Capstone Design Final Report
Drywall Cart Redesign

ME 4182 – A

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Instructor: Dr. Jariwala

Faculty Advisor: Dr. Green

Team “The Good Guys”

Ryan Grajewski, Will Hagler, Graham Brantley, Garrett Rodino

Nischal Bandi

Sponsor: Gypsum Management & Supply, Inc.

Contacts: andrew.horner@gms.com, jeff.johnson@gms.com

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Executive Summary

Drywall is a vital construction material, as it is used in the construction of interior walls and ceilings. However due to its heavy weight, most construction companies hire subcontractors such as GMS (Gypsum Management & Supply Inc) to deliver it to a specified location on the jobsite. These locations can be anywhere from the top floor of an apartment building or the basement of a residential home, so an efficient way of moving the drywall around must be utilized. For the past 40 years, GMS has used a drywall cart from Adapa as their primary tool for transporting drywall around jobsites. However, the unsafe design of this cart has cost GMS close to $1 million annually in work-related injuries, so they would like to explore alternative drywall cart solutions. By working closely with GMS, our team aims to design a new and safer cart design to reduce the number of work-related injuries in the drywall shipping industry.

In order to match the performance of the current drywall cart, our design must safely transport up to sixteen sheets of drywall, weighing up to 3000 lbs, in a variety of construction environments. The main safety concerns with the current design are twofold. First, the cart can easily tip over if it is pushed when its caster wheels are not pointing in the direction of the force applied to it. Second, the cart's caster wheels can often puncture the soft flooring of the jobsite under the immense weight of the drywall, which can lead to the wheels getting stuck and the cart tipping. By going through a standard ideation process, our team generated multiple potential designs to minimize these safety concerns. After using an evaluation matrix to rank our best concepts, a final design involving a two wheel steering mechanism and an automatic kickstand was chosen. The steering mechanism aims to allow the user to point the wheels of the cart in the direction of the applied force, preventing a key tipping mechanism. The kickstand is a last resort failsafe to prevent user injury in the event of the cart tipping.

After we completed the CAD model of our concept, we evaluated each component of the design through hand calculations and finite element analysis in order to ensure the viability of our design. We then built a prototype that employed our kickstand mechanism. We were unable to prototype our steering mechanism due to fabrication related issues. We evaluated our prototype by testing the reliability of the kickstand mechanism and by measuring the cart's tipping moment under different loads. Since our design passed all of our specifications and

requirements, we strongly believe that implementing this design will improve GMS jobsite safety and prevent unnecessary work-related injuries.

Nomenclature

- **A-Frame**: A support structure shaped like the letter A
- **Caster Wheels**: An undriven wheel that allows free rotation about the vertical axis
- **Tipping Moment**: The critical torque value above which the cart will tip over

Glossary

Term	Definition
DFM	Acronym for: Design for Manufacturability
GMS	Acronym for: Gypsum Management & Supply Inc.
MMH	Acronym for: Manual Materials Handling

1. Introduction and Project Background

The use of drywall panels for interior walls is ubiquitous throughout the U.S. construction industry. In 2020 alone, approximately 26 billion ft^2 of wallboard products were sold in the U.S [1], accounting for 95% of all U.S. interior wall construction schemes [2]. This massive demand for drywall has steadily encouraged growth for leaders in the commercial material supply sector such as GMS (Gypsum Management & Supply Inc.), who source and deliver drywall to job sites across the United States. The most labor-intensive aspect of the delivery process is the transportation of the drywall from the delivery truck to the jobsite through the use of a drywall cart. This process is also where the majority of worker-related injuries occur, with GMS reporting roughly 90 drywall cart related injuries per year that total to approximately $1 million in worker's compensation. It is likely that every major drywall supplier in the U.S. incur similar losses as they all use the same drywall cart design, and thus there exists a widespread need for improvements in drywall cart safety.

GMS has sponsored this Capstone Design Project in an effort to pursue a safer drywall cart design. GMS currently employs the industry-standard DC-2020-P drywall cart manufactured by Adapa, shown in Figure 1, which is a rudimentary A-frame cart with four caster wheels. Two operators are required to move this cart due to the heavy weight of the drywall, which they can only do by pushing on the drywall panels itself due to their size (up to 4 ft by 16 ft). The cart must also be narrow in order to navigate in tight indoor spaces, raising its center of mass and making it prone to tipping. Additionally, the weight on the cart can cause its caster wheels to puncture through jobsite flooring or even fail, causing weight imbalances and subsequent tipping. GMS suggests that this tipping is the most common cause of work-place accidents. Thus, our design aims to minimize both the chance and danger that cart tipping poses on jobsite while maintaining the current cart's maneuverability, durability, and efficiency.

