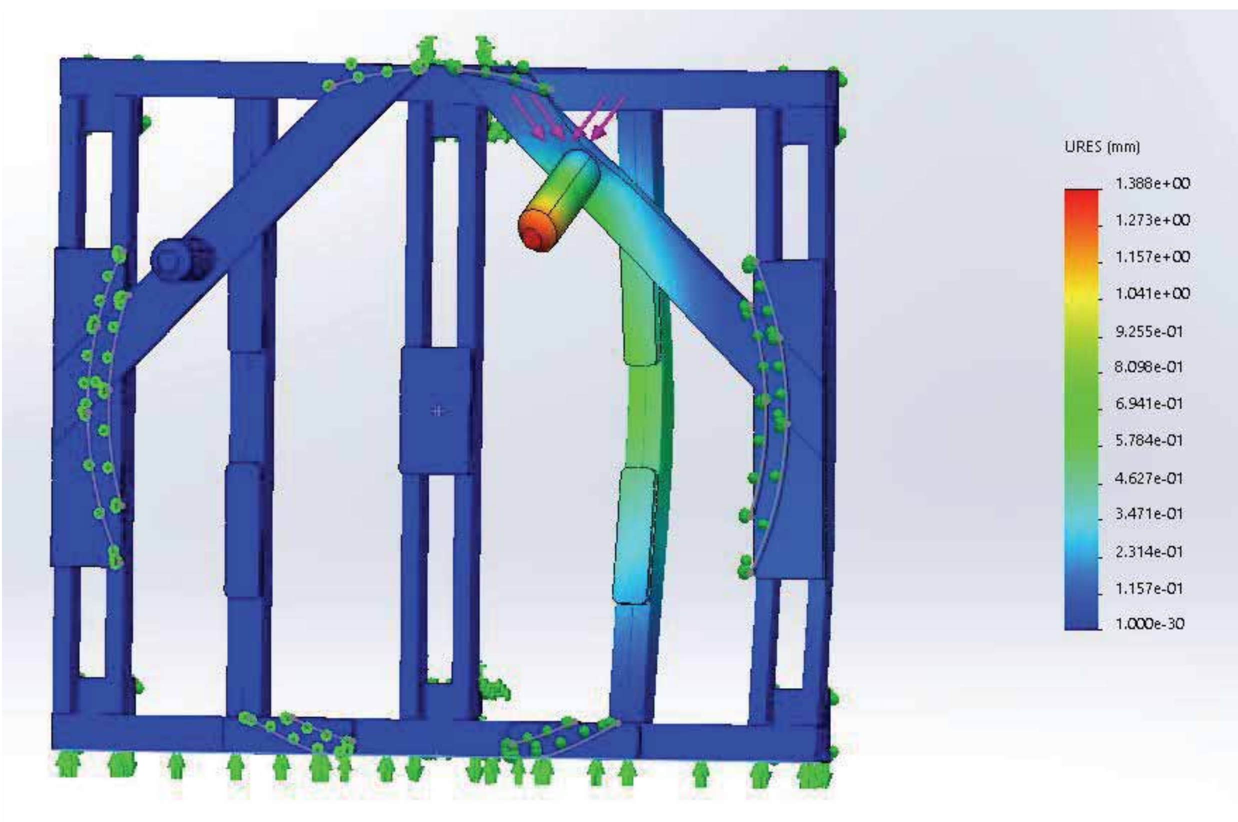


Figure 41. Current iteration FEA deformation of the pallet structure in vertical position

The FOS plot in Figure 42 also shows good results, except for one area which has a FOS of about 0.27. This failure area is shown in zoomed version as Figure 43**.** This again occurs where the load is bending the top beam over the beam below it.

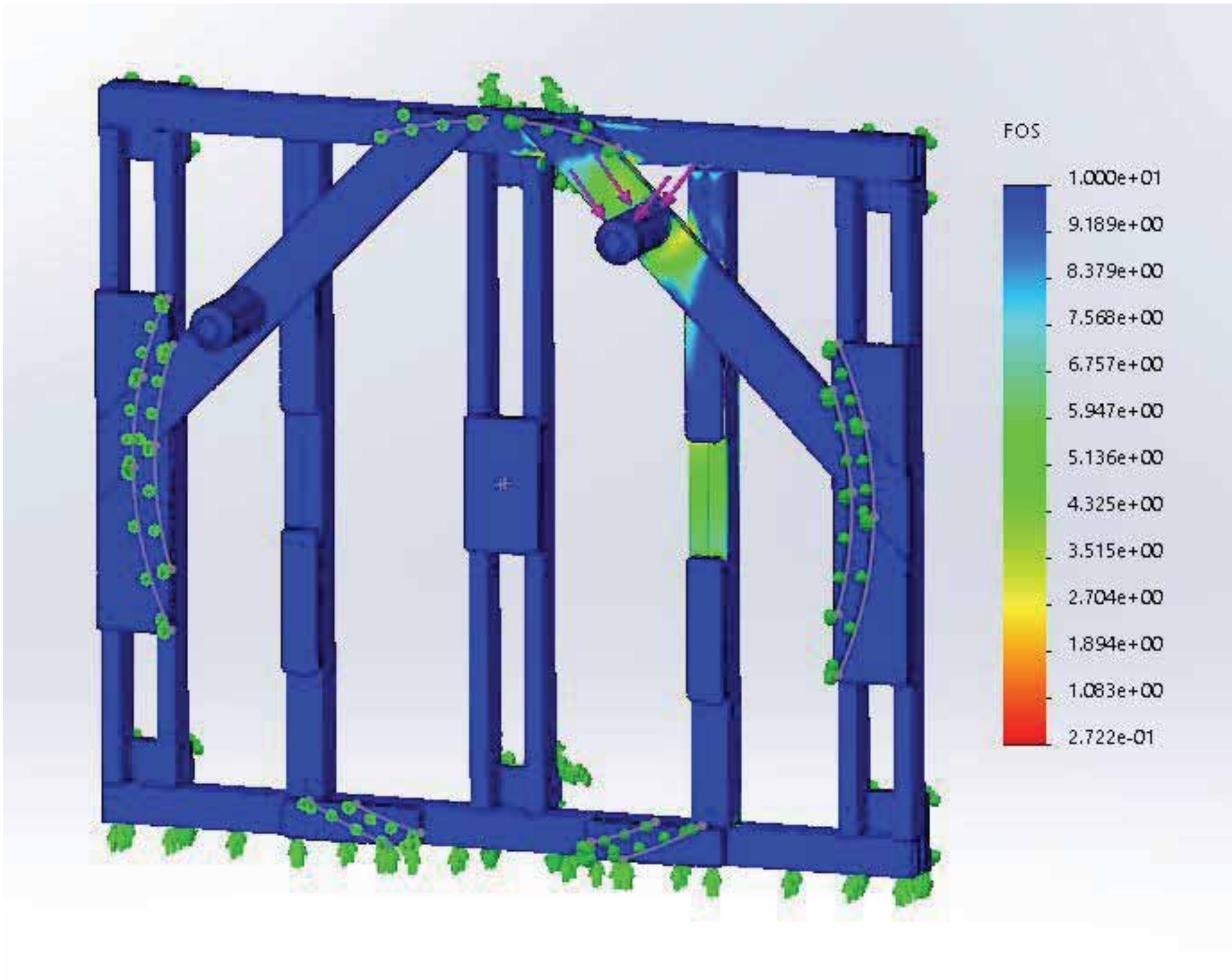


Figure 42. Current iteration FOS deformation of the pallet structure in vertical position

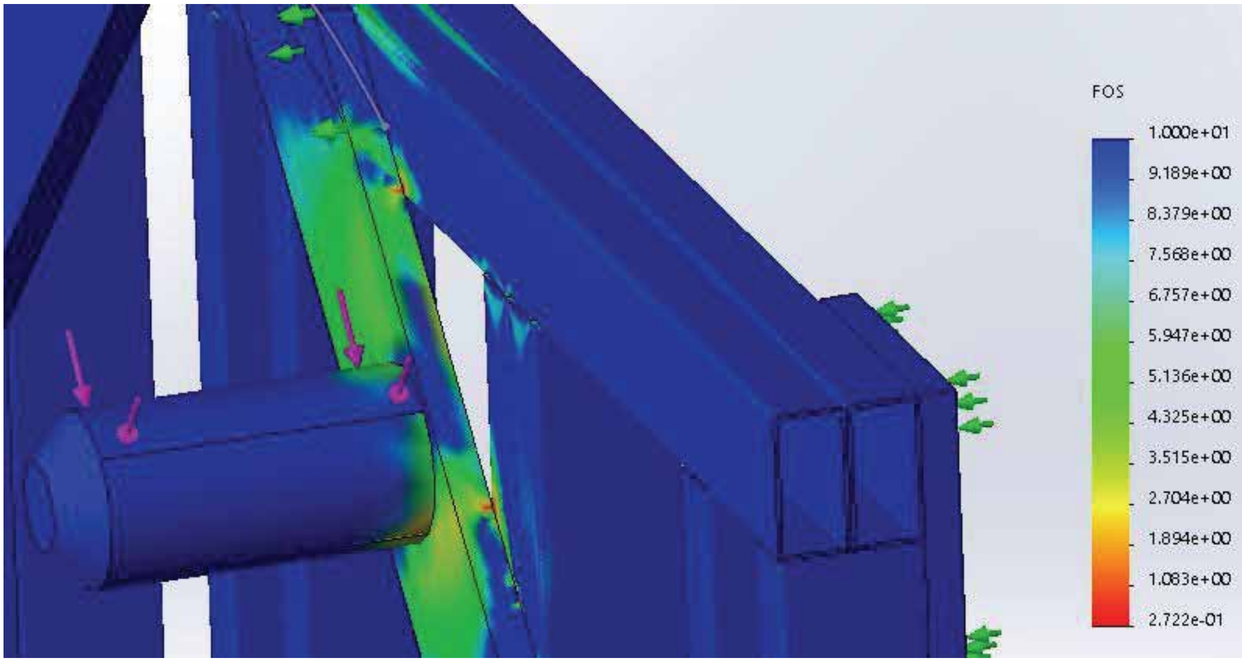


Figure 43. Zoomed in on problematic point in FEA FOS

After many modifications were made, the design seemed to have fundamental errors that simply could not be fixed without make a new structure that was fundamentally different as seen in Figure 44.

Figure 44. Final iteration of the pallet structure

Essentially this new design takes out the diagonal beams entirely, spreads out the vertical beams, and accounts for all the discs lying on one contact zone instead of supporting different sized discs with different contact zones. This design finally produced significantly better FEA results seen in Figures 45 and 46 which gave a minimum FOS of 3.0 and 2.2 respectively. At this point, it was considered that there was not much more to learn from FEA simulation and that the design was ready to be prototyped and tested. This is based on the fact that the design will be welded together and that it is difficult to truly know how it will respond to heavy loads.

