Mech Masters: Sketch Model Challenge

Shagufta Naaz, Hong Wei Tan, Vincent Mei, Saksham Malik, Dylan Sokol and Alexander OClaire
MMAE 432: Design of Mechanical Systems
Illinois Institute of Technology

***Abstract*—The objective of this report is to describe the process of designing and building a device for the sketch model challenge. This device is made from XPS foam board and cardboard pipes. The strength of these materials were analyzed through experimentation. Initially, few designs were hand-sketched by each member of our team. Then, using a Pugh chart, an optimal design was selected. This device was designed using CAD software and evaluated with finite element stress analysis (FEA). This report details the different techniques used such as the design process, stress concentration analysis, strengthening and prototyping. Finally, the device was assembled and tested. The final design of the device proved to be successful and was able to meet all the functional requirements.**

I. Introduction

The goal of the sketch model challenge is to help students learn about the design process and to understand craftsmanship. For this challenge, we had to create a device that could be pushed or pulled while carrying a fellow group member during a game of dodge-ball. The design process for this device involved drawing hand sketches, experimentation and evaluating the device using Pugh chart and stress analysis. The sketch chosen by the decision matrix was designed using CAD software. It was then assembled and tested. Fig. 1 shows the final prototype of the device that was successful in completion of the sketch model challenge. This report describes the functional requirements, design evaluation, and results of the prototype.

II. Functional Requirements

As a team, we picked out the following functional requirements for our device:

- Hold a $170kg(235lb)$ and $6'3$" tall rider
- Weigh less than $25lb$
- Traverse at least $1km(3280ft)$ in snow or grass
- Be able to rotate/turn $360°$
- Have a maximum seat height of 16
- Maintain a $0°$ angle with the ground for the rider

Based on the above functional requirements, our team picked the top three design sketches that were evaluated using a Pugh chart (see Table 1). This chart was used as a decision matrix to select the most optimal design of the prototype. Design 1 was used as the datum. The concepts evaluated using a Pugh chart were:

- Maneuverability
- Style
- Strength
- Durability

Fig. 1: The Final Prototype: Rickshaw Cart

TABLE I: Pugh Chart

Criteria	Weight	Design #1(Datum)	Design #2	Design #3
Maneuverability	2	0	+	-
Style	1	0	+	+
Strength	3	0	-	-
Durability	3	0	-	+
Total		0	-3	-1

As a result of using the Pugh Chart, design 1 seemed most reasonable. The tube style device looked elegant but lacked in strength and durability and the rocker bogie style was a complex design. It was harder to assemble this device with foam board and cardboard pipes. This design would have required more heavy weight materials which would have a incurred a huge cost for us. Thus, to maintain a lightweight and most efficient design, we chose the rickshaw style.

III. Design Concept Generation

After the generic shape of our Sketch Model Challenge was chosen, the team decided to break down the device into four key design areas: the design of the wheels, the design of the interface between the main axle and the wheels, the chassis design, and the rider area design. The way the rider ”sits” in this device changed from the initial sketch idea of sitting shown in figure 2, to laying down on the device. This decision was made to help distribute the load across the entire foam instead of being a point load, which lowers the chance of the foam fracturing due to shear force and bending stress.

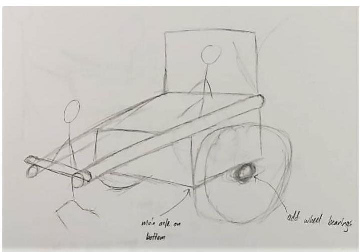


Fig. 2: Design 1 - Rickshaw Style

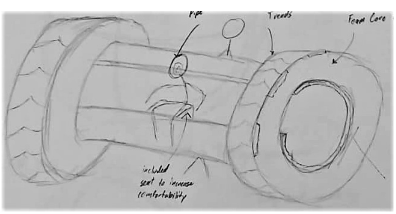


Fig. 3: Design 2 - Tube Style

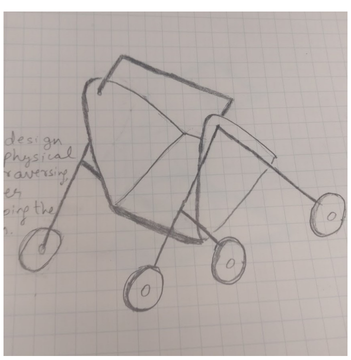
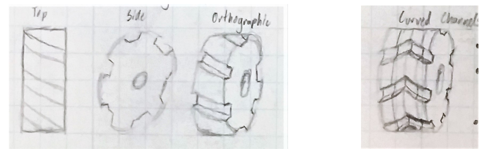


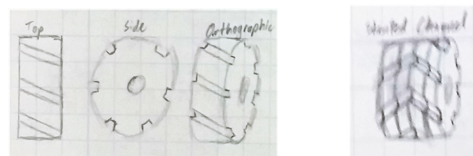
Fig. 4: Design 3 - Rocker-Bogie Style

For the wheel design, there were four different concepts that we came up with: the curved channeled tire (see figure 5), the slanted channeled tire (see figure 6), the straight channeled tire (see figure 7), and the solid tire (see figure 8). The channels are meant to help increase traction in anticipation of snow-covered ground.



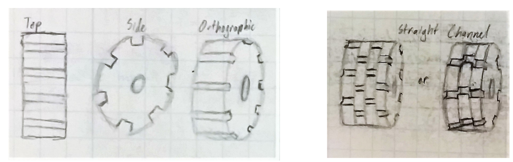
(a) Single Layer (b) Multilayered

Fig. 5: Curved channel design



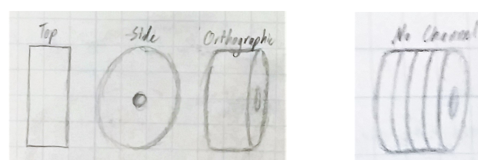
(a) Single Layer (b) Multilayered

Fig. 6: Slanted channel design



(a) Single Layer (b) Multilayered

Fig. 7: Straight channel design



(a) Single Layer (b) Multilayered

Fig. 8: Solid tire design

In order to determine which design for the wheels we wanted to go forward with, we used a design matrix to evaluate different criteria of what our wheel should have (see table II).