The selected design concept, which comprises a modified adapa cart frame with a steering system and emergency kickstand mechanism, has been further developed throughout the ideation, engineering feasibility analysis, and CAD/prototyping phases. Because this project is intensely mechanical, the engineering feasibility testing phase required the most significant efforts to establish validity for the chosen design. Finite element analyses of the adapa cart frame, including the designed modifications, was first conducted in order to establish that those modifications could still support the full load of drywall. Using that FEA as a baseline, machine design calculations for the bevel gears, gearing system, and timing belt were performed in order to ensure that the required input torque could sufficiently translate to the calculated torque required to turn each wheel. Further, stress, buckling, and finite element analysis were conducted to validate the design of the emergency kickstand mechanism. These calculations helped inform the chosen material, geometry, and stress concentrations apparent in the initial design concept. The final result of these efforts is a fully validated prototype model which meets the customer and engineering requirements developed by GMS.

Figure 1: Model DC-2020-P Adapa Drywall Cart currently used by GMS [3]

2. Market Research

Market research was gathered through a variety of approaches. First, interviews were conducted with both GMS risk managers and worksite employees. The risk managers provided the current cart specifications, cart operation liabilities, the size of the drywall shipping market, and desired functions for the new cart design. The worksite employees helped by demonstrating how drywall carts are used onsite and their current functionality. Second, research on the general use and injury cases of carts throughout the construction and material/drywall supply industries helped to better understand the financial and human impacts of drywall cart related injuries. Finally, an anonymous survey was distributed to several drywall and construction worker groups on the internet to get clearer insight into what issues were identified by drywall cart users not affiliated with GMS. This research allowed us to pinpoint exactly what functions our drywall cart should perform.

The next step in our market research process was to fully understand the benefits and limitations of the current cart design. The current Adapa cart design used by GMS, seen in Figure 1, features a slanted A-frame base designed to lower the center of mass of the drywall payload [3] and sells for $650. While Adapa does not monopolize the drywall cart industry, it does currently produce the best drywall cart for construction material supplies on the market. Thus, our design must at minimum meet the Adapa cart's performance in terms of durability, stability, price, and safety. It is important to note that the drywall cart market includes not only construction material supplies like GMS, but also independent contractors throughout the U.S. Additionally, regions such as Western Europe and East Asia are rapidly adopting the use of drywall, so there is potential for our product to compete in future global markets [4].

As stated before, GMS reports roughly $1 million in workers' compensation per year, and we found that other companies in the space reported similar numbers [5]. It is therefore clear that there is a real and present need to produce a safer drywall cart design. Our research also found that roughly 60% of manual materials handling (MMH) claims involved the lower back, upper arms, wrists, hands, or fingers, all of which are key to pushing and tightly maneuvering carts that are heavily loaded with drywall [5]. Additionally, more than 57% of all MMH claims involved strains or sprains caused by workers overexerting their muscles to stabilize the cart [5]. Thus, these injuries are directly correlated with the instability of the current drywall cart design.

3. Relevant Prior Art

There are many different material transport carts currently available on the market, including pallet trucks for transporting heavy loads, platform carts for moving large materials, and A-frame carts for moving material boards. Due to the large number of material transport cart approaches, the scope of this prior art search was not limited to drywall transportation devices. Instead, we focused on identifying any prior art that could be relevant to our goal of improving drywall transportation safety.

3.1 The Classic Drywall Cart

The current market standard for drywall carts, and the drywall cart that defines our baseline performance, is the model manufactured by Adapa shown in Box A of Table 1 [3]. This design consists of an angle A-frame wheeled cart with caster wheels. The cart frame is made of welded steel tubing and the platform is covered with Teflon to reduce friction during loading and unloading. This cart benefits from being low cost and easy to manufacture, but it suffers from not having a brake to keep the cart stationary during loading and unloading, from not having a guide rail to ensure product is correctly loading, and from the aforementioned tipping risks.

3.2 Flatbed Carts, Troll Carts, Centered A-Frame Carts

Flatbed, troll, and centered A-frame carts are all iterations on the classic drywall cart that have different base designs. Flatbed carts have a platform parallel to the ground that is located between the caster wheels to lower the center of mass of the cart and improve stability. Troll carts have an H-frame base so that the drywall can rest on two support beams rather than a platform, providing two contact points and allowing the transportation of irregularly shaped items. Centered A-frame carts have a second angle platform, allowing them to centralize their center of mass at the expense of raising it. Examples of these carts can be seen in Boxes B [6], C [7], and D [8] of Table 1.