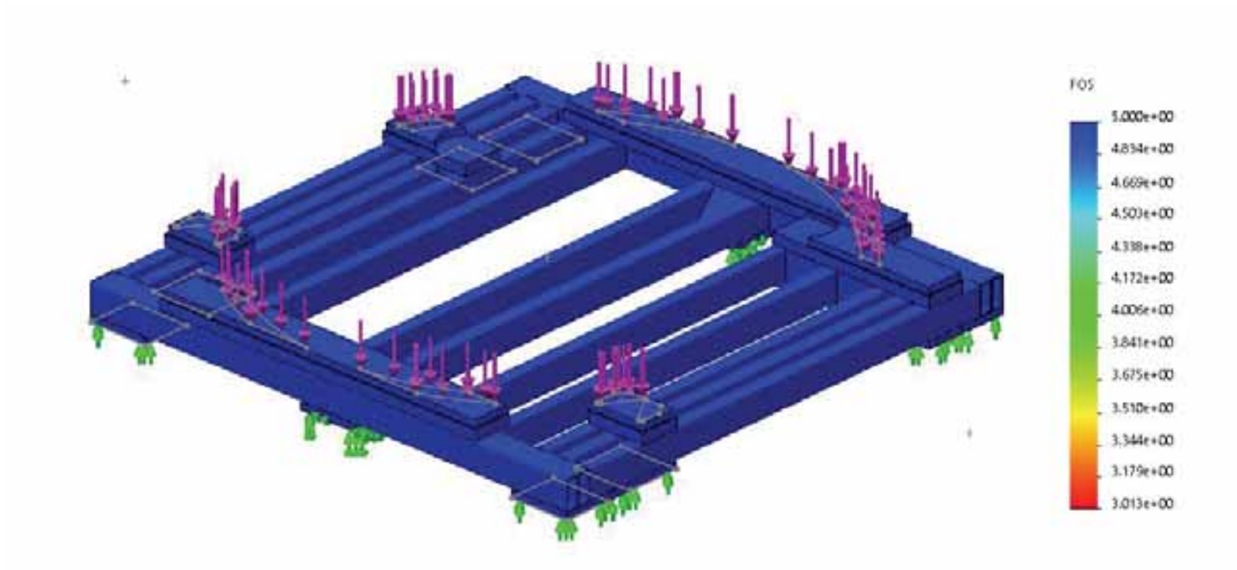


Figure 45. Final iteration horizontal FEA

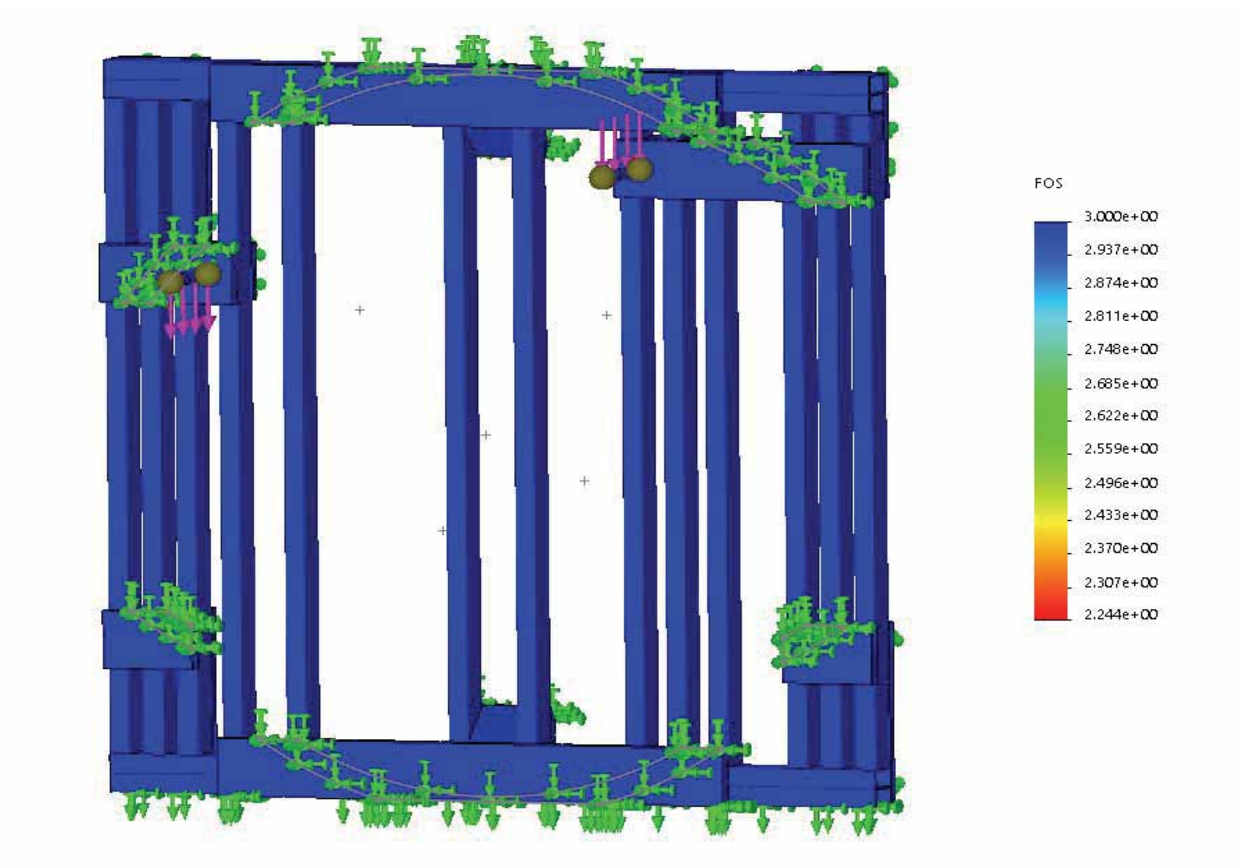


Figure 46. Final iteration vertical FEA

The Cart

In the cart, there are three components of concern for the cart: the frame, the wheel forks, and the crossmember on the steering assembly. Each component will be analyzed individually. The frame experiences the forces and reactions shown in Figure 47. The distributed weight of the pallet and disc, *F*, can slide along the frame, *L*, which changes the reaction forces exerted by the wheels, *R*. Due to the design of the cart, the maximum force that the front wheels will experience is half of the weight heaviest disc, 18.8 kN, when the load is towards the front of the cart. Likewise, the steering assembly crossmember will experience at most 18.8 kN, when the load is the furthest back along the rails.

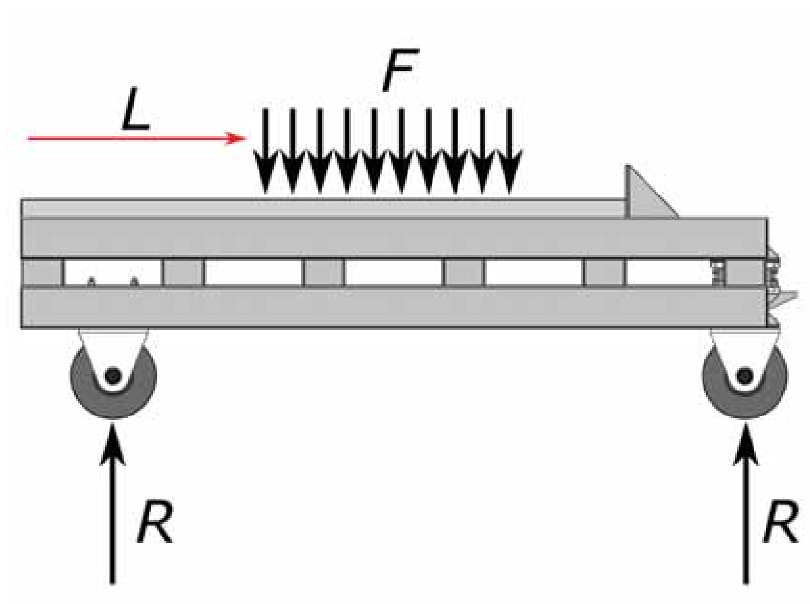


Figure 47. FBD of cart frame

When sizing the square tubing for the cart's frame, a balance had to be made between structural integrity and weight. For a hollow square tube, shown in Figure 48, the cross-sectional moment of area about the axis of bending is

$$I_x = \frac{w^4 - (w-t)^4}{12} \quad (1)$$

where w is the width of the square and t is the thickness of the walls. This value should be maximized to increase the strength of the beam. Similarly, the cross-sectional area is

$$A = w^2 - (w-t)^2 \quad (2)$$

which should be minimized to reduce the overall weight of the cart.

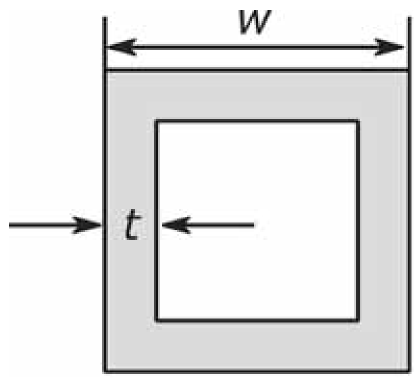


Figure 48. Square tube cross-section

Several square tubes available on the McMaster-Carr catalogue were compared to determine the best tube for this application. The comparisons are provided in Table 2. Eighth inch and quarter inch thicknesses were compared at widths of 2 inches and 4 inches. The minimum and maximum widths were compared, holding the thickness constant. Then the minimum and maximum thicknesses were compared, holding the width constant. The following table shows the relative increase in moment of inertia and mass for each comparison, using the first entry of each comparison as a baseline.

Table 2. Comparison of different beam cross sections

Width	Thickness	Relative MoI	Relative Area
Comparison 1			
2”	0.125”	100%	100%
4”	0.125”	880%	207%
Comparison 2			
2”	0.25”	100%	100%
4”	0.25”	969%	214%
Comparison 3			
2”	0.125	100%	100%
2”	0.25	165%	187%
Comparison 4			
4”	0.25”	100%	100%
4”	0.125”	182%	194%
Comparison 5			
2”	0.25	100%	100%
4”	0.125	533%	111%

These comparisons make it clear that the width of the beam has the highest impact on moment of inertia and the thickness has the highest impact on area. As shown in comparison 5, increasing width while decreasing thickness can lead to 5 times increase in moment of inertia while only increasing area, and thus weight, by 1.1 times. Therefore, square tubes with 4” width and 0.125” thickness were selected for further design analysis. The frames are composed of ASTM A500 low-carbon steel, as this is the only material offered in the McMaster catalogue for tubes of sufficient thickness and width. Fortunately, ASTM A500 is well suited to forming and welding.

For the frame simulation, a distributed load of 38,700 N, which represents the weight of the heaviest disc and 1 pallet, was placed along the intersection geometry between the pallet rollers and frame V-rails. The end stop on the frame positions the disc and pallet in the center of the frame, such that the weight of the disc is supported evenly by the frame. The stress simulation in Figure 49 indicates that the steel beams will not yield under theoretical maximum loading condition, with the maximum von Mises stress in the frame being 91% of the yield stress. Next, the displacement simulation in Figure 50 indicates that the maximum displacement occurs at the end stop in the frame, as a displacement of 0.4865 mm. However, since the frame does not yield at any point during this loading simulation, the displacement is elastic and will not cause the end stop to deform. Lastly, the safety factor simulation in Figure 51 calculates the factor of safety for the frame in terms of the maximum von Mises Stress criterion. The minimum FOS is 1.1, which is concerning for the frame since the factor is near 1; as a result, an additional iteration was pursued.

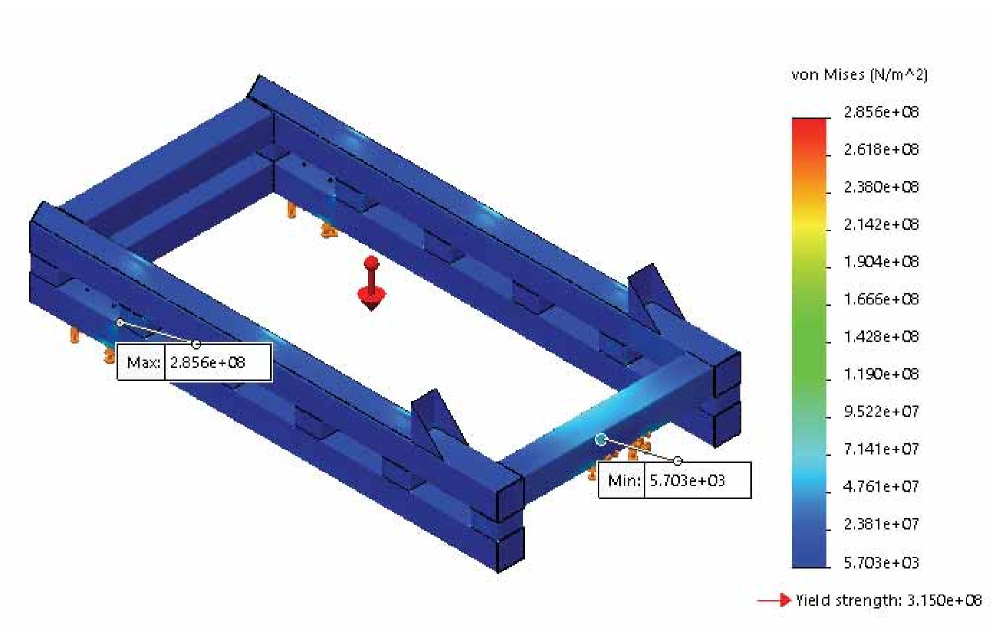


Figure 49: Frame Von Mises Stress

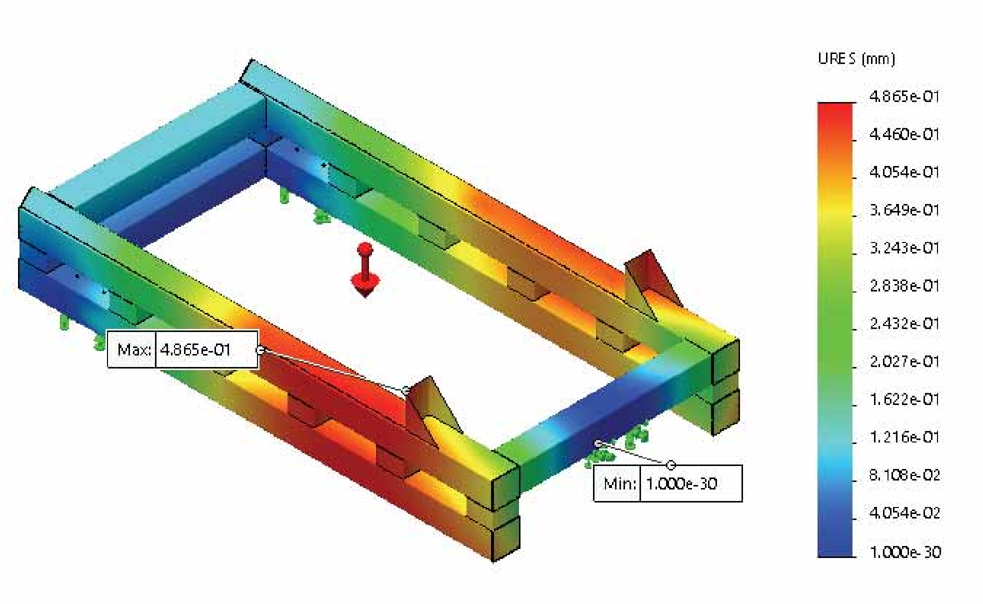


Figure 50: Frame Displacement

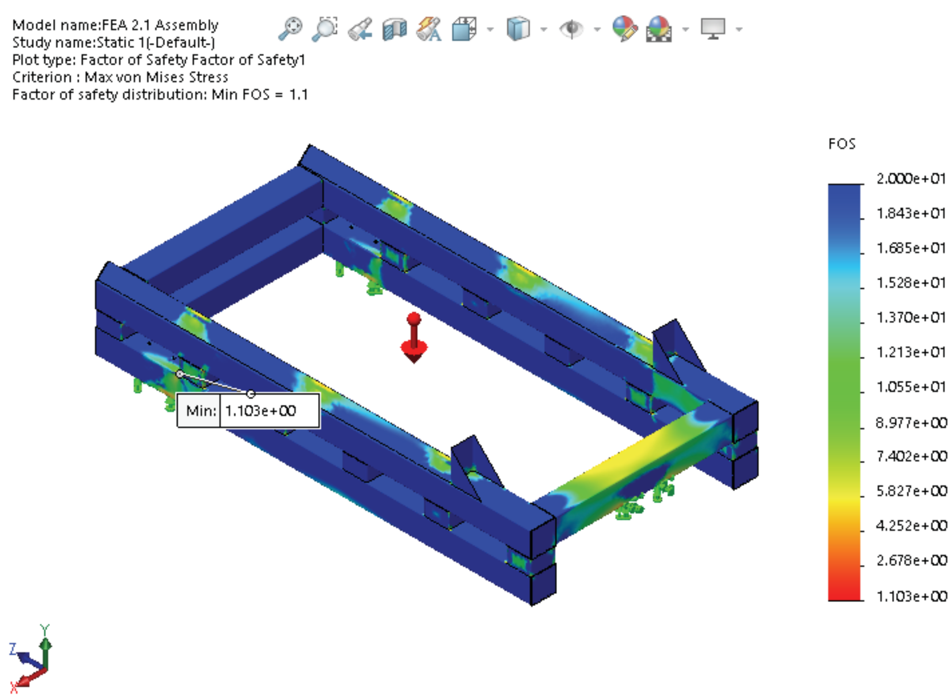


Figure 51: Frame Max Von Mises Factor of Safety

As seen in Figure 52, the final cart iteration introduced 2 changes to the previous frame; the back wheels were moved inwards, such that they are directly below one of the vertical support beams. In addition, triangular bolt-on brackets were added to the 2 vertical beams furthest from the handle as a means to combat the low factor of safety at these locations. As seen in Figure 53, the latest and final cart iteration, when subjected to an identical loading case, resulted in a maximum von Mises stress of 158 MPa, compared to 286 MPa for the previous iteration. It is worth noting that the location of the maximum stress has moved as well; the maximum stress now occurs where the steering assembly connects to the frame of the cart (Figure 53 and 55), whereas the previous maximum stress occurred at one of the vertical support beams (Figure 49). This shift of the maximum stress location can be attributed to both changes implemented in the final design iteration. Since the frame itself seems like it is subject to very high stress concentrations, a stress hotspot plot was also generated for the latest cart iteration, as seen in Figure 54. In the stress hotspot plot, the solid gray areas indicate locations in the frame where the stress values spike in magnitude compared to the surrounding stress values. Evident from the plot, a majority of the stress hotspots now occur on the newly added triangular brackets; this is advantageous since the brackets can serve as an indicator of the overall cart wear, since the stress builds up in the brackets. Since the brackets are simply bolted on to the cart frame, they can easily be replaced when needed, thus extending the lifespan of the cart as a whole. Lastly, factor of safety plot, found in Figure 55, shows that the final cart iteration has a minimum factor of safety of 1.99 at the same location as the maximum stress. This is a very conservative estimate of the true factor of safety, since the simulation modeled the area where the steering mechanism attaches to the cart frame as perfectly rigid, thus artificially increasing the stress buildup at that location since in reality, the steering mechanism would also deform slightly when the cart is loaded. Additionally, since the steering mechanism is to be welded onto the frame, this will strengthen the area where the minimum factor of safety and maximum stress occurs by a factor of 1.75. A consequence of welding is that the area just outside the weld, known as the heat affected zone, generally weakens as a result of the high temperatures needed during welding; however, the stress experienced by material in the heat affected zone are small enough such that any weakening due to the heat affected zone should not result in any additional structural vulnerabilities in the cart.