TABLE II: Wheel Design Decision Matrix

Wheel Decision Matrix									
		Curved Channels		Straight Channels		Slanted Channels		Solid Wheel	
Criteria	Weighting	Score	Total	Score	Total	Score	Total	Score	Total
Style	2	3	6	1	2	2	4	1	2
Strength/Durability	4	2	8	2	8	2	8	4	16
Cost	3	3	9	3	9	3	9	3	9
Creativity	3	3	9	1	3	2	6	1	3
Traction	4	3	12	2	8	3	12	1	4
Grip	4	3	12	3	12	3	12	1	4
Feasibility	5	1	5	3	15	3	15	5	25
	Total Score		61		57		66		63

The winning design for our wheels were the slanted channel wheels. This design achieved the job of adding traction and grip to our wheels. The design also allowed for snow to escape from our tires without the added complexity of manufacturing the curved channels on the wheels.

For the design of the interface between the main axle and the wheels, there were three different design concepts that we came up with: nothing between axle and wheels (see figure 9), creating a bearing between the axle and wheels (see figure 10), and having tape or paper between the axle and wheels (see figure 11). The purpose of this was to ensure that our wheel would still be able to rotate while on the main axle. It was also noted that the XPS foam could be easily torn through shearing.

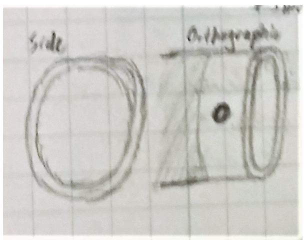


Fig. 9: Cardboard and XPS foam rubbing

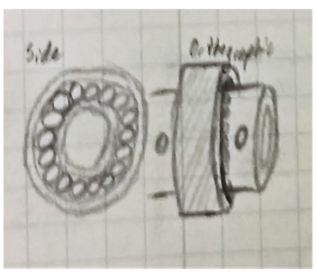


Fig. 10: Dowel bearings

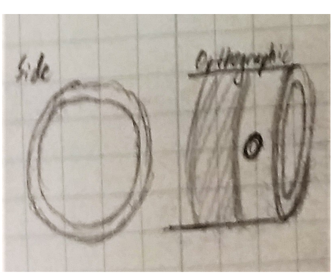


Fig. 11: Duct Tape or Wax/Parchment Paper

In order to determine which design for the interface between the main axle and tire we wanted to move forward with, we used a decision matrix to evaluate different criteria of what our interface should have (see table III).

TABLE III: Interface Decision Matrix

Main Axle Decision Matrix									
		Nothing		Wheel Bearing		Wax/Parchment		Duct Tape	
Criteria	Weighting	Score	Total	Score	Total	Score	Total	Score	Total
Style	2	1	2	3	6	2	4	2	4
Strength/Durability	4	1	4	3	12	2	8	2	8
Cost	3	5	15	1	3	3	9	3	9
Creativity	3	1	3	3	9	2	6	2	6
Mating Friction	4	1	4	4	16	3	12	2	8
Feasibility	5	4	20	3	15	4	20	5	25
	Total Score		48		61		59		60

The winning design for our interface was the wheel bearing design. By sandwiching wooden dowels between two concentric cardboard tubes, we allow the wheel to rotate independently of the main axle.

For the design of the chassis, we decided to go with a simple and robust design showcased in figure 12.

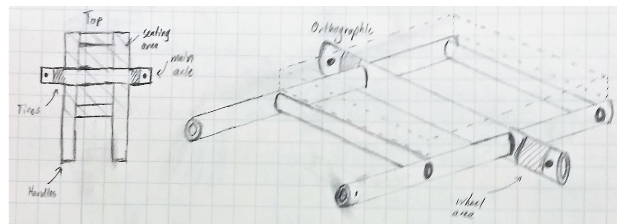


Fig. 12: Chassis design

For the rider area design, we came up with two different designs: a single piece of XPS foam board and sandwiching a cardboard lattice between two XPS foam boards.

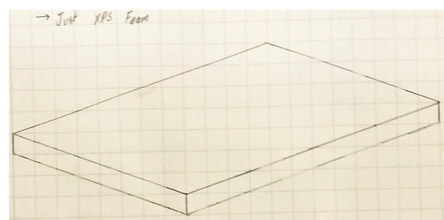


Fig. 13: Single layer of XPS Foam board

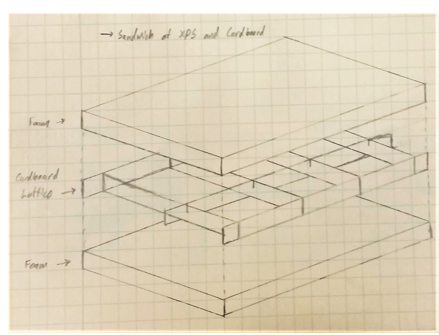


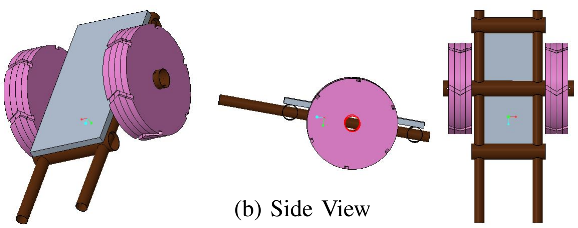
Fig. 14: Sandwiching of cardboard lattice between two XPS foam boards

Moving forward with these concepts, we needed to know generic dimensions and loads applied for our device. Measurements of the extremes in our group was recorded in table IV.