3.3 Swiveling Carts

Swiveling carts allow the user to manipulate the orientation of the drywall on the cart by rotating the payload about multiple axes. This can allow the cart to fit into elevators or other tight spaces. These carts typically have square (Box E [9] Table 1) or X-shaped (Box F [10] Table 1) bases that are attached to a central beam. It is notable that this is the only cart design that allows for customisation of the drywall positioning depending on the situation, resulting in greatly increased maneuverability.

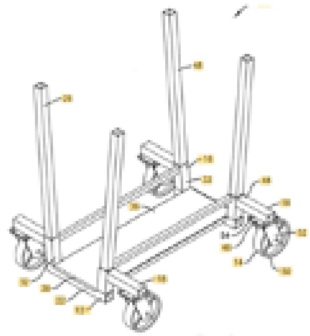
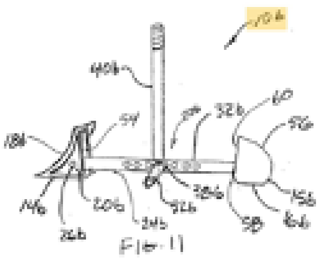
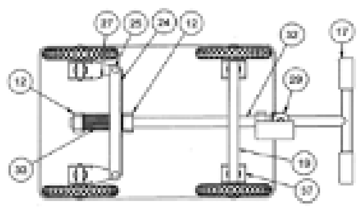
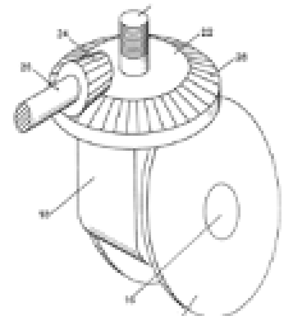
3.4 Wheel Brakes

Keeping a drywall cart stationary makes the loading and unloading processes significantly easier and safer. Some carts use clamp breaks, as shown in Box G [11] of Table 1, to stop the rotational motion of the caster wheels, but this does not stop the casters from swiveling. Another alternative is to use a chock to secure the cart, such as the one integrated into the design shown in Box H [12] of Table 1.

3.5 Steering and Wheels

While the classic drywall cart uses caster wheels to effectively maneuver itself in tight situations, there are some designs that instead use mechanical linkages to control the direction of the wheels. This can be done through a full steering system, such as the one in Box I [13] of Table 1, or through a mechanism that allows for manual control of the caster wheels, such as shown in Box J [14] of Table 1.

Table 1: Prior art designs referenced in the report [3] [6] [7] [8] [9] [10] [11] [12] [13] [14]

 A – Adapa Drywall Cart	 B – Flatbed Cart	 C – Telpro Troll Cart	 D – Center A-frame Cart	 E – Swivel Elevator Cart
 F – Haley Material Handling Cart	 G – Caster Wheel Clamp Brake	 H – Integrated Wheel Chock	 Fig 5 I – Gear Train Steering System	 J – Wheel Steering Mechanical Linkage

4. Applicable Codes and Standards

Although there are no explicit codes and/or standards that apply to the production and operation of drywall carts, there are company guidelines concerning the operation of drywall carts that should be considered. The safety and handling guidelines for drywall carts at a typical construction company like Island Acoustics calls for the following [15]:

1. Operating carts with at least 2 workers
2. Not modifying carts
3. Not overloading carts
4. Not using carts in a manner inconsistent with the manufacturer's suggestion
5. Not using damaged carts
6. Not storing carts in non-designated areas or with materials loaded
7. Keeping drywall carts stable and stationary during loading
8. Keeping the center of gravity of the cart low by stacking with lighter ones at the top
9. Securing particularly bulky payloads with straps

These company guidelines do not officially limit the design of drywall carts, but they do clarify best practices for operating such carts, which can help determine features that we may want to consider incorporating, such as foot brakes and side walls. Another possible standard of interest to us was the minimum width requirement for doorways. However, while we found that all doorways are required to be at least 80 inches tall [16], there is apparently no firm answer on the minimum width of a doorway. Thus, we decided to keep the width of our design similar to that of the current design in order to ensure that we would meet any required specifications.

5. Customer Requirements and Engineering Specifications

5.1 Stakeholder Analysis

In order to determine our customer requirements, it was vital to first determine our primary stakeholders, or the people that are invested in our project. The three main stakeholders for this project were identified: GMS risk managers, GMS worksite employees, and Georgia Tech. Each stakeholder was ranked by their relative importance and influence on the project. Importance was defined as the relative value this project will provide to a given stakeholder, while influence was defined as a stakeholder's native ability to influence the project.