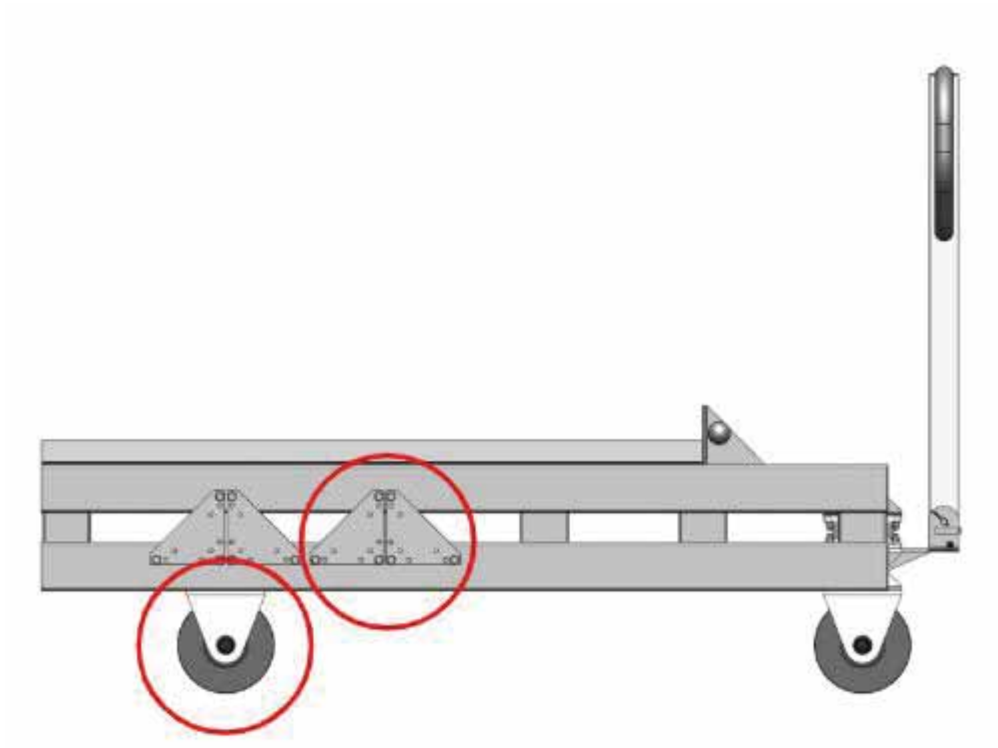


Figure 52: Cart Frame Final Adjustments

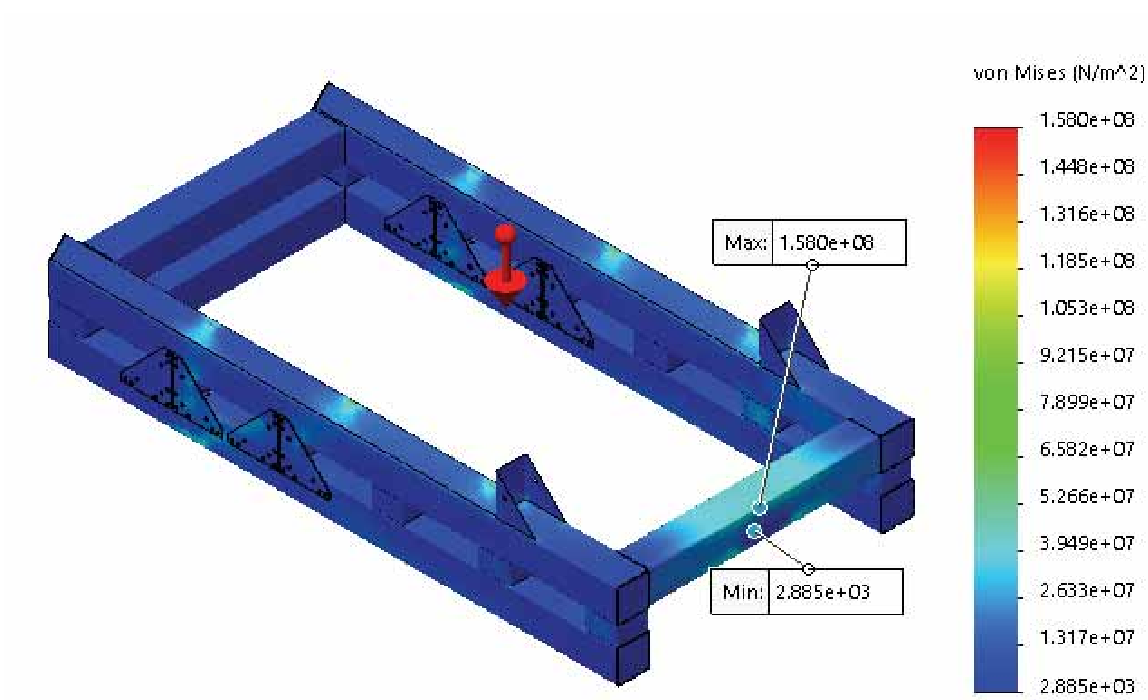


Figure 53: Frame Von Mises Stress

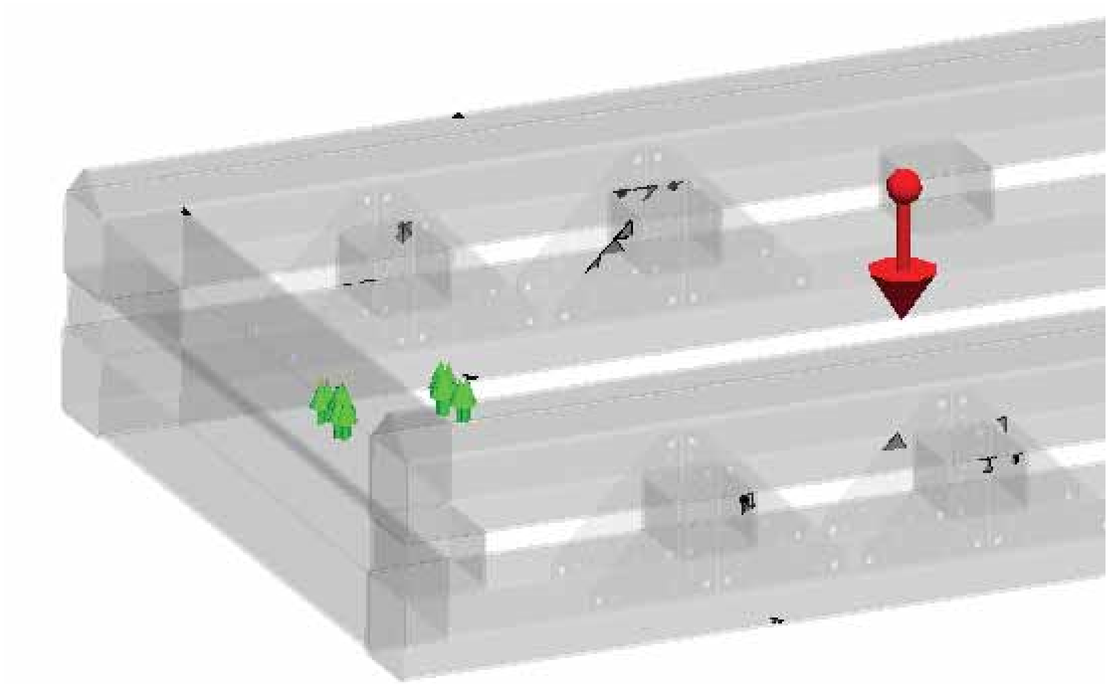


Figure 54: Stress Hotspots after Cart Frame Adjustments

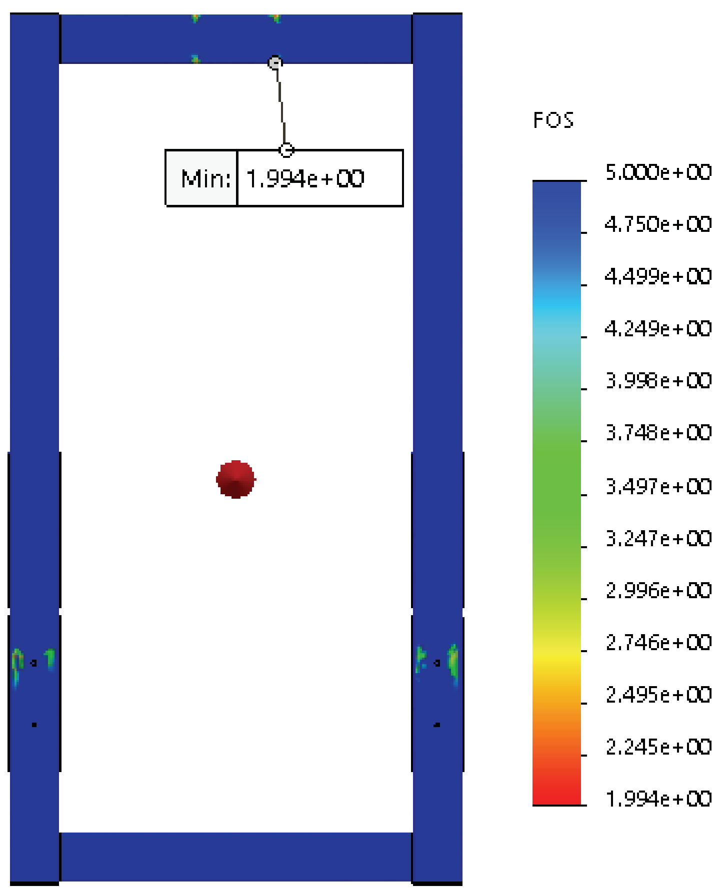


Figure 55: Frame Max Von Mises Factor of Safety

The wheels are attached to the frame via wheel forks, seen in Figure 56. A bolt serves as a fixed axle, while the wheels spin on an integrated bearing hub. The wheels are rated for a load of 33.8 kN, giving them an additional FoS of 1.8 over the manufacturer's innate FoS. The wheel forks are custom-designed pieces, so an analysis must be performed to determine their strength. In the initial design, the wheel forks were made of 0.5" AHSS steel sheets. Simulation revealed that this design has a FoS of 11, as shown in Figure 57.

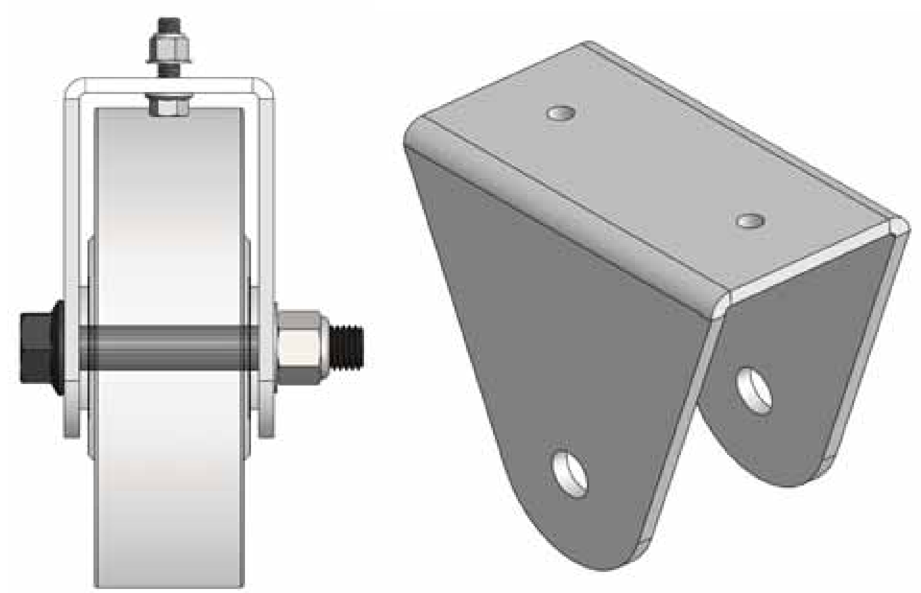


Figure 56. Wheel fork

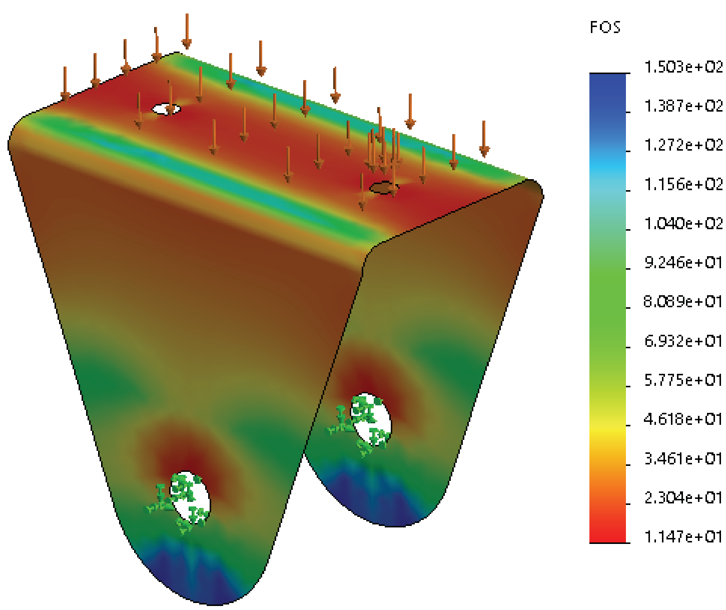


Figure 57. FEA results of 0.5" AHSS, Top Loading

However, 0.5” thick steel sheets are very difficult to bend without damaging the material, so the thickness was changed to 0.25” and the simulation was run again. The new FoS was 3.2 as seen in Figure 58.