TABLE IV: Measurement Extremes of Group Members

Dimensions	*Value*
Weight	237 lbf
Height	75 in
Palm to Floor Distance	30.5 in
Chest to Palm Distance	16 in
Shoulder to Shoulder Distance	24 in

Knowing these values, we knew that our design needed to be at most 16 inches off the ground, the bed width had to be at least 24 inches, the handle bar placement should be 30.5 inches above the ground, and the device must withstand 237 lbs of force. The first iteration of CAD modeling for our device is shown in figure 15.

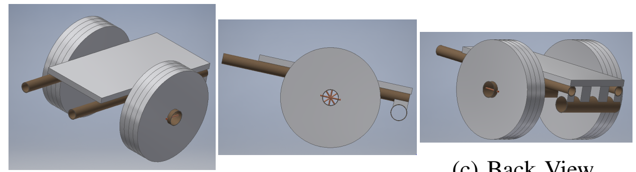


(a) Isometric View (b) Side View (c) Bottom View

Fig. 15: CAD Model Iteration 1

Professor Vural's feedback about our first CAD model was that by connecting the tubes through one another, we are weakening the cardboard tubes and increasing the chance of failure at the joint locations. We could easily mitigate this by just having the cardboard tubes be stacked on top of one another. Professor Vural's other feedback was that by creating channels in our tires, we need to know the depth, angle, and spacing to optimize the traction, grip, and escape of snow. This would be rather hard to do in such a small amount of time.

Utilizing Professor Vural's feedback, we had a second iteration of our CAD model complete (see figure 16). Although we did improve upon how the handles joined to the main axle and improved the wheel design by choosing the more simplistic route of a solid tire, which was second place based off of our decision matrix (see table II), we came across another problem which was the attachment of the back cardboard tube and dowel placements.



(a) Isometric View (b) Side View (c) Back View

Fig. 16: CAD Model Iteration 2

Despite the problems we encountered aforementioned, we had to move on with the manufacturing of our device due to time limitations. In order for the team to move forward with the second iteration design, we had to have four major components completed before building: experiment on materials to help us determine its strength and threshold, finite element analysis to see stress concentrations and problem areas to fix, discuss manufacturability and complexity with IdeaShop, and implement additional feedback from our professor into our design.

IV. Experiments

In order to understand the behavior of our device under certain loads, either the material properties had be determined or experimental tests on the material had to be done.

To determine the elastic modulus of the foam, which we planned to use for our wheels and our bed, we conducted a cantilever beam test (see figure 17). This is because of the material's displacement is equal to a function of force applied (P), length from end to load application (L), elastic modulus (E), and moment of inertia (I). Namely:

$$\delta = PL^3/3EI \tag{1}$$

By rearranging this equation to solve for E:

$$E = PL^3/3I\delta \tag{2}$$

The moment of inertia was first calculated by cutting a strip of XPS Foam to the base and height dimensions shown in table V and a length greater than that of what is shown in table V. The equation to solve for the moment of inertia is:

$$I = bh^3/12 \tag{3}$$

TABLE V: Dimensions of Cantilever

Dimensions	Values
Base	2.75 in
Height	2 in
Length of Applied Load	25 in

Using equation 3, the calculated moment of inertia for this cantilever was 1.83 in^4. Continuing on with the experiment, force was applied to a point 25 $inches$ away from the fixed end. The amount of force applied and deflection at the point of load application was recorded in table VI.

(a) Load application

(b) Deflection measurement

Fig. 17: Cantilever Beam Experiment

TABLE VI: Collected Cantilever Bending Experimental Data

$PL^3/3I(lbf/in)$	$Deflection(in)$
1168	0.625
1515	0.75
2159	1
2455	1.125
3640	1.875
3883	2
4898	2.5

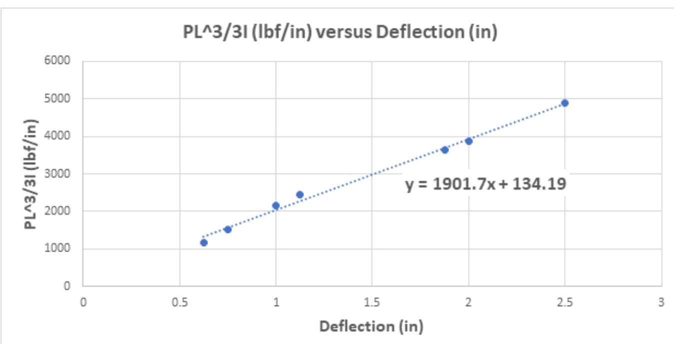


Fig. 18: Plot of $PL^3/3I$ vs $Deflection$ where the slope of this graph is the Young's Modulus

By finding the slope of $PL^3/3I$ versus $Deflection$ graph, we get the Young's Modulus to be equal to 1902 psi. This material property is used in the analysis of our design which will be discussed in the "Analysis of the Design" section.

Knowing that our chassis and main axle was to be made of cardboard shipping tubes, we also tested whether or not the cardboard shipping tubes could sustain the full weight of our heaviest member. This was achieved by placing supports for the cardboard tubes at least 24 inches apart from one another and having our heaviest member apply their entire weight onto the cardboard tube. If the cardboard shipping tube could withstand the entire weight of our heaviest member, we knew that it would be fine to move forward with those cardboard shipping tubes. The results of this test is shown in table VII.