GMS risk managers were found to be a high importance and high influence stakeholder, as not only does this project have the potential to greatly influence their business, but their help will be key in making this project a success. On the other hand, GMS worksite employees were found to have high importance but low influence since our project has the potential to directly impact their work, but they cannot directly impact the direction of the project. Finally, Georgia Tech was found to have low importance but high influence, as our grades directly depend upon Georgia Tech's grading scheme but Georgia Tech is not affected by our project in any way. A copy of our diagram is located in Appendix A as Figure A1.

5.2 Customer Requirements

After key stakeholders were identified, we settled upon the customer requirements shown in Table 2. This table contains both requirements from the currently used model, such as being able to support the product load and be lifted by one person, and desired improvements, such as not tipping over during use and remaining stationary during loading and unloading.

Table 2: Table of customer requirements sorted by category

Category	Customer Requirement
Function	• Hold and support product load • Move easily over multiple surfaces • Remain stationary during loading and unloading • Navigate through narrow thresholds • Easily lifted by one person

Geometry	• Similar shape to previous design
Cost	• Use manufacturing processes similar to previous design • Cost similar to previous design
Reliability	• Weatherproof • Does not tip during use

5.3 Engineering Requirements

Once we had gathered our customer requirements, we tried to tie each of them into a corresponding engineering requirement. This allowed us to quantify how well we met each requirement through a numerical target value. Some key engineering requirements were to have a width less than 30” to fit through door frames, the ability to support a weight of up to 3000 lbs, and for the frame to not plastically deform during use. For more information on the engineering requirements, please see the full specifications chart located in Appendix A as Table A1.

5.4 Engineering Constraints

In addition to all of our engineering requirements, two additional engineering constraints were identified. First, due to the narrow thresholds in many job sites, it was decided that our design must be similar in size to the current cart. Second, in order for our cart to deliver drywall effectively, it must be able to traverse uneven terrain and strange substrates. This also meant that our cart would be prone to wear and must therefore be easily repairable. These constraints were also considered as engineering requirements during the concept evaluation phase of our project.

5.5 House of Quality

The last step in our quest to comprehensively describe our cart’s requirements was to organize our customer and engineering requirements into a House of Quality. Our House of Quality determined that our most important customer requirements were safety, maneuverability, and stability, while our most important engineering requirements were the tipping moment and height of the center of mass of our cart. For more information on our House of Quality, please see the full document located in Appendix A as Figures A2a and A2b.

6. Design Concept Ideation

6.1 Function Tree

The first step in the design concept ideation phase was to define the essential functions that each concept must be capable of fulfilling. In general, it was evident that the final design would need to fulfill 4 main functions: be able to maneuver through tight spaces, be able to easily load and unload drywall, be able to support and secure drywall sheets during transportation, and be able to roll over uneven surfaces. These 4 functions were then broken down in further detail as sub-functions, which can be seen in the function tree shown below in Figure 2.