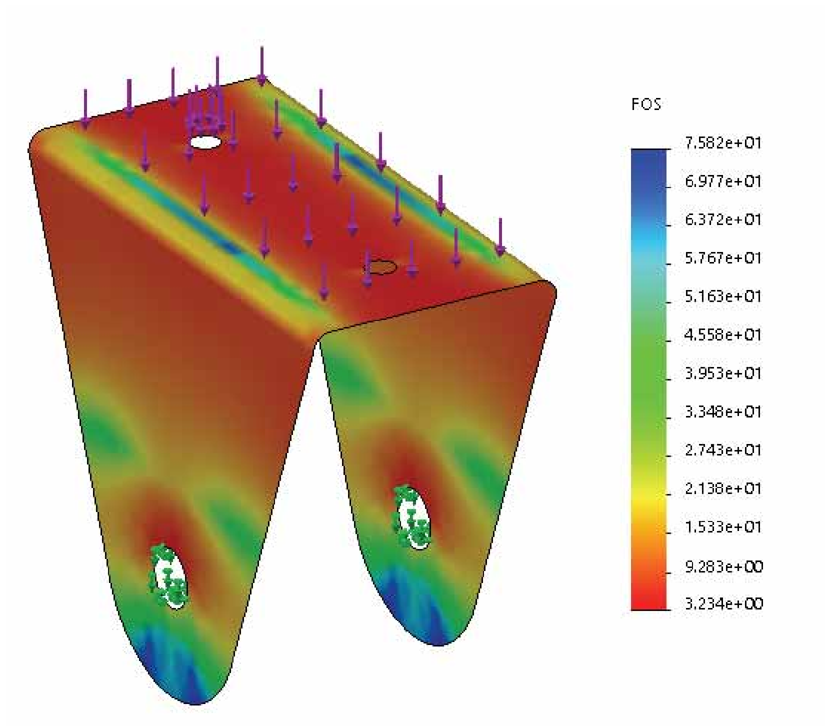


Figure 58. FEA results of 0.25 ” AHSS, Top Loading

A thickness of .157” was also tested, with a FoS of 1.3. However, adding a side-loading of 2 kN causes failure, as shown in Figure 59. Side-loading can occur if the wheel fork is not perfectly vertical. 0.25” AHSS was selected for the final design, which has a factor of safety of 1.7 even with additional side loading, as shown in Figure 60. AHSS is used because it has significant strength while maintaining the formability of weaker steels and is actually *cheaper* than weaker steels. For example, from the McMaster catalogue, for a sheet that is 24”x24” and 0.25” thick AHSS costs $114.78 whereas low carbon steel costs $224.95. Low carbon steel’s yield strength is only 35% of AHSS, however.

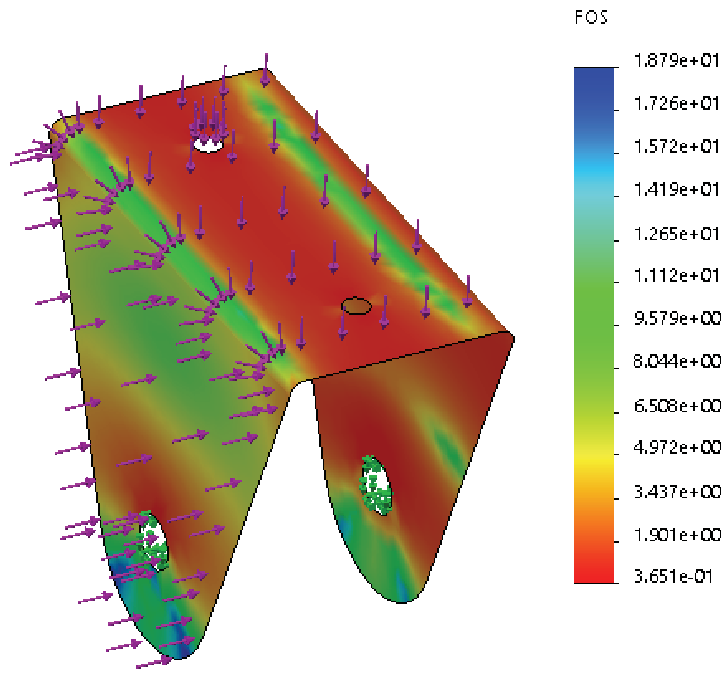


Figure 59. FEA results of 0.157 " AHSS, Top and Side Loading

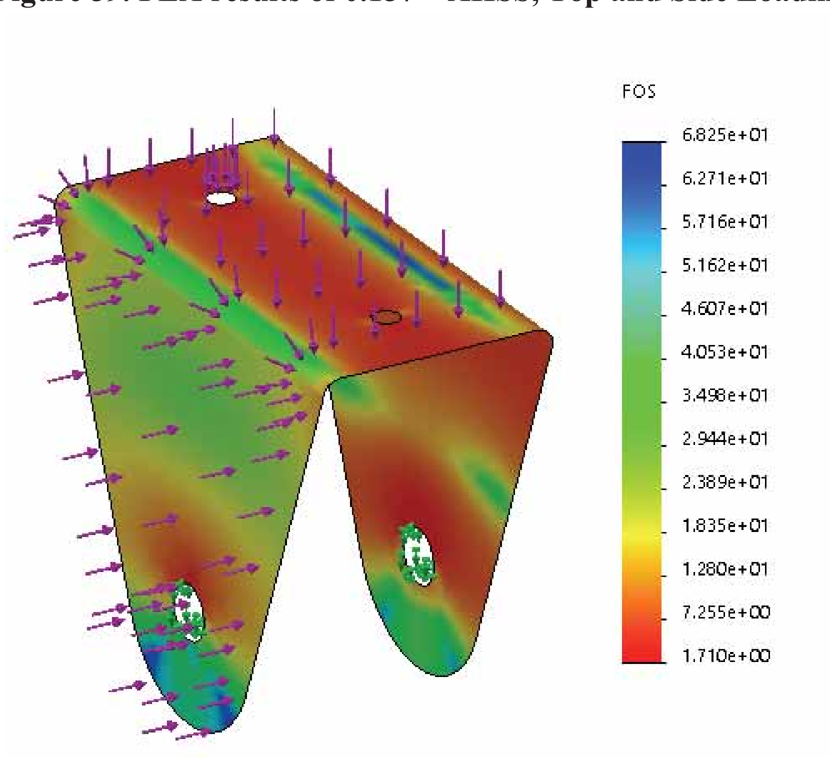


Figure 60. FEA results of 0.25 " AHSS, Top and Side Loading

The crossmember of the steering assembly is also made from a square tube. In order to keep the work surface of the cart at an ergonomic height, it was chosen to be 3” wide. Its length was set to 24” in order to maximize the stability of the rear wheels, as narrower spacing decreases stability. 24” is the maximum length that still allows for the steering assembly to turn without interference. 0.25” and 0.125” tube thicknesses will be analyzed with the aforementioned constant values.

Figure 61 shows the crossmember in the assembly. It can be modeled as a beam with one fixed end and one sliding end, as shown in Figure 62.

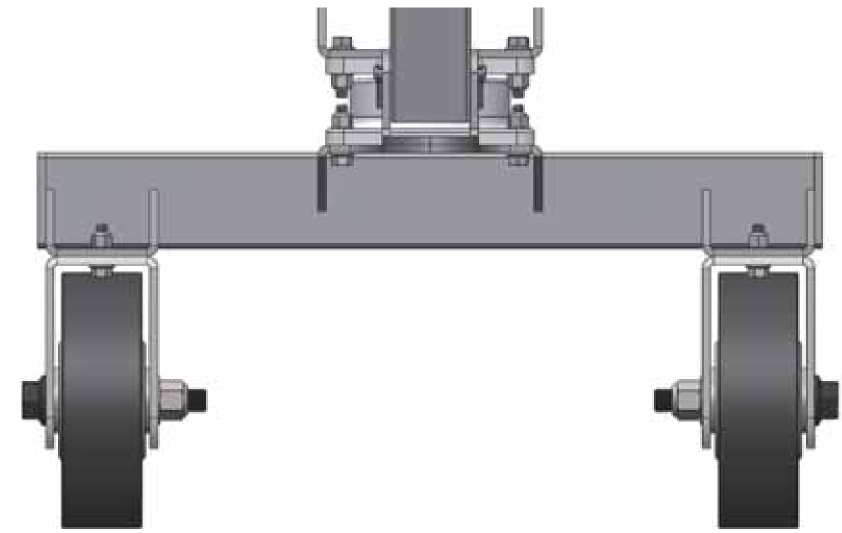


Figure 61. Crossmember in assembly

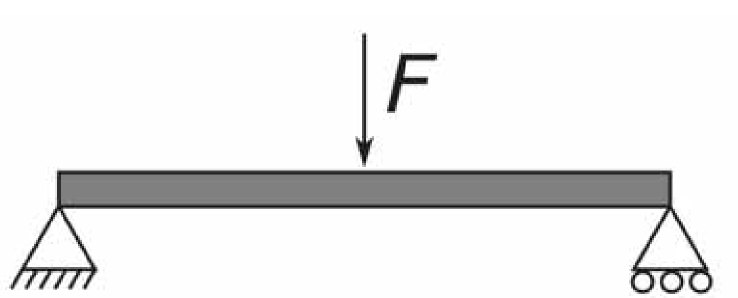


Figure 62. Crossmember FBD

Simulating this configuration with a load of 18.8 kN distributed over the area where the turntable mount contacts the beam shows that the beam has a factor of safety of 2.8 when the thickness is 0.25” and a factor of safety of 1.1 when the thickness is 0.125”. In both cases the weight of the crossmember is negligible compared to the rest of the cart, so the 0.25” thick tube was selected for its larger factor of safety. Simulation results for 0.125” and 0.25” tubes are shown in Figures 63 and 64.

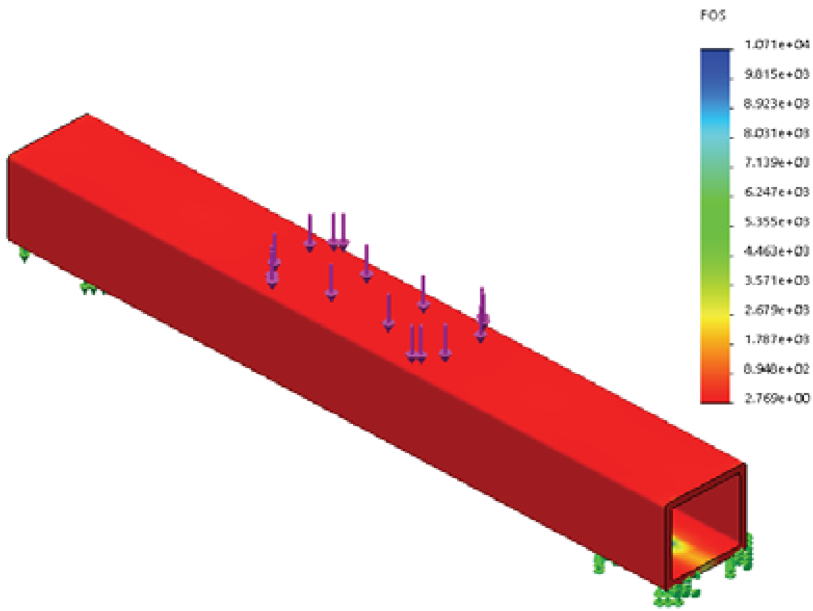


Figure 63. FEA results of 0.25” thick pipe

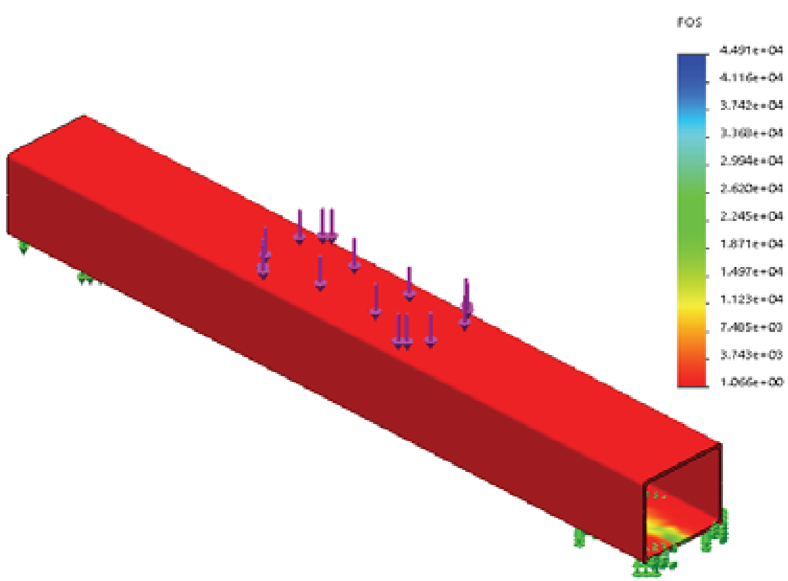
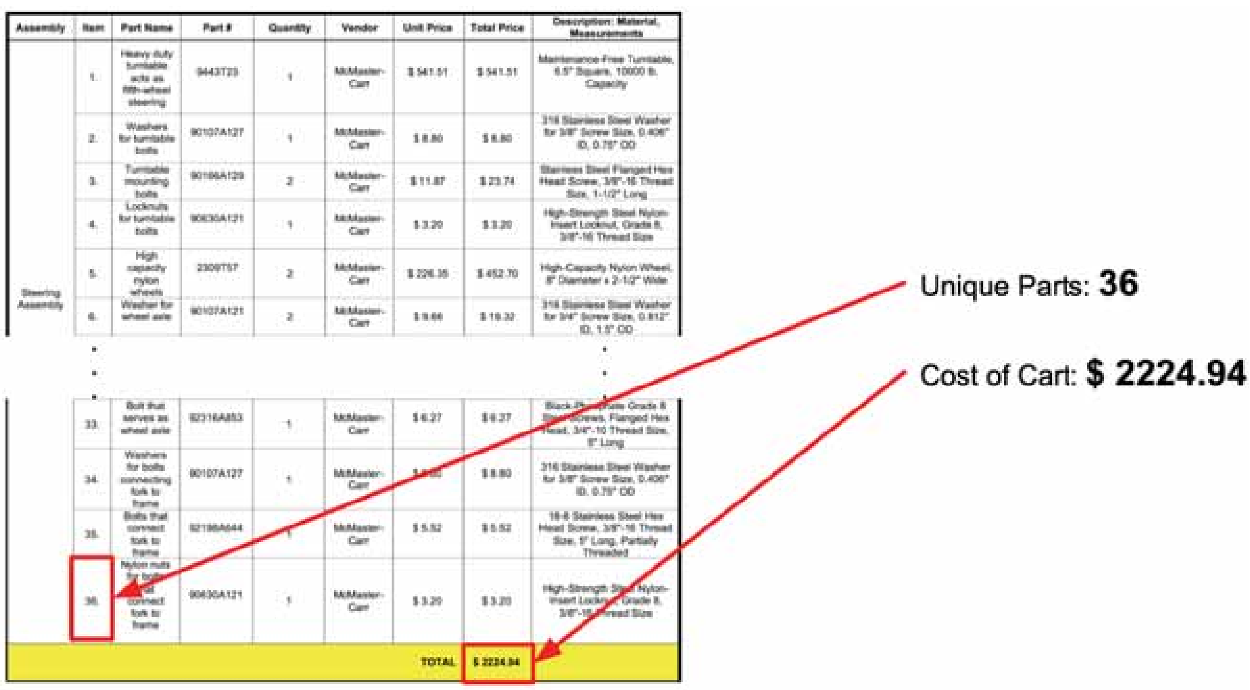


Figure 64. FEA results of 0.125” thick pipe

J. Final Design, Mockup and Prototype

The design process and final design were pitched to MHPS after few members of Team *Rotordynamics* traveled to the sponsor facility in Savannah. MHPS was supplied with a Bill of Materials and Detailed Drawings of the final design by the means of a fabrication package. The same fabrication package will also be submitted along with this report. The cart consists of 36 unique parts totaling to $2224.94, and the pallet consists of 14 unique parts totaling to $2881.83 as seen in Figures 65 and 66. The renderings of the final design are also shown in Figures 67, 68 and 69.