TABLE VII: Cardboard Tube Weight Test

Outer Diameter of Tube	Withstood 237lbf?
3.5 inches	Yes
5.25 inches	Yes

Assuming 2-D beam bending for our main axle, a distance of 26 inches between our supported ends, and a distributed force of 9.12 lbf/in across entire length of the axle, we can find the shear force created at different x locations using the shear equation:

$$V(x) = w((L/2) - x) \tag{4}$$

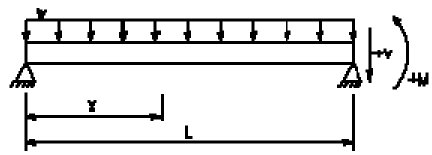


Fig. 19: Load distribution on 2D Beam

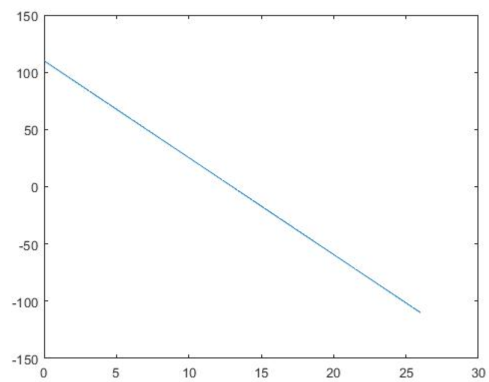


Fig. 20: Shear Force as a function of x. Absolute max value being 118.5 lbf.

V. Analysis of the Design

Utilizing the experiment results, we did finite element analysis on the bed and wheel of our design using ANSYS (see figure 21 to figure 22. The engineering data used for XPS Foamular 150 was Young's Modulus of 1902 psi and a safe Poisson's Ratio of 0.3 because we couldn't experimentally find out XPS Foamular 150's Poisson Ratio.

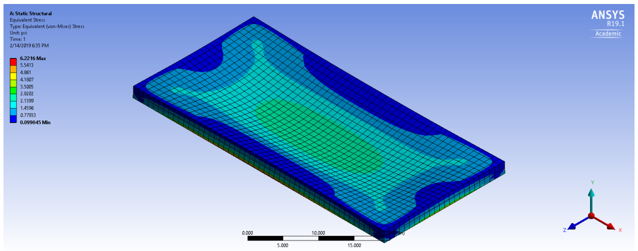


Fig. 21: Equivalent stress results of our bed with load of 237lbf. Max = 6.22 psi

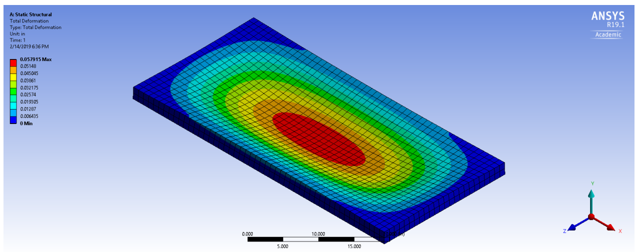


Fig. 22: Total deformation results of our bed with load of 237lbf. Max = 0.058 in

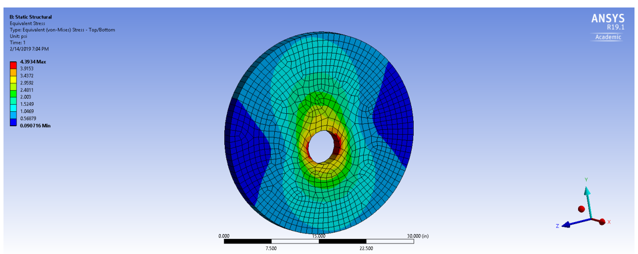


Fig. 23: Equivalent stress results of our wheel under load of 118.5lbf. Max = 4.4 psi

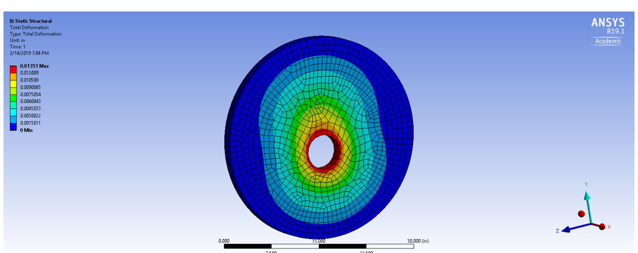


Fig. 24: Total deformation results of our wheel under load of 118.5lbf. Max = 0.013 in

Note that these results are not 100% accurate. FEA was only used to help us predict the behavior of our XPS foam parts.

Based on figure 21 and figure 22, we can confidently say that there will be stress concentrations and large deformation in the center, however due to the main axle being positioned in the center, what we see in ANSYS is not entirely true. In order to assist with the stress and deformation distribution, we must include multiple support areas along the length of the bed.

Based on figure 23 and figure 24, we can confidently say that there will be large stress concentrations around inner part of our wheel, however due to the wheels being rotated around while the load is being applied, there will be completely reversed stress being applied throughout our wheel, causing it to fail much quicker. In order to combat this, we must include multiple layers of XPS foam for the wheels, and reinforce the inner area of the wheel.

We then performed a manual analysis for the seat and wheel to ensure that our heaviest rider did not exceed their maximum compressive and flexular strength. According to the Owens Cording company, the maximum compresssive strength is 25 psi, and the maximum flexular strength is 75 psi.

We first considered the shear force caused by the maximum compressive strength. There was two areas of the seat to consider: the area normal to the x-axis and the area normal to the z-axis. The area normal to the x-axis was 24x2-in. The one normal to the z-xis was 50x2-in. Thus, the shear force experienced by the 24x2-in area was 1200 lbf, and the shear force experience by the 50x2-in area was 2500 lbf. These were the maximum shear force values seat would be able to experience due to compression before yielding.

Next, we considered the shear force caused by the maximum flexular strength. For the 24x2-in area, it was 3600 lbf. For the 50x2-in side, it was 7500 lbf.

Then, we considered the bending moment caused by the maximum compressive strength. We used the following equation:

$$M = I\sigma/y \tag{5}$$

Note that y = 1-in.