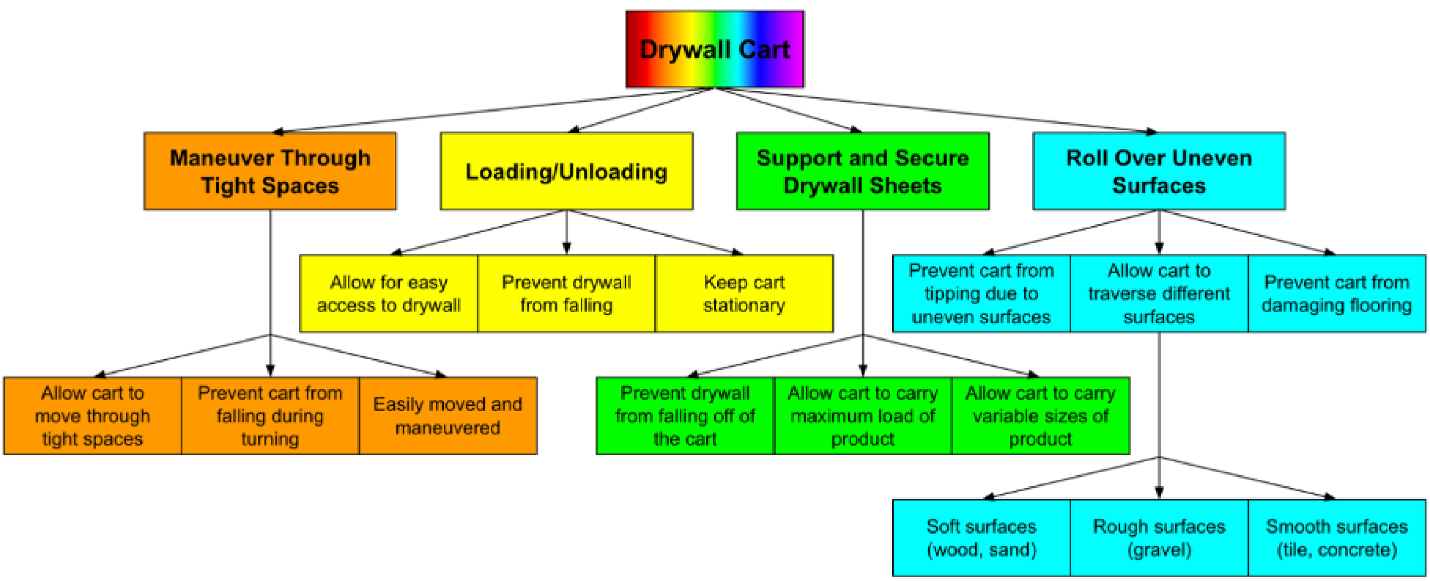


Figure 2: Drywall cart function tree showing 4 main functions and their sub-functions

6.2 Morphological Chart

Once the functionality of the drywall cart had been thoroughly defined, individual concepts or mechanism ideas were generated as solutions to each of the specific sub-functions defined in the function tree. Due to the modular nature of the drywall cart, many of the concepts could be used to satisfy multiple functionalities at once. A morphological chart was then used to compile each individual component idea into sub-function categories for the purpose of facilitating alternative design generation. For more information on our morphological chart, please see the full document listed in Appendix A as Figure A3.

6.3 Full Concept Designs and Evaluation Matrix

Each alternative design was selected in a piecewise fashion, incorporating one or multiple concepts from each sub-function category to result in a full cart design concept. The following five alternative designs were put forward for evaluation:

1. A 2-wheel drive steering cart with an angled base A-frame and an external kickstand
2. A 4-wheel drive steering cart with an angled A-frame base and an internal kickstand
3. A caster-wheel directed cart with an angled A-frame base, suspension, and a footbrake
4. A caster-wheel directed cart with a flatbed frame and a foot pedal brake
5. A caster-wheel cart with an angled A-frame base, internal kickstand, side guards, and footbrake

An evaluation matrix was then used to quantitatively compare each concept against the customer requirements. Each concept was given a score from 1 to 5 for how well it met each user need. To account for the varying importance levels of each user need, scores were weighted accordingly so that a high score in a highly important customer requirement category would have a higher impact. The sums of the scores for each alternative design were calculated and Design #1 was selected. For more information on our evaluation matrix, please see the full chart listed in Appendix A as Table A2.

7. Selected Design Concept and Justification

Our selected design concept, “2-Wheel Steering + External Kickstand”, is shown in Figure 3.