Assembly	Item	Part Name	Part #	Quantity	Vendor	Unit Price	Total Price	Description: Material, Measurements
Steering Assembly	1.	Heavy duty turntable acts as fifth-wheel steering	9443T23	1	McMaster-Carr	$ 541.51	$ 541.51	Maintenance-Free Turntable, 6.5" Square, 10000 lb. Capacity
	2.	Washers for turntable bolts	90107A127	1	McMaster-Carr	$ 8.80	$ 8.80	316 Stainless Steel Washer for 3/8" Screw Size, 0.406" ID, 0.75" OD
	3.	Turntable mounting bolts	90166A129	2	McMaster-Carr	$ 11.87	$ 23.74	Stainless Steel Flanged Hex Head Screw, 3/8"-16 Thread Size, 1-1/2" Long
	4.	Locknuts for turntable bolts	90630A121	1	McMaster-Carr	$ 3.20	$ 3.20	High-Strength Steel Nylon-Insert Locknut, Grade 8, 3/8"-16 Thread Size
	5.	High capacity nylon wheels	2309T57	2	McMaster-Carr	$ 226.35	$ 452.70	High-Capacity Nylon Wheel, 8" Diameter x 2-1/2" Wide
	6.	Washer for wheel axle	90107A121	2	McMaster-Carr	$ 9.66	$ 19.32	316 Stainless Steel Washer for 3/4" Screw Size, 0.812" ID, 1.5" OD
	• • •							• • •
	33.	Bolt that serves as wheel axle	92316A853	1	McMaster-Carr	$ 6.27	$ 6.27	Black-Ph[illegible]ate Grade 8 S[illegible] Screws, Flanged Hex Head, 3/4"-10 Thread Size, 5" Long
	34.	Washers for bolts connecting fork to frame	90107A127	1	McMaster-Carr	[illegible]	$ 8.80	316 Stainless Steel Washer for 3/8" Screw Size, 0.406" ID, 0.75" OD
	35.	Bolts that connect fork to frame	92196A644	1	McMaster-Carr	$ 5.52	$ 5.52	18-8 Stainless Steel Hex Head Screw, 3/8"-16 Thread Size, 5" Long, Partially Threaded
	36.	Nylon nuts for bolts [illegible] connect fork to frame	90630A121	1	McMaster-Carr	$ 3.20	$ 3.20	High-Strength S[illegible] Nylon-Insert Lock[illegible] Grade 8, 3/8"-1[illegible]hread Size
						TOTAL	$ 2224.94	

Figure 65. Highlights of Bill of Materials for the Cart

Assembly	Item	Part Name	Part #	Quantity	Vendor	Unit Price	Total Price	Description: Material, Measurements
Roller Assembly	1.	Steel for Roller Mounting	3845T412	3	McMaster-Carr	$61.22	$ 183.66	Hardened High-Strength A514 Alloy Steel, 6" x 12" x 1/2"
	2.	Steel for Roller Mounting	3845T411	3	McMaster-Carr	$41.74	$ 125.22	Hardened High-Strength A514 Alloy Steel, 6" x 6" x 1/2"
	3.	Caster	P5004200VG2	6	Steel Caster Store	$ 55.59	$ 333.54	4" x 2" Zinc Plated Steel V-Groove Caster -1500 lbs Capacity
Shaft Assembly	4.	Steel Shaft	N/A	2	Midwest Steel Supply	$ 13.56	$ 27.12	1018 Cold Roll Steel Round Bar 2-3/8" – 5.5 in
Cover Assembly	5.	Delrin Sheets	1310N37	1	McMaster-Carr	$ 91.74	$ 91.74	Black Delrin® Acetal Resin Sheet 1/2" Thick, 12" Wide x 24" Length
	6.	Top Sheet Metal	6544K75	1	McMaster-Carr	$ 107.50	$ 107.50	Low-Carbon Steel Sheet 24" x 48" x 0.1340"
Fasteners	7.	Screw # 1	92196A557	8	McMaster-Carr	$ 1.00	$ 8.00	18-8 Stainless Steel Socket Head Screw 1/4"-20 Thread Size, 3-3/4" Long
	8.	Screw # 2	92196A555	2	McMaster-Carr	$ 4.51	$ 9.02	18-8 Stainless Steel Socket Head Screw 1/4"-20 Thread Size, 3-1/4" Long
	9.	Nut # 1	92673A113	1	McMaster-Carr	$ 2.27	$ 2.27	18-8 Stainless Steel Hex Nut 1/4"-20 Thread Size, ASTM F594
Frame Assembly	10.	Frame Support 1	6566K56	4	McMaster-Carr	$ 154.48	$ 617.92	Easy-to-Weld 4130 Alloy Steel Rectangular Tube 0.065" Wall Thickness 1" High x 2" Wide Outside Size - 6 ft length
	11.	Frame Support 2	6566K56	13	McMaster-Carr	$ 89.60	$ 1,164.80	Easy-to-Weld 4130 Alloy Steel Rectangular Tube 0.065" Wall Thickness 1" High x 2" Wide Outside Size - 3 ft length
	12.	Frame Support 3	8910K37	1	McMaster-Carr	$ 119.76	$ 119.76	Low-Carbon Steel Bar, 3/4" Thick, 3" Width – 6 ft length
	13.	Frame Support 4	8910K37	1	McMaster-Carr	$ 53.89	$ 53.89	Low-Carbon Steel Bar, 3/4" Thick, 3" Width – 2 ft length
	14.	Frame Support 5	8910K702	1	McMaster-Carr	$ 37.39	$ 37.39	Low-Carbon Steel Bar, 1/2" Thick, 3" Wide – 2 ft length
						TOTAL	$ 2881.83	

Unique Parts: **14**

Cost of Pallet: **$ 2881.83**

Figure 66. Highlights of Bill of Materials for the Pallet

Figure 67. Render of the Pallet

Figure 68. Render of the Cart

Figure 69. Render of Pallet-Cart-Disk system

The final design is a cart-pallet system that serves as a mobile workstation and interfaces with an inverter to flip the discs. As seen in the diagram in Figure 70, the pallet is first loaded onto the cart, followed with the disc being loaded onto the pallet. The operator can then push/pull this cart to the desired location. To flip the disc, the operator moves the cart-pallet-disc system to an inverter where the pallet-disc system is loaded onto the inverter. Another pallet that is attached to the top of the inverter is lowered until the disc is sandwiched between two pallets. The inverter rotates, flipping the disc with it. The disc, now lying on what was previously the top pallet in the inverter, is rolled out of the inverter and the bottom pallet - now the top pallet - sits in the inverter until the next inversion.

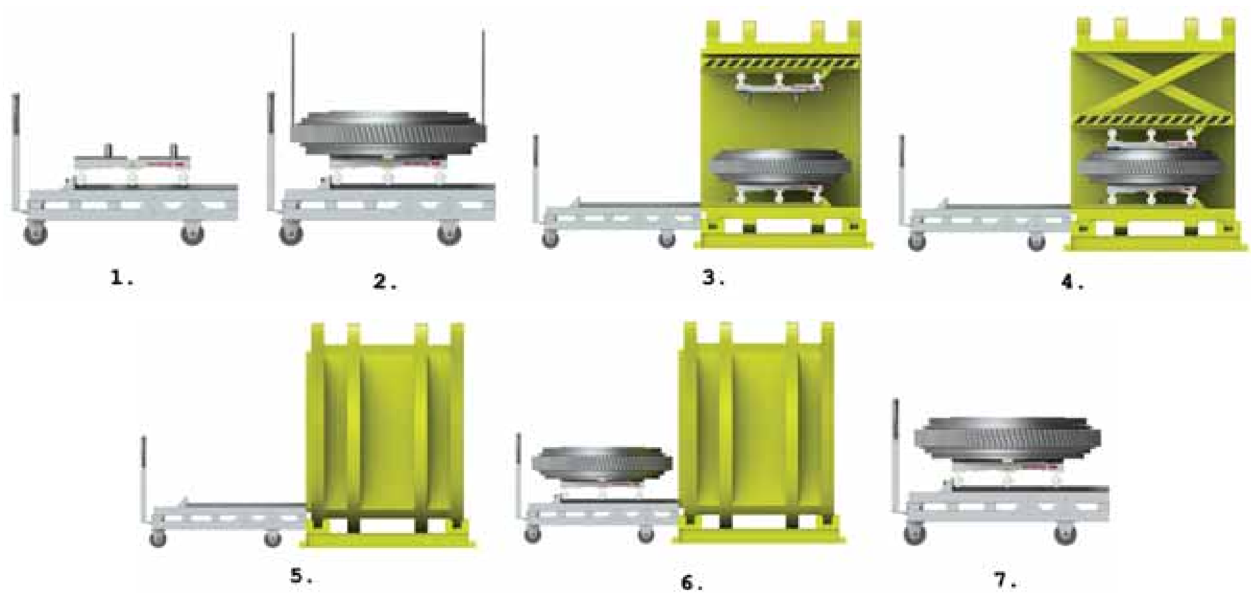


Figure 70. Diagram of the process

The theoretical detailed design meets all of the requsirements of the project as it can support all of the desired discs (maximum loading capacity of 10000 lbs), allows for the transportation and inversion of these discs, and is ergonomically suitable as a mobile workstation. MHPS also manufactured an initial prototype of the cart for the Capstone Expo, seen below in Figure 71. This prototype does not reflect everything that was in the final CAD such as safety latches and ergonomic decals, because it is a prototype that was primarily built to verify the structure that was developed in the FEA iterative design process. All components of the prototype, specifically the pallet, were not complete at that time as the manufacturing process is still in progress, therefore no prototypes have yet been tested.

Figure 71. Initial cart prototype

K. Manufacturing

MHPS ordered the materials and manufactured the initial cart prototype according to the fabrication package. Much of the material was ordered in very long beams of steel which had to be cut to specific lengths within given tolerances Figure 72. Most tolerances were +/- 0.1 in., but areas with connections had a tolerance of +/- 0.01 in.

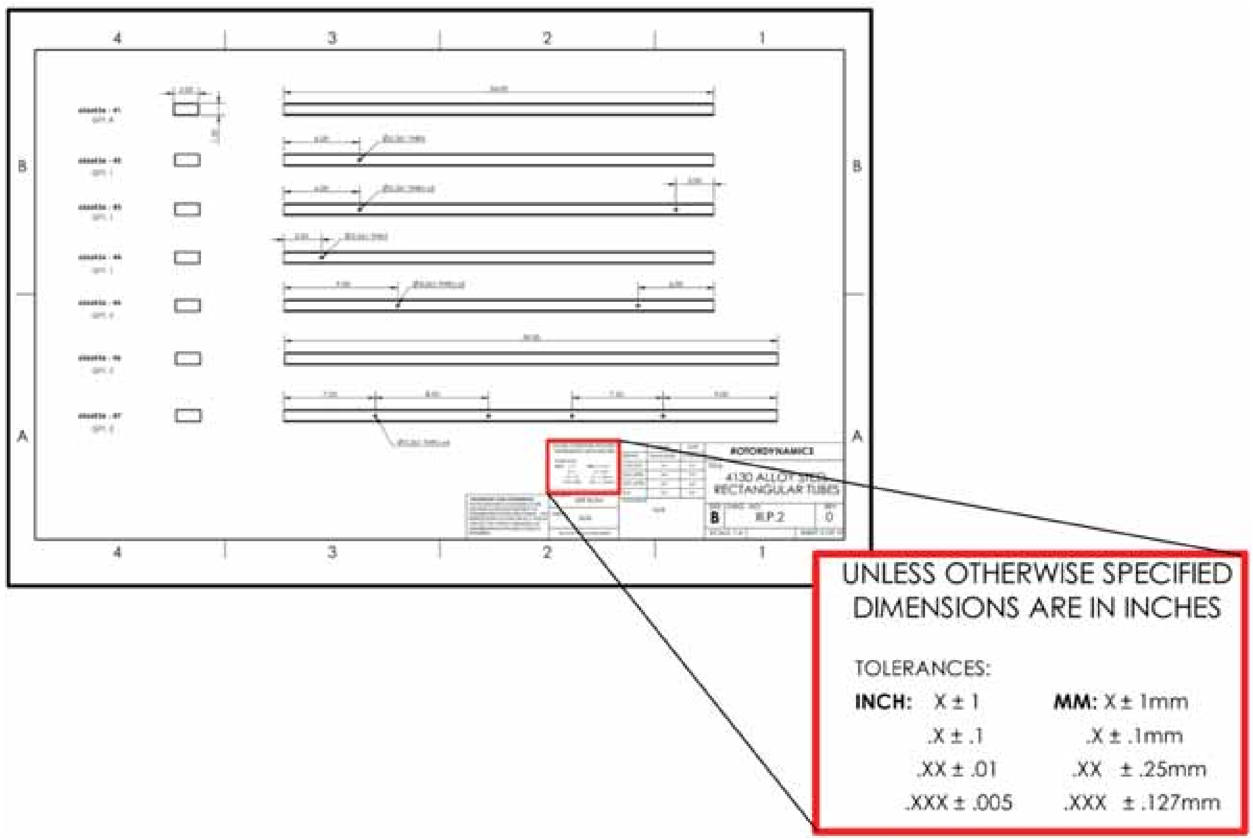


Figure 72. Example Manufacturing Drawing with tolerances

Several subassemblies assembled with bolts such as the cart handle and the Delrin pads on the pallet can be seen in Figures 73 and 74.