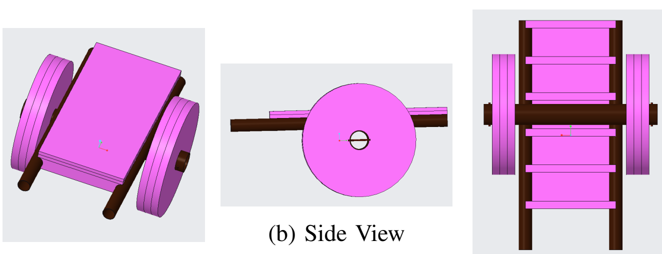
For the 24x2-in area, the maximum bending moment was 200 lbf-in. For the 50x2-in area, the maximum bending moment was 417 lbf-in.

We then used all of the above calculated values to determine if our seat and wheel design could withstand our heaviest rider. We treated the seat as a beam and analyzed the maximum shearing force and bending moment. The maximum shear force experience by the seat was 26 pounds, which is well below our maximum calculated values. The maximum bending moment was 28 lbf-in, which is also well below our maximum limits. The maximum compressive stress experience by the wheel was 3 psi, well below the maximum compressive strength of the XPS foam.

VI. Final Design

During the fabrication phase, we realized two key issues in our design that was affected by manufacturing and amount of materials. The first being that having a bearing design as our interface between the axle and the wheel is too complex to manufacture and secure onto our design given the limitation of time. Thus as a team we decided to go with the second best option based off of our decision matrix (see table III), which is duct tape. This achieves the same job as the bearing, which is to decrease the rolling friction between cardboard and foam. We are also able to reinforce the wheel by applying the duct tape to the inner surface of the wheel. The second being the amount of XPS foam layers for the wheels and the bed. In our initial design we had four layers per wheel and one layer for the bed, however due to the Idea Shop only having two 2" thick sheets and one 1" thick sheet of XPS foam board left, we had to settle with three layers of 2" thick XPS foam per wheel and two layers of 1" thick XPS foam for the bed.

Utilizing additional feedback from our design, our analysis, and our experimental testing, we came up with our final design (see figure 25).



(a) Isometric View

(b) Side View

(c) Bottom View

Fig. 25: Final CAD Model Iteration

Despite these setbacks, our final physical model still functioned the way we had envisioned it to. It held our heaviest member and traversed the ground perfectly.

VII. Things Learned from Game Day

Upon final testing during game day, the device was able to meet all functional requirements without fail. However we still learned critical feedback about the flaws in our design. Our original idea of pulling proved to be more difficult than pushing due to the handles being too short for the driver to pull while running. The driver's heels would constantly hit the bed due to the short spacing between the end of the bed and the end of the handles. In addition to the lack of space between the bed and handle, the rider could not grab the ball when positioned behind the driver. The wooden dowel used to secure the wheel in place began to shred the wheel (see figure 26). Although the cart met the required distance intended, it would have failed after a longer period of time.

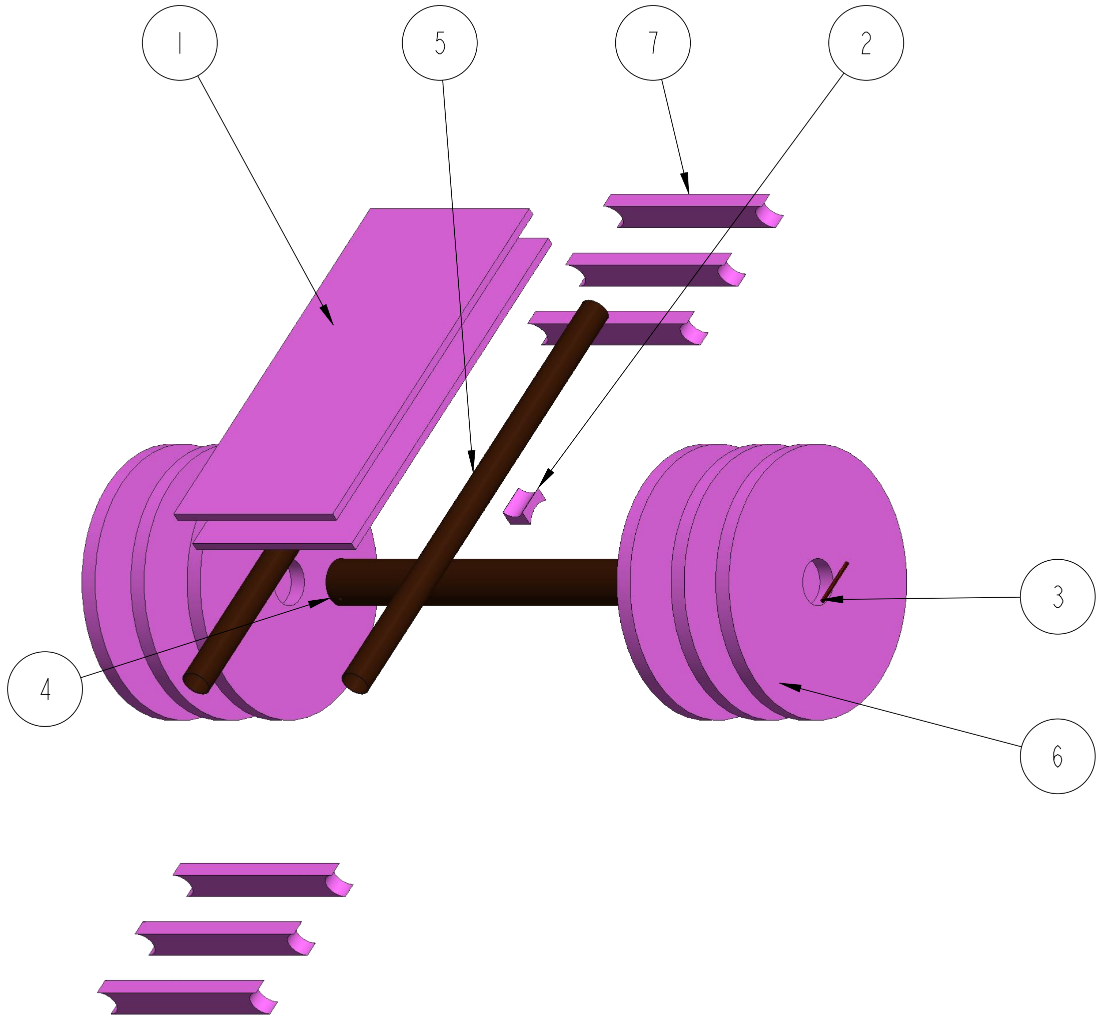
Fig. 26: Securing dowel pin began to tear the wheel apart