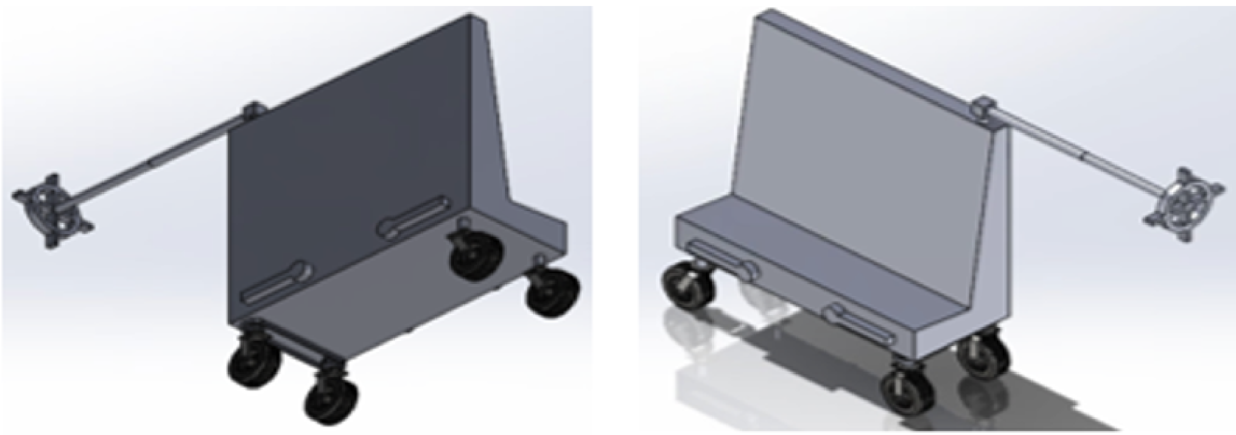


Figure 3: Selected design concept art

This design utilizes a steering system for the front set of wheels to allow the operator to steer the cart without having to apply a horizontal force to the cart, which could possibly tip the cart. Operators will also be able to use the steering to have much greater control over where the cart will go when it is pushed forward. The extended steering column allows the operator to steer the cart while holding the drywall. This design also utilizes an external safety mechanism that will automatically deploy when tipping begins. Once balance is restored, the “kickstand” arms can be quickly moved back into place so the cart can operate normally. The angled base also allows for quick loading and unloading of the material.

This design was selected because it scored highly in many of the important customer requirements, particularly in “Safe to Use”, “Highly Maneuverable”, and “Stable”. However, it did very poorly in the “Easy to Use” requirement due to the higher amount of training and coordination that the steering system requires. For more information on how our selected design performed in the evaluation matrix, please see the full chart listed in Appendix A as Table A2.

8. Final Design and Prototype Testing

The final CAD model of our design is shown in Figure 4. The design consists of 3 key subsystems: the frame, the steering, and the kickstand.

Figure 4: Final CAD model of our drywall cart design

8.1 Subsystem Descriptions

The frame is designed to support the drywall payload as well as to provide a framework for the other subsystems. It consists of 2 U-shaped tubes and an angled base. The lower U-shaped tube is designed to support the drywall's weight while the upper U-shaped tube allows the cart to be more easily maneuvered by an operator and houses part of the steering mechanism. The angled base tilts the drywall payload in order to lower its center of mass and improve stability.

The steering subsystem allows the front two wheels of the drywall cart to be manually controlled. In the current design, operators have to shove the cart in order to get the caster wheels going in the correct direction. This was one of the most common reasons that forces were applied to the drywall cart that were large enough to tip it over. Thus, by implementing the steering subsystem we are removing a key failure mechanism of the current drywall cart. In order to allow the user to steer the cart even when under the maximum payload of 3000 lbs, a gear ratio of 1:36 was implemented to magnify the torque applied to the steering wheel.

The kickstand was the last key component of our design. It is the safety mechanism of last resort, as it is designed to hold the cart up in the event that tipping is inevitable. As the drywall tips, it hits a trigger on the kickstand that releases its swinging arm. This arm is propelled by torsion springs so that it reaches a 45˚ angle with respect to the kickstand before the cart hits the ground. The kickstand can also be rotated downward to allow for the easy loading and unloading of payloads.

8.2 Final Prototype and Testing

A photograph of the final prototype can be seen in Figure 5. A bill of materials for our design can be found in Table C1 of Appendix C.

Figure 5: Final prototype design

Of the three subsystems, only the kickstand mechanism was able to be implemented. The frame was not able to be modified to fit our design due to manufacturing constraints. The upper U-shaped tube was not completely vertical, which was necessary for the steering column to fit inside it, meaning that it would have to be bent backwards. We did not have the necessary tools to make that modification. This difficulty also led the steering mechanism to not be able to be implemented. Since the upper U-shaped tube could not be made vertical, it would have been necessary to add our own vertical tubing to the cart. This would have required a significant amount of welding that we simply did not have time to perform. Additionally, after meeting with a machining expert from the Student Competition Center, we were told that we would need to perform some additional and significant machining to get our gearing system to work on our prototype. Due to these issues, we decided to not implement the steering mechanism and instead focus on the kickstand.

The prototype was evaluated through two tests. First, the reliability of the kickstand was tested by tipping the cart over repeatedly and recording the success rate of the mechanism. The cart had a small payload of a sheet of plywood so that the kickstand could be triggered. The cart was tipped over 20 times and the kickstand successfully supported the cart in 17 of those events, amounting to an 85% success rate. In 2 of the 3 failure cases, the cart tipped along with the payload, which prevented the plywood from hitting the trigger mechanism. In practice, we do not expect this to be a common failure mechanism as all of the injury reports we have collected have been caused by the drywall payload being pushed rather than the cart. In fact, GMS states that tipping usually occurs because the drywall itself is what begins the tipping motion, and the cart then follows suit under its weight. In the final failure case, the torsion springs did not propel the swinging arm fast enough for it to deploy before it hit the ground. We expect that this reliability can be easily improved by using more powerful springs.