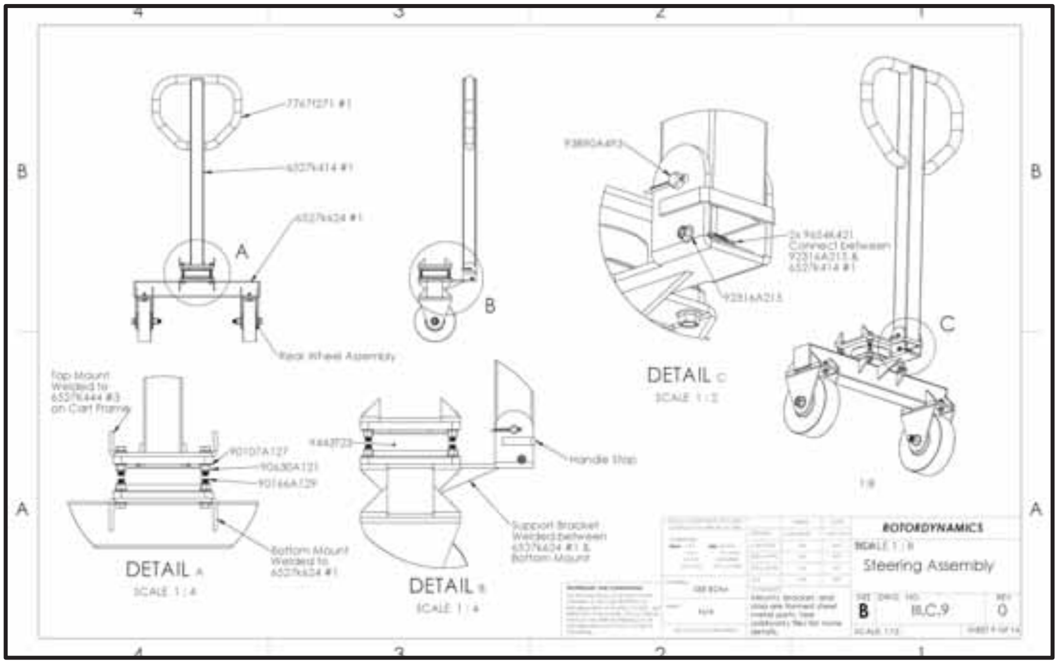


Figure 73. Manufacturing drawing of the cart steering mechanism

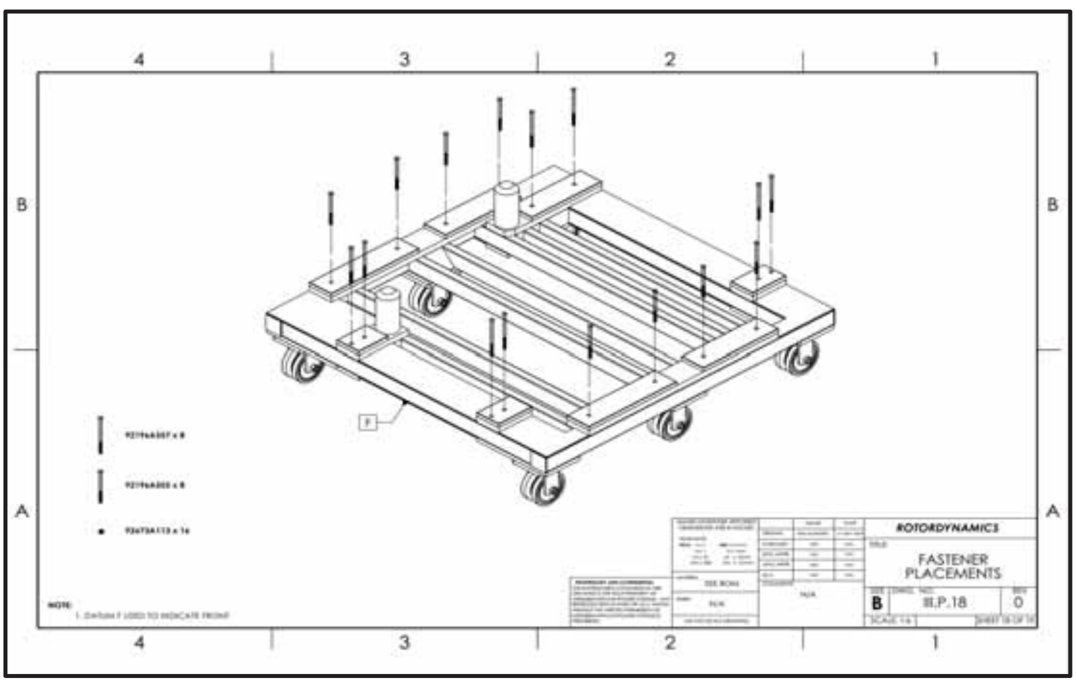


Figure 74. Manufacturing drawing of the pallet

The primary method of manufacturing used in building the prototype was welding. Assuming it is perfect, the weld would be 1.75 times stronger than the parent material (in this case steel). Furthermore, 0.25 in. radius steel welds were used to connect all the beams together. The MHPS ongoing welding process for the cart can be seen in Figure 75.

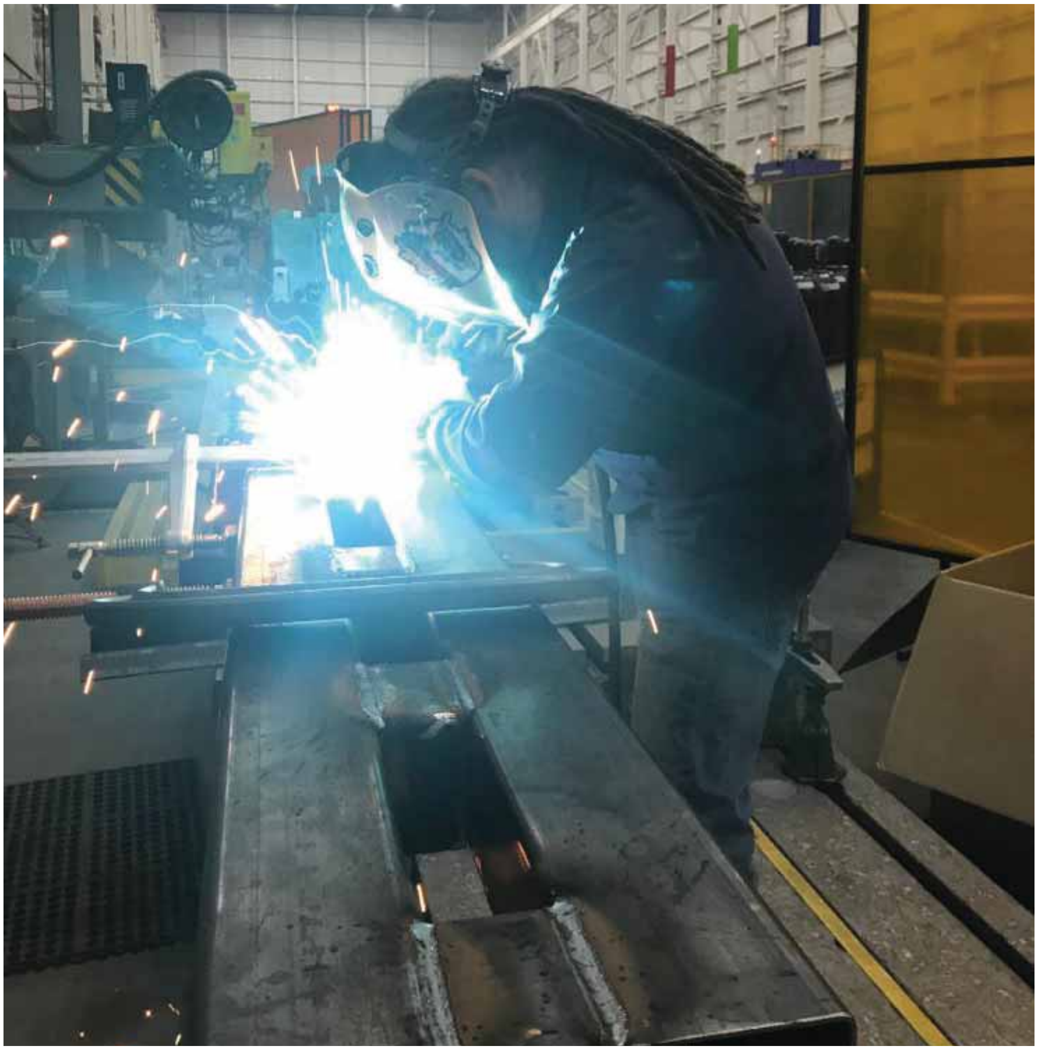


Figure 75. Professional welder in operation at MHPS facility

It is possible that MHPS will produce a large number of these carts and pallets. Because they transport twenty discs per turbine, all of which are flipped several times, it would be highly beneficial for MHPS to produce a large number of these carts and pallets to greatly speed up their inspection process. They have a large workspace which could easily store a large number of these carts and pallets.

A detailed cost analysis was conducted by Team *Rotordynamics*. Table 3 and Figure 76 show the cart cost, the pallet cost and the total cost for 7 different design iterations of this project. As seen in Figure 76, total cost was high in the first 3 design iterations. However, the cost was optimized in the following iterations using techniques of material selection and FEA simulations. The parts selection from McMaster Carr significantly aided in optimizing costs. Each design iteration was also supported with an individual FEA simulation.

Figure 77 shows the percent of total cost occupied by the cart cost and the pallet cost. In the initial design iterations, the pallet cost (approximately 80%) dominated the total cost of the project, while the cart cost (approximately 20%) was minimal. However, as further optimization was done, the curves in Figure 77 leveled out close to each other near the 50% line. The MATLAB script used for the cost analysis can be seen in Appendix B. As seen in Table 3, the cost of design iteration #7 (the final iteration before prototyping) was $5106.77. The final cost was approved my MHPS and all parts were ordered from the vendors (as listed in the Fabrication Package).

The cost of the inverter is seen in Appendix C. The original quote by Bushman Equipment Inc. puts the cost of the inverter as approximately $200,000 before any negotiations. Our sponsor, MHPS, has agreed to inquire about the quote and negotiate further as the inverter is vital for the success of this project.

Table 3. Total Cost for each Design Iteration

Iteration	Total Cost [$]
1.	$ 5808.79
2.	$ 6545.05
3.	$ 4692.28
4.	$ 4781.88
5.	$ 4971.93
6.	$ 4977.81
7.	$ 5106.77

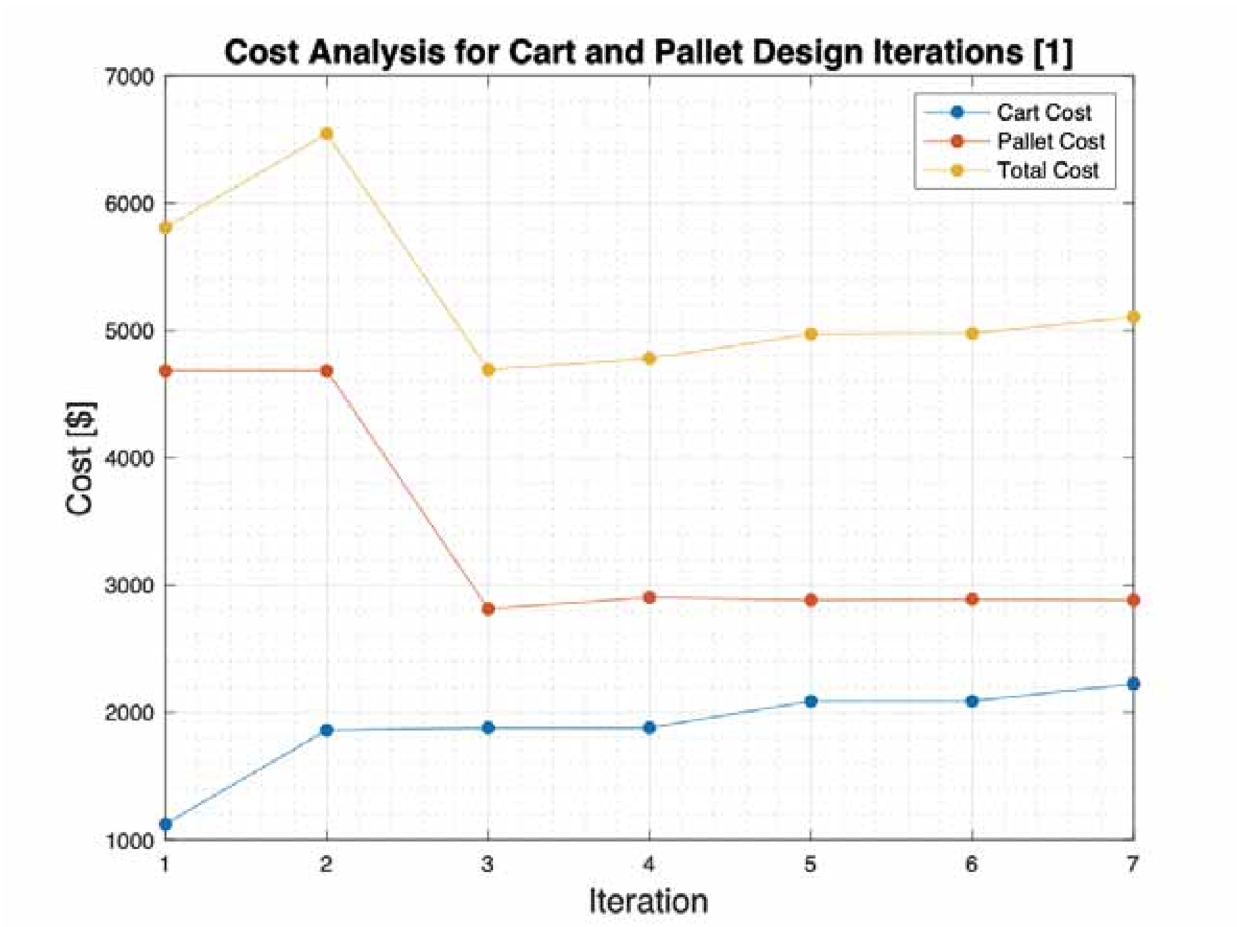


Figure 76. Cart, Pallet and Total Costs across all Design Iterations

Table 4. Total Cost for each Design Iteration

Iteration	% of Cost	% of Cost
1.	80.64%	19.36%
2.	71.57%	28.43%
3.	59.96%	40.04%
4.	60.71%	39.23%
5.	57.96%	42.04%
6.	58.01%	41.99%
7.	56.43%	43.57%