VIII. Conclusion

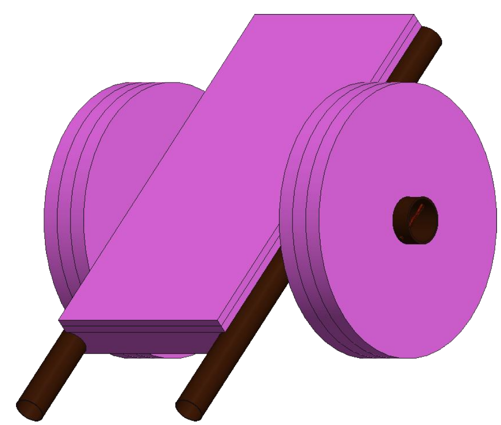
The purpose of this report was to outline the process of designing, analyzing, and prototyping a device used for sketch model challenge. This project began with 30 different hand drawn sketches by each member of our group. These sketches were evaluated using the Pugh chart. The selected sketch was designed using CAD software. It was also evaluated using finite element analysis through ANSYS. This allowed us to test the device virtually with loads and forces to see if it would be successful or not. Experiments were also conducted to find the properties of the materials and to understand the strength of the device. Finally, the device was assembled and tested. The device met all requirements and was successful in the sketch model challenge.

Appendix

See attached for Engineering Drawings of our final model. This document was written in LaTeX



REF	QTY	DESCRIPTION
1	2	BED
2	2	CONNECTOR
3	2	DOWEL
4	1	FINAL_MAIN_AXLE
5	2	HANDLES
6	6	PRT0001
7	6	SUPPORTS

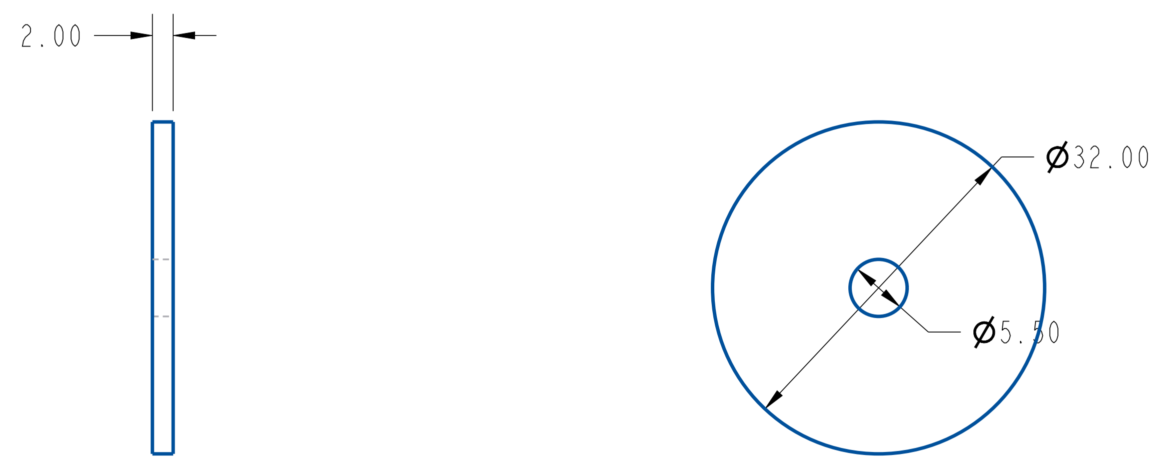


Matl: Mix

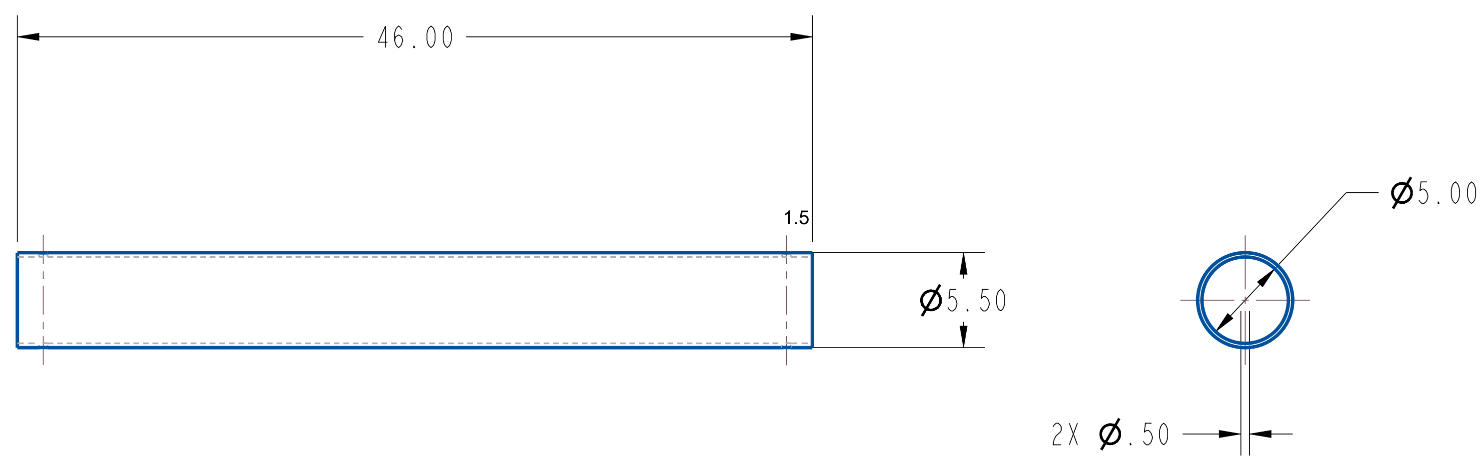
Drwn By: Vincent Mei

Date:Feb-08-19 Appd:

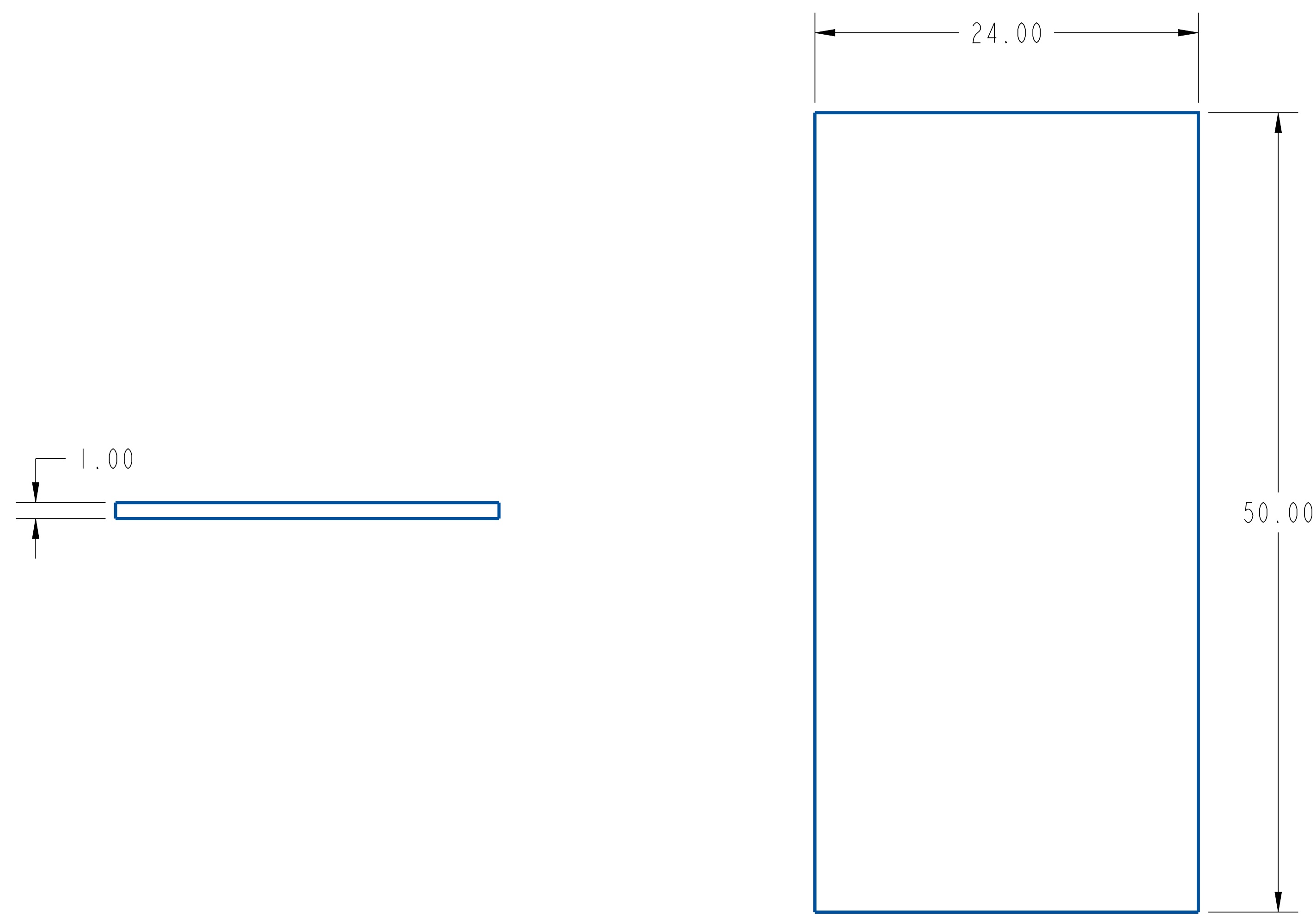
Dwg No: 001



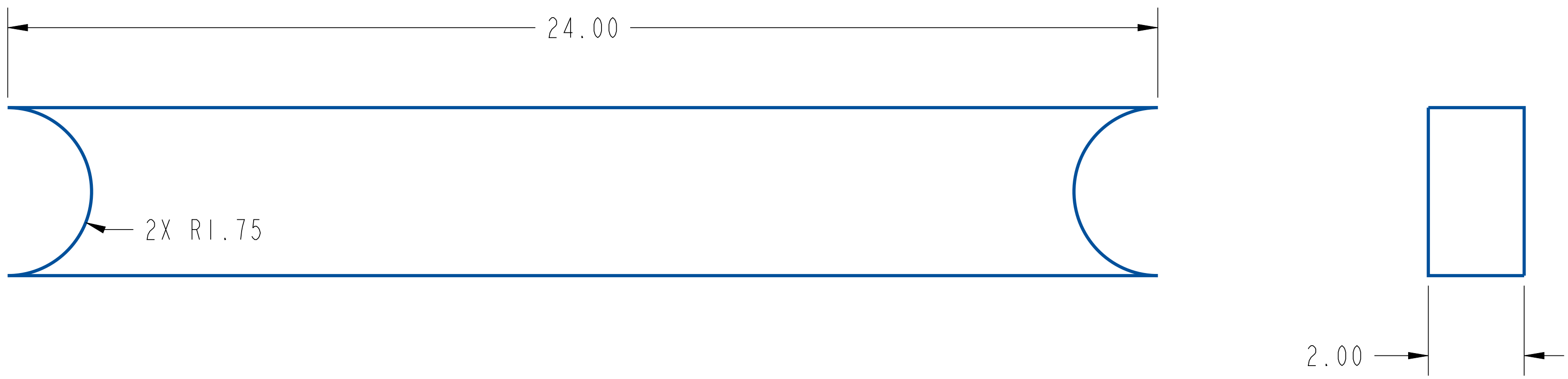
		Matl: XPS Foam 150	prt001 (wheels)
		Drwn By: Vincent Mei	
		Date:Feb-08-19 Appd:	Dwg No: 002