The second test consisted of calculating how hard it was to tip the cart. Payloads of varying weights were added to the cart and a force gauge was attached to the top of the upper U-shaped tube to determine the tipping force required. The data was then plotted and extrapolated, as can be seen in Figure 6, to determine how much force would be required to tip a cart with the full 3000 lbs load.

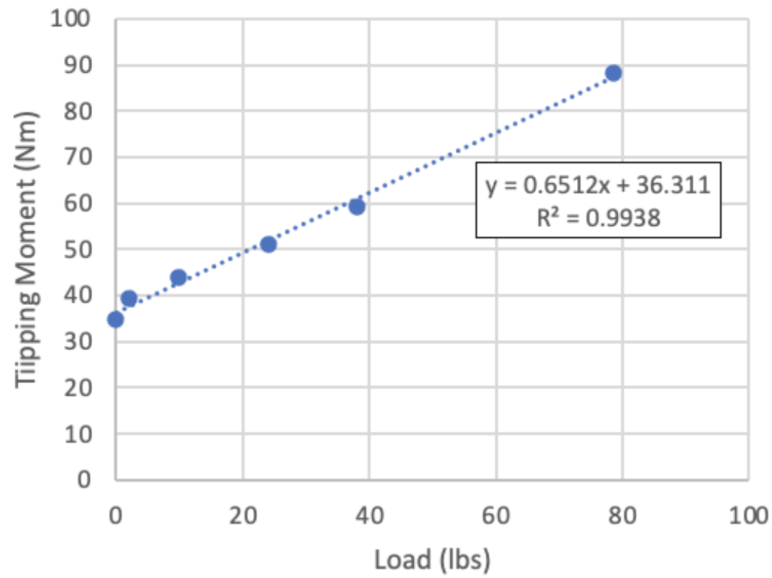


Figure 6: Plot of tipping moment vs the payload of the drywall cart with a linear trendline

Using the linear trendline, it was found that around 2000 Nm of torque, or 1.5 kN of force applied to the top of the upper U-shaped tube, would be needed to tip the fully loaded cart. This is well within our target specification of 300 lb ft or 408 Nm.

9. Engineering Analyses and Experimentation

Each component of our design underwent rigorous theoretical calculations to ensure its structural integrity and validity, as is described below.

9.1 Frame

We chose to use the same tilted A-frame base as the Adapa cart design. However, five key modifications were made in order to fit in the steering system. First, a box was placed on the top right corner of the back support bar in order to house the bevel gear system. Second, the top bar of the back support bar was extended to the right in order to house the steering column. Third, a bar was added to help support the steering wheel and column. Fourth, the angle of the front support bar was decreased to ensure that the drywall did not hit the steering wheel or bevel gear box. Finally, a plate was added to the bottom of the frame in order to allow the gearing system to be directly attached. The material selected for all of these additions was AISI 1010 low carbon steel due to its low cost, good machinability, and good weldability, making it easy to work with.

We then ran FEA analyses to determine how our frame would react to the 2 types of load we expected it to experience: the weight of the drywall and a downwards on the steering wheel. The first simulation consisted of a 3000 lbs rigid drywall block load with fixed constraints at the bottom of the frame. The second simulation consisted of a 100 lbs downwards load on the end of the steering column with fixed constraints at the bottom of the vertical pipe and at the far side of the bevel gear box. More details about these FEA analyses can be found in Figures B1 and B2 in Appendix B. Ultimately our analyses found factors of safety of 19.7 and 2.11 respectively by using the material properties of AISI 1010 steel [17], proving that our frame design was feasible.

9.2 Shafts and Bevel Gears

The next components of our design to be systematically analyzed were our shafts and bevel gears. The bending and torsion stresses of the shafts were calculated through Equations B1 and B2 in Appendix B [18]. The material selected for our shafts was AISI 1045 carbon steel, a reasonably priced medium carbon steel with a tensile strength of 310 MPa [19]. We estimated our input torque to be 10 Nm, generated by a 175 N force applied to our 4.5 inch diameter steering wheel. By plugging in values for each variable in the above equations, the details of which can be found in Table B1 in Appendix B, we found our shafts had a minimum factor of safety of 6.24, again validating our design.