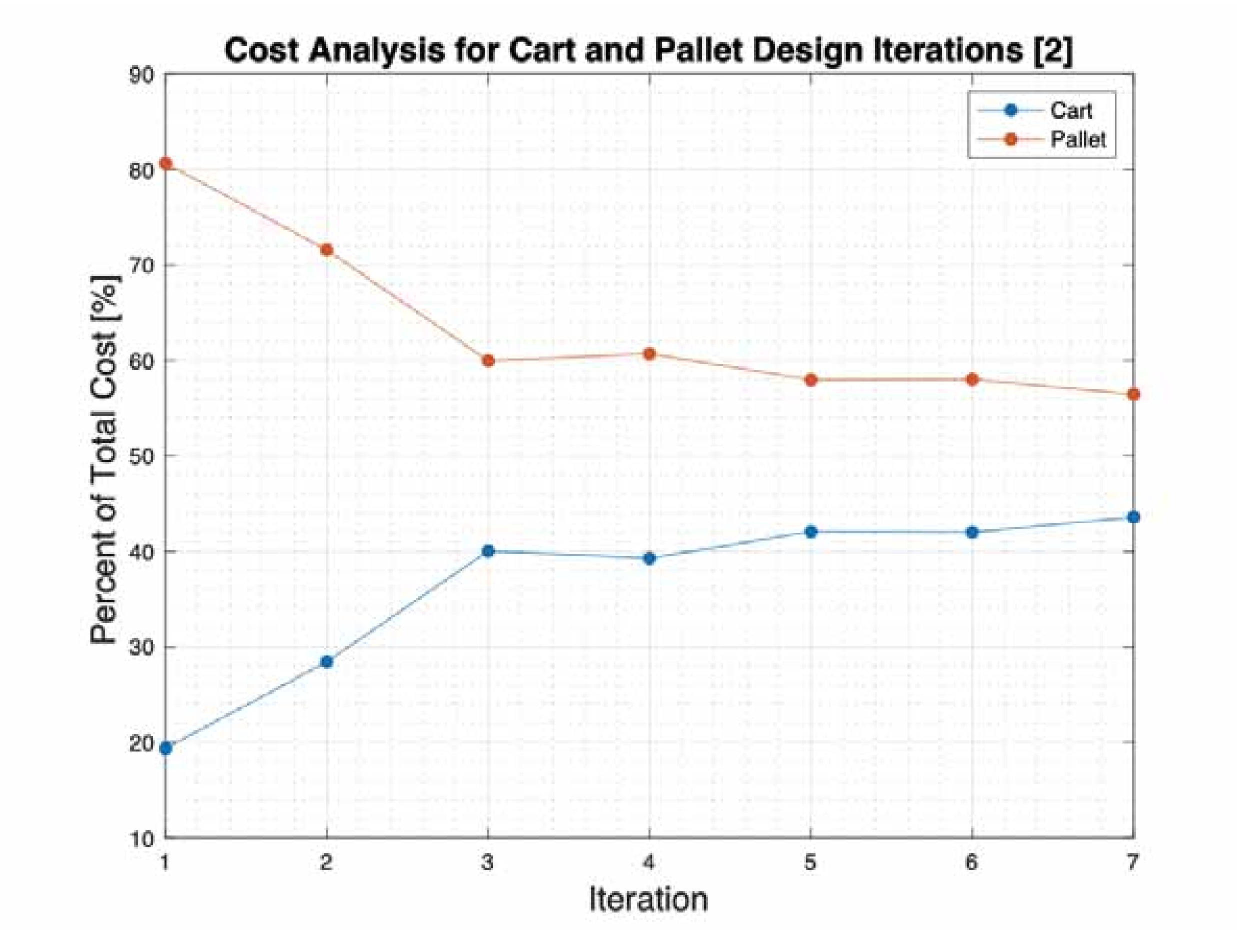


Figure 77. Cart Cost and Pallet Cost across all Design Iterations

L. Societal, Environmental and Sustainability Considerations

Several potential positive social impacts are anticipated from the lifecycle activities of the cart/pallet/inversion system. Improving the efficiency of the turbine repair process means that resources can be better allocated to both increase the lifetime of turbines as well as the rate of turbines which can be repaired. Global energy needs continue to grow rapidly, and any improvement in the turbine lifecycle will help the energy sector grow to meet these needs.

Due to the limited scope of applications for this product, direct negative impacts on society are expected to be limited. Instead, greater care will be taken with regards to the individual safety of both the workers manufacturing the system as well as the safety of the customer in their use of the system. Additionally, consideration must also be given to its end-of-life care regardless of the expected scale of product use.

The system is primarily composed of steel and Delrin. For the workers producing the system, these materials and associated manufacturing processes used are all well documented and regulated within the United States. The most potential for harm is expected to be posed to the consumers of the system. In this case, this refers to the technicians within the MHPS facility that will be using the system in their daily work routines. While the system effectively replaces dangerous overhead crane maneuvers, the danger of manually transporting significant payloads is obvious. For this reason, warning signs and well-documented safety information must be made available for the system. Significant testing of potentially harmful failure modes must be completed before the system reaches full-scale deployment.

In addition, it is also the responsibility for the consumers of our system to care for its end-of-life disposal and recycling. As stated before, the system is comprised solely of steel and Delrin components. The recyclability of steel is obvious, but the recyclability of Delrin is also high. As a thermoplastic, Delrin can be recycled using industry standard recovery techniques [7]. Thus, the ease with which the system can be recycled or sold to a scrapping company is apparent.

Section summaries of the goal and scope and inventory analysis can be found in Tables 5 and 6 respectively.

Table 5. Goal and Scope Section Summary

Objective of Assessment	Design Function	Functional Unit	Lifecycle Stages Considered	Associated Activities
Assess social impacts of the disk transportation/ manipulation system	Improve the efficiency of the turbine disk repair process.	1 cart/pallet pair	Manufacturing	Product assembly
			Product Use	Customer use of product
			End of Life	Recycling/Reuse

Table 6. Inventory Analysis Section Summary

Product Lifecycle Stage	Stakeholder Group	Social Impact Category	Impact Indicators
Manufacturing	Workers	Health and Safety	Adequate general occupational safety measures are taken [6]
Product Use	Consumers	Health and Safety	Quality of or number of information/signs on product health and safety [6]
End of Life		End-Of-Life Responsibilities	Strength of national legislation covering product disposal and recycling [6]

The design is intended to be manually operated with as little complexity as possible in a closed warehouse environment. Because of this, it has no detrimental impact to the environment and no materials that are subject to regulations. Instead, it has a positive impact - this design will replace the use of forklifts and cranes which will reduce not only time and cost, but also chemical and thermal energy output as it is purely mechanically operated. The main consideration is sustainability. MHPS intends for this design to be a reusable mobile workstation which the workers can use to transport, manipulate, and inspect the discs. To accommodate this, the design is made of high strength materials such as steel which can support repeatedly applied high loads, ensuring that the design is both reliable and reusable.

M. Risk Assessment, Safety and Liability

A risk assessment analysis was done using the risk assessment matrix in Tables 7, 8 and 9. As seen in the figure, the matrix was color-coded to indicate the risk level of each hazard. The risk level was a combination of both the severity and the frequency of each hazard. Since the design is intended to transport and flip discs, each hazard would be experienced on a regular basis, giving an A or B level frequency to each. All of the hazards also involved the manipulation of heavy loads which ran the risk of injury to the worker or damage to the system if something were to go wrong, so all the hazards had either a high or medium-level risk level. The goal of this risk assessment was to minimize these risk levels as much as possible.

Hazard No. 1, for example, was shaft failure while the disc is being inverted. At this stage, the shafts on the pallet would be bearing the full weight of the disc, so static failure was a threat. Furthermore, the pallets would be used to flip multiple discs, so the shafts would also experience fatigue that would weaken them. To mitigate this risk, the shafts were designed with an FOS of 6.2 which would guarantee that static failure of the shafts would not occur. A fatigue analysis was also done on the shafts which confirmed a fatigue life of at least 1000000 cycles - well above the number of times MHPS would use the pallet. This brought the risk level from high to low.

Hazard No. 3 was inversion operator error. The operator would have to ensure that the pallet is properly oriented when inverting the disc. This hazard had the same frequency as that of Hazard No. 1 - B level - since both were during inversion of the discs. It also had a severity level of 1 since improper orientation could cause major damage to the disc and the rest of the system. To mitigate this risk, clear decals were placed on the pallet to mark the correct orientation of the pallet. However, this would still depend on the operator reading and understanding the decals, meaning mistakes could still be made, so the risk level was brought down only to medium, though this was still better than a high-risk level.

A similar process was followed for each hazard. After the analysis and appropriate design adjustments, all of the hazards were reduced from a high-risk level to a low or medium risk level. The final risk levels were all based on severity and not on frequency as the design is meant to improve the disc inspection and cleaning process which occurs at the same frequency - about one disc every two weeks. The current analysis was deemed acceptable for initial prototyping. After the first prototype is built, further tests may reveal new hazards which will allow for further adjustments, making the design even safer.

Table 7. Risk Assessment [Section 1]

Hazard No.	Hazard	Frequency	Severity	Initial Risk Level	Mitigation	Final Risk Level
1	Shaft Failure	B	1	High	Designed with high FOS of 6.2 and guaranteed fatigue life of least 1000000 cycles	Low
2	Dynamic Loading Failure	A	1	High	Designed cart/pallet system with minimum FOS of 2	Medium
3	Inversion Operator Error	B	1	High	Placed clear labels on pallet specifying the correct orientation	Medium
4	Improper Use of Cart	A	3	Medium	Designed cart and pallet with an open base to make any other use impractical	Low
5	Unsecure Pallet	A	1	High	Implemented an automatic latching system that requires manual operation to release the pallet from the cart	Low
6	Grit Ingress	B	4	Medium	Designed open cart and pallet frame to allow grit to fall through	Low
7	Misaligned Disc on Pallet	A	4	High	Designed chamfered shafts on pallet to allow disc to slide on easier	Low

Table 8. Risk Assessment [Section 2]

Frequency of Exposure		Severity		
	Catastrophic (1)	Critical (2)	Marginal (3)	Negligible (4)
Frequency (A)	A1	A2	A3	A4
Probable (B)	B1	B2	B3	B4
Occasional (C)	C1	C2	C3	C4
Remote (D)	D1	D2	D3	D4

RISK LEVELS:

High	Medium	Low

Table 9. Risk Assessment [Section 3]

Legend		
1	Catastrophic	Major injury to operator; significant damage to disc
2	Critical	Injury to operator requiring medical attention; some damage to disc
3	Marginal	Minor injury to operator; minor damage to disc
4	Negligible	No injuries; repairable damage to disc
A	Frequent	During loading and transport of disc
B	Probable	During inversion of a disc
C	Occasional	During inspections
D	Remote	Not expected during operation of the cart-pallet system

N. Patent Claims and Commercialization

Although the cart or pallet cannot be patented as these are commonly used warehouse products, the process itself - loading a disc onto a pallet, a pallet onto a cart, and using this as a mobile workstation and to interface with an inverter - can be patented. The general criteria are that the process be new, useful, and non-obvious, which this process is as it has not been used before and it will improve operations. That being said, because this device will most likely only be used inside the MHPS workspace, it will most likely not be patented. But MHPS's largest competitors - Siemens and GE - most likely also face this same problem of disc inspection and cleaning, so it is up to MHPS to decide whether or not to patent the process if they find that it will help them stay ahead of big businesses. As far as commercialization, this product is very specific to MHPS's workspace, so it most likely will not be commercialized. However, many large companies that deal with transportation and flipping of large materials could conceivably put in a customized order for a similar process.

O. Future Work and Project Deliverables

With Week #16 coming to an end, Team *Rotordynamics* has transcended the prototyping and continuous improvement phase. Through completion and utilization of various design tools (i.e. specification sheet, house of quality, function tree, morphological chart, comparison matrices), a final conceptual design that the team felt would perform the desired functions the best was chosen. A detailed design then followed with the creation of engineering sketches, free-body diagrams, and CAD designs. The design was analyzed at a high level using fundamental stress analysis and was followed with a detailed analysis using FEA simulation, which resulted in many iterations of the design. Experiments were done as a proof of concept for the feasibility of the design. The design was then sent to MHPS for review and it was approved. An initial prototype of the cart was manufactured and brought to the capstone expo for demonstration. Next steps include finishing the fabrication of the pallet and testing the prototype to verify the simulations. This will be followed with further improvements and better prototypes until a final design is reached and the solution can officially be implemented in the MHPS factory. The progress of this design project is on track as seen in Figure 78, the Gantt Chart for Team *Rotordynamics*.

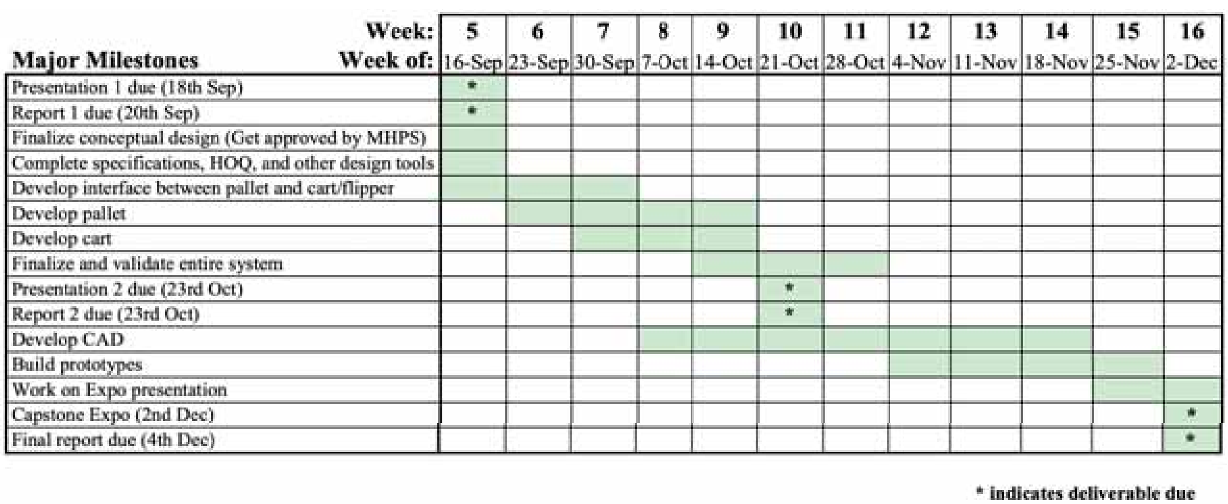


Figure 78. Gantt Chart

The team met for the last time with Dr. Wang at the Capstone Design Expo and there are no more scheduled conference calls with MHPS. While MHPS will continue improving the design, Team *Rotordynamics* has officially completed their senior capstone course, so there remains no work for them to do unless they choose to work for MHPS, at which point, they may be involved in the improvement process. But first, Team *Rotordynamics* will be graduating in the coming weeks and completing their time at the Georgia Institute of Technology as undergraduate students.

P. Summary

A roadmap summary of this Capstone Design Project can be seen in Figure 79.