Matl: Cardboard Shipping Tube	main_axle
Drwn By: Vincent Mei	
Date:Feb-08-19 Appd:	Dwg No: 003

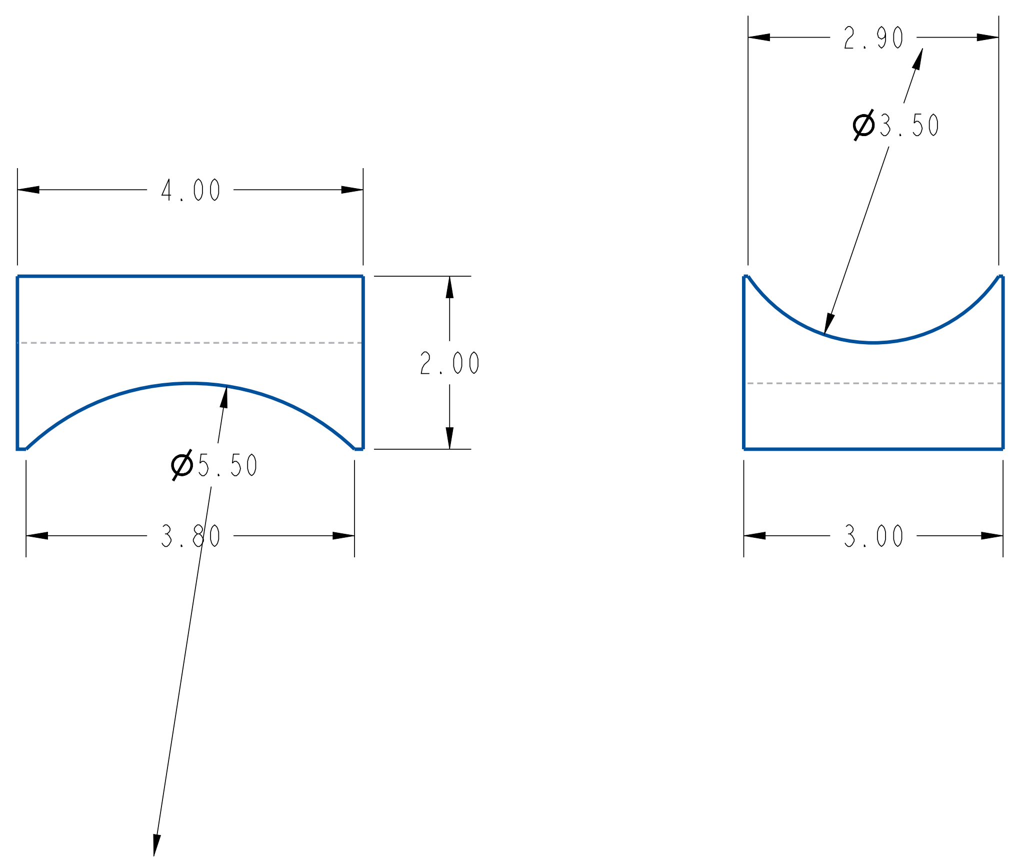


		Matl: XPS 150 Foam	Bed
		Drwn By: Vincent Mei	
		Date:Feb-08-19 Appd:	Dwg No: 004

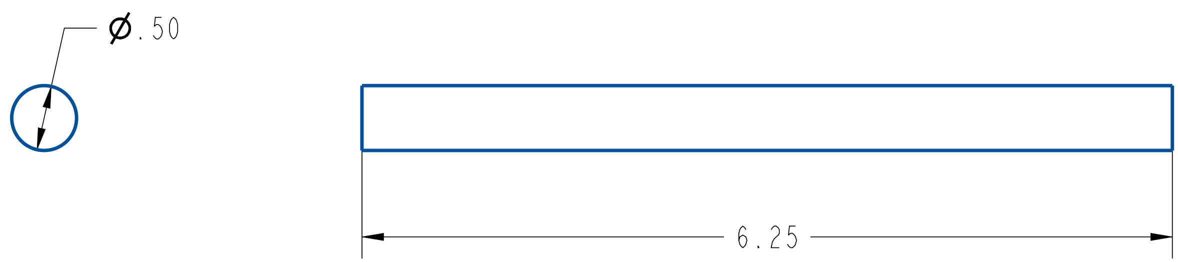


		Matl: XPS 150 Foam	support
		Drwn By: Vincent Mei	
		Date:Feb-08-19 Appd:	Dwg No: 005

		Matl: Cardboard Shipping Tube	handles
		Drwn By: Vincent Mei	
		Date:Feb-08-19 Appd:	Dwg No: 006



		Matl: XPS 150 Foam	connector
		Drwn By: Vincent Mei	
		Date:Feb-08-19 Appd:	Dwg No: 007



		Matl: Wood	dowel
		Drwn By: Vincent Mei	
		Date:Feb-08-19 Appd:	Dwg No: 008