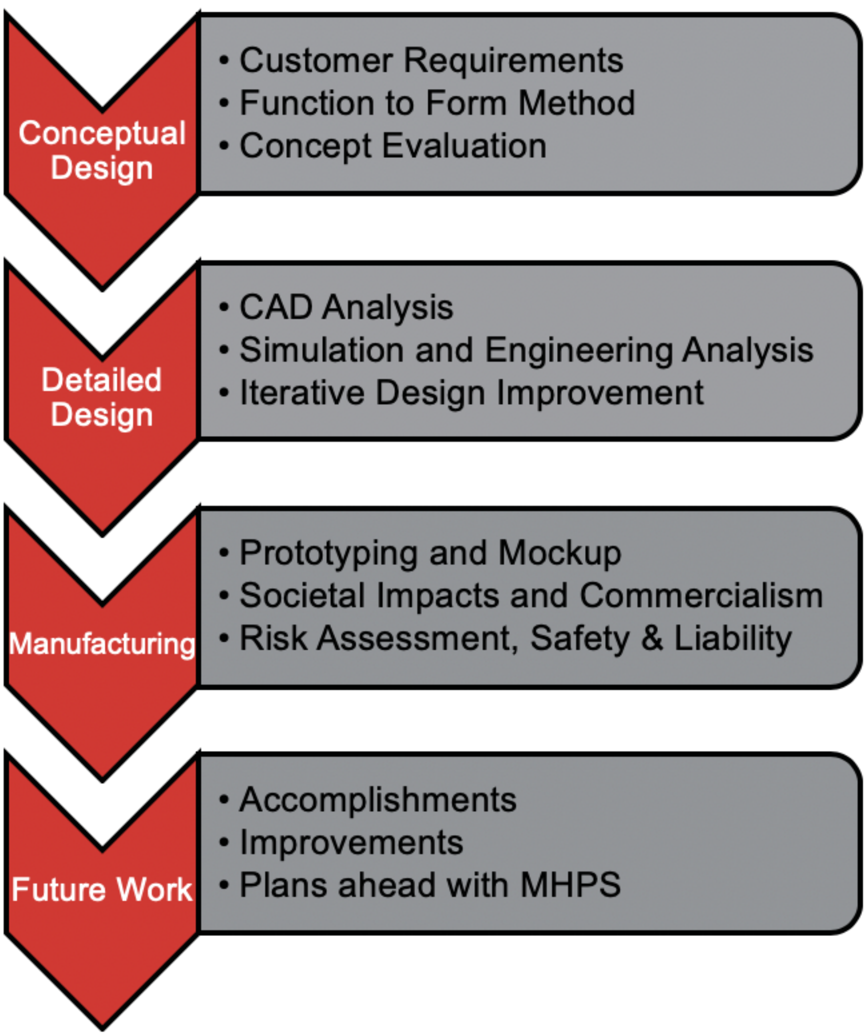


Figure 79. Roadmap Summary

Team *Rotordynamics* wishes to thank the following supporters of the project:

1. **Dr. Yan Wang**

   Professor and Primary Advisor of Team *Rotordynamics* at Georgia Tech

2. **Chris Tate**

   Advanced Manufacturing Engineering Manager at Mitsubishi Hitachi Power Systems America

3. **Alex Richardson**

   Continuous Improvement Manager at Mitsubishi Hitachi Power Systems America

4. **Callie Daniel**

   Manufacturing Engineer at Mitsubishi Hitachi Power Systems America

5. **Sam Gaskins**

   Manufacturing Engineer at Mitsubishi Hitachi Power Systems America

6. **Entire Team at MHPS**

IV. APPENDIX A

References/Citations

[1] R. Kinnicut & W. Hill, ‘Coil inverter’,US4013177A ,1977

[2] OSHA, “Important Safety Measures,” in *Materials Handling and Storage,* 2002, pp. 7-9.

[3] OSHA, “Materials Handling: Pushing, Pulling and Carrying”, *Ergonomics eTool: Solutions for Electrical Contractors.* [Online]. Available: https://www.osha.gov/SLTC/etools/electricalcontractors/materials/pushing.html. [Accessed Sept. 9, 2019]

[4] *Other portable tools and equipment.,* OSHA Standard 1910.244, 1984.

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[7] DuPont, "DuPont Delrin Acetal Homopolymer White Paper," 2015.

V. **APPENDIX B**

MATLAB Codes

Shaft Analysis:

```
% SHAFT DESIGN
% ---------------------------------------------------------------------
-----
%  Calculates the minimum diameter needed for the shafts of the pallet
%
%                        FBD
%                                                   |
%                                                   |
% ---|                                              |
%    |                                             \|/
%    |-------------------------------------------
%    |
% ---|
%
% ---------------------------------------------------------------------
-----
close all; clear; clc

%% Constants
% Disc thickness (same as shaft length) (m)
t = 0.12717;
% Disc mass (kg)
m = 3833;
% number of shafts
N = 2;
% Applied point load (N)
F = (m * 9.81) / N;
% Maximum bending moment on shaft (at fixed end) (Nm)
M = F * t;
% Desired safety factor
n = 2;
% Maximum allowable diameter of shaft (m)
Dmax = 0.0664;
% Yield strength of material (Pa) (currently using A36 steel)
Sy = 250e6;

%% Equations
% Moment of inertia of shaft (m^4)
I = @(D_) pi * D_.^4 / 64;
% Axial stress on shaft (Pa)
sigma = @(D_) M * (D_/2) ./ I(D_);
```

```
% Shear stress on shaft (Pa)
tau = @(D_) 4 * F ./ (3 * pi * (D_ / 2).^2);
% Principle stress (Pa) Note: - stress in y can be neglected (sy = 0)
s1 = @(D_) max(abs([ 0.5 * sigma(D_) + sqrt((0.5 * sigma(D_)).^2 +
tau(D_).^2);...
    0.5 * sigma(D_) - sqrt((0.5 * sigma(D_)).^2 + tau(D_).^2) ]));
% Von Mises Stress
sv = @(D_) sqrt(s1(D_).^2 + 3 * tau(D_).^2);

%% Calculate minimum diameter
f = @(D_) (Sy ./ sv(D_));
D = fzero(@(D_) f(D_) - n,0.1);
fprintf('The minimum required diameter for a safety factor of %.2f is
%.2f mm.\n',n,D * 1000);

%% Plot
figure; hold on
fplot(f,[ 0.001 0.1 ],'k-','HandleVisibility','off');
plot(D,f(D),'ro');
plot([ Dmax Dmax ],[0 f(0.1) ],'b--');
grid on; grid minor

legend('Selected Diameter','Maximum Diameter','Location','Northwest');
xlabel('Shaft Diameter (m)');
ylabel('Safety Factor');
title('Safety Factor vs Shaft Diameter');
```

Cost Analysis:

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Syntax: costAnalysis.m
% Description: Cost Analysis for Team Rotordynamics
%
% Inputs: none
%
% Outputs: none
%
% Author: Parth Patki
% Course: ME 4182-A
% Year: Fall 2019
% Instructor: Dr. Yan Wang
% Institute: Georgia Tech
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%% ------------------------ BEGIN CODE ------------------------
close all; clear; clc

% cart [qty 1] cost per revision
cart_rev = [];
cart_rev(1) = 1124.37; % $
cart_rev(2) = 1860.63; % $
cart_rev(3) = 1878.76; % $
cart_rev(4) = 1878.76; % $
cart_rev(5) = 2090.10; % $
cart_rev(6) = 2090.10; % $
cart_rev(7) = 2224.94; % $

% pallet [qty 1] cost per revision
pallet_rev = [];
pallet_rev(1) = 9368.84/2; % $
pallet_rev(2) = 9368.84/2; % $
pallet_rev(3) = 2813.52; % $
pallet_rev(4) = 2903.12; % $
pallet_rev(5) = 2881.83; % $
pallet_rev(6) = 2887.71; % $
pallet_rev(7) = 2881.83; % $

% total cost per revision
total_rev = cart_rev + pallet_rev; % $

% percent total cost per revision
cart_rev_percent = cart_rev./total_rev;
pallet_rev_percent = pallet_rev./total_rev;

% plot
figure(1)
p1 = plot(cart_rev,'o-','MarkerSize',5);
set(p1, 'markerfacecolor', get(p1, 'color'));
hold on

p2 = plot(pallet_rev,'o-','MarkerSize',5);
```

```
set(p2, 'markerfacecolor', get(p2, 'color'));

p3 = plot(total_rev,'o-','MarkerSize',5);
set(p3, 'markerfacecolor', get(p3, 'color'));

grid on; grid minor
xlabel('Iteration','FontSize',15)
ylabel('Cost [$]','FontSize',15)
legend('Cart Cost','Pallet Cost','Total Cost','FontSize',10)
xticks(0:length(cart_rev))

title('Cost Analysis for Cart and Pallet Design Iterations
[1]','FontSize',15)

figure(2)
p4 = plot(cart_rev_percent*100,'o-','MarkerSize',5);
set(p4, 'markerfacecolor', get(p4, 'color'));
hold on

p5 = plot(pallet_rev_percent*100,'o-','MarkerSize',5);
set(p5, 'markerfacecolor', get(p5, 'color'));

grid on; grid minor
xlabel('Iteration','FontSize',15)
ylabel('Percent of Total Cost [%]','FontSize',15)
legend('Cart','Pallet','FontSize',10)
xticks(0:length(cart_rev))

title('Cost Analysis for Cart and Pallet Design Iterations
[2]','FontSize',15)

%% ------------------------ END CODE -------------------------
```

VI. **<u>APPENDIX C</u>**

VII. **Quote from Bushman Equipment Inc. for inverter on succeeding pages**

Custom Designed Material Handling Solutions
BUSHMAN EQUIPMENT, INC.®

Mailing address
P.O. Box 309
Butler, WI 53007-0309

Shipping address
W133 N4960 Campbell Dr.
Menomonee Falls, WI 53051

Phone (262) 790-4200
FAX (262) 790-4202
www.Bushman.com • Custinfo@Bushman.com

QUOTE NUMBER GQ-20-092519-4

Date
September 25, 2019

Tom Bamford
Georgia Tech
Email: Tom.Bamford@Live.com

BUDGET QUOTE

Ship Via	Delivery Terms	Payment Terms
MOST COST EFFICIENT	FOB - Origin Prepay & Add	See Below

TERMS OF PAYMENT ARE SUBJECT TO CREDIT APPROVAL AT TIME OF ORDER!

Payment Terms:
25% invoiced upon receipt of purchase order
50% invoiced 60 days before scheduled ship date
Balance invoiced at shipment
All payments due net 30

ITEM	DESCRIPTION	QUANTITY	NET PRICE	NET EXT. PRICE
MODEL IC	**INVERTER IC FRAME STYLE**	**1.0**	**$200,000.00**	**$200,000.00**

Material Information:

Material to be inverted: Steel Discs

Material Dimensions: 70” diameter x 24” tall

Center of Gravity: Physical Center.

Material Weight: 9,000 LBS.

Inverter Information:

Bushman Model: IC-10000

Capacity: 10,000 lbs.

Rotation: 180 degrees.

Platform Dimensions: 72” Deep x 72” Wide

Max Opening Height: 30”

Min Opening Height: 22”

Clamp Stroke: 8”

Custom Designed Material Handling Solutions
BUSHMAN EQUIPMENT, INC.®

Mailing address
P.O. Box 309
Butler, WI 53007-0309

Shipping address
W133 N4960 Campbell Dr.
Menomonee Falls, WI 53051

Phone (262) 790-4200
FAX (262) 790-4202
www.Bushman.com • Sales@Bushman.com

QUOTE NUMBER GQ-20-092519-4

Date
September 25, 2019

Description: A custom-engineered 180-degree C-frame-type load inverter with one fixed platform and one moveable platform (for clamping) will be shipped fully operational with the following features:

Heavy-duty construction including;

- A welded steel inversion cradle (two circular cradle plates and two circular chain plates) mounted on 4 machined steel bogey wheels with lubricated roller bearings.
- Chain drive powered via sprockets and a gear motor with brake combination.
- Limit switches to limit the ends of rotation and mechanical over-travel stops.
- Maintenance safety pins for the load platforms and the barrel rotation.

The clamping action provided by dual acting hydraulic cylinders. The moving platform will move toward the fixed platform and clamp the load before it can be rotated.

Hydraulic power unit is provided with solenoid valves, pump, and pump motor, reservoir with oil, high quality breather and manifold block. HPU will be a remote mounted unit. Hydraulics for cylinders will be introduced into the inverter by a pair of rotary swivel couplers.

Motor controller mounted in electrical enclosure for semi-automatic operation and provided separately. Unit is wire for 460/3/60 VAC unless otherwise specified. The controls will consist of a manual & automatic switch. In manual, the operator has the ability to initiate all of the motions separately. In automatic, he has two buttons; Invert & Home.
A photo-eye arrangement will be provided between the two load platforms so that the unit will not rotate if a load is seen on the platform and the load is not clamped.

The customer will be responsible for preventing the operator or others from coming in contact with the equipment during operation. Auxiliary safeguards including (but not limited to) sensing devices, mechanical obstructions and guards designed for customer's unique application should be used to prevent injury to personnel and is the responsibility of the customer.

Activation Sequence:

1. The inverter is loaded with a fork truck.
2. The operator selects "Invert" button.
3. The clamping mechanism will close until the pressure switch is engaged and the load secured.
4. The barrel will rotate 180 degrees until the position limit switch is engaged.
5. The clamping mechanism will retract once the rotation is complete and the inverter has come to a stop.
6. The load may be removed with a fork truck.
7. To return the inverter to its starting position, the operator will select "Home" and the unit will rotate 180 degrees to the starting point.

Approximate shipping weight: 10,000 lbs.

Custom Designed Material Handling Solutions
BUSHMAN EQUIPMENT, INC.®

Mailing address
P.O. Box 309
Butler, WI 53007-0309

Shipping address
W133 N4960 Campbell Dr.
Menomonee Falls, WI 53051

Phone (262) 790-4200
FAX (262) 790-4202
www.Bushman.com • Sales@Bushman.com

QUOTE NUMBER GQ-20-092519-4

Date
September 25, 2019

Paint: One prime coat plus one top coat of Bushman Safety Yellow enamel

Drawing approval: required prior to fabrication. Approval drawings will be dispatched 3-4 weeks ARO.

Delivery: approximately 22-26 weeks after receipt of signed approval drawings.

Manuals: Two Installation, Maintenance Instruction and Parts Manuals will be provided.

The following items or services are NOT included in our above price:

- Sales or use taxes
- Export packaging.
- Freight to jobsite.
- Factory load testing full or partial (we will perform factory functional tests of moving parts).
- Field installation, startup & checkout, load testing, minor adjustments during product break in period, inspections or preventive maintenance.
- Safety fencing for perimeter of unit.

Warranty: Twelve (12) months from date of shipment, covering defects in material and workmanship and does not include field labor. Full warranty terms are disclosed in a separate document available upon request.

Proposal validity: Our offer is valid for 30 days from date of this quotation.

Bushman Equipment, Inc.'s current standard terms and conditions: Terms and Conditions for the sale of goods or services can be found at our website, www.bushman.com. All sales are subject to these standard terms and conditions of sale and these terms and conditions are incorporated by reference into all quotations, proposals or sales acknowledgements issued by Bushman Equipment as if expressly set forth therein. All quotations or proposals issued by Bushman Equipment are an offer to sell the products or services specified pursuant to the standard terms and conditions.

Paul Karrels
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