The calculations for the bevel gears were also straightforward. From a machine design textbook [18], the maximum allowable contact stresses and bending stresses could be found from Equations B3 and B4 in Appendix B. In these equations, the Z, K, and Y variables are all multipliers that can be estimated using AGMA equations found in the machine design textbook [18]. Using those equations and the material constants of our bevel gear material, found in Table B2 in Appendix B, resulted in maximum contact and bending stresses of 1495 MPa and 120 MPa, which were well below the estimated 49.7 MPa and 44.2 MPa shear and bending stresses applied to the shafts. Thus our bevel gears, just like our shafts, should be able to easily withstand the applied stresses that our cart will undergo during normal use.

9.3 Gearing System and Wheels

One of the most important aspects of our design was the gearing system that drove the wheels of the cart. With an input torque of 10 Nm and an estimated torque of 211 Nm required to turn to each wheel, our gear ratio needed to be at least 1:21. The CAD of the gearing system, shown in Figure 7, had a ratio of 1:36 to account for unmodeled effects. The system consisted of a set of bevel gears with a 1:2 ratio, a set of gears underneath the cart with a 1:6 ratio, and a timing belt system with a ratio of 1:3.

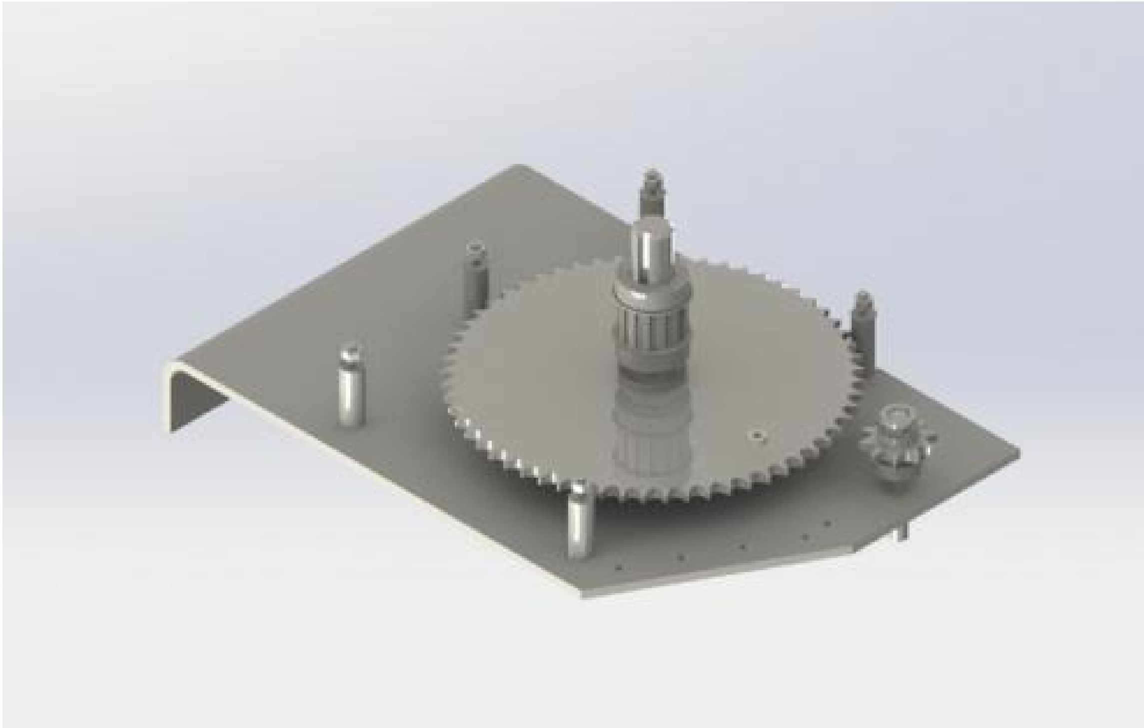


Figure 7: Gear System Assembly

Hand calculations were then performed using equations B5, B6, B7, and B8 [18] in Appendix B to ensure that each gear had a factor of safety of at least 1.2 for both contact and bending stresses. The pinion and gear had 17 and 102 teeth respectively. The inputs used in these equations and their results are shown in Table B3 in Appendix B. These equations yielded minimum factors of safety of 1.24 and 1.35 for the pinion and gear, which are above our required value of 1.2.

9.4 Calculations for the Timing Belt

The timing belt pulley system is shown in Figure 8. Simple tensile calculations were done to verify if the belt can withstand the force from the input and output torques. The max allowable belt tension for our chosen material, urethane with kevlar reinforcement, was 49.2 $\frac{N}{mm}$ [20] and the belt width was 1 inch, resulting in a max allowable belt tension of 1250 N. By multiplying the torque on the belt by the gear's radius, the maximum tensile force on the belt was 146 N, which was well below the max allowable belt tension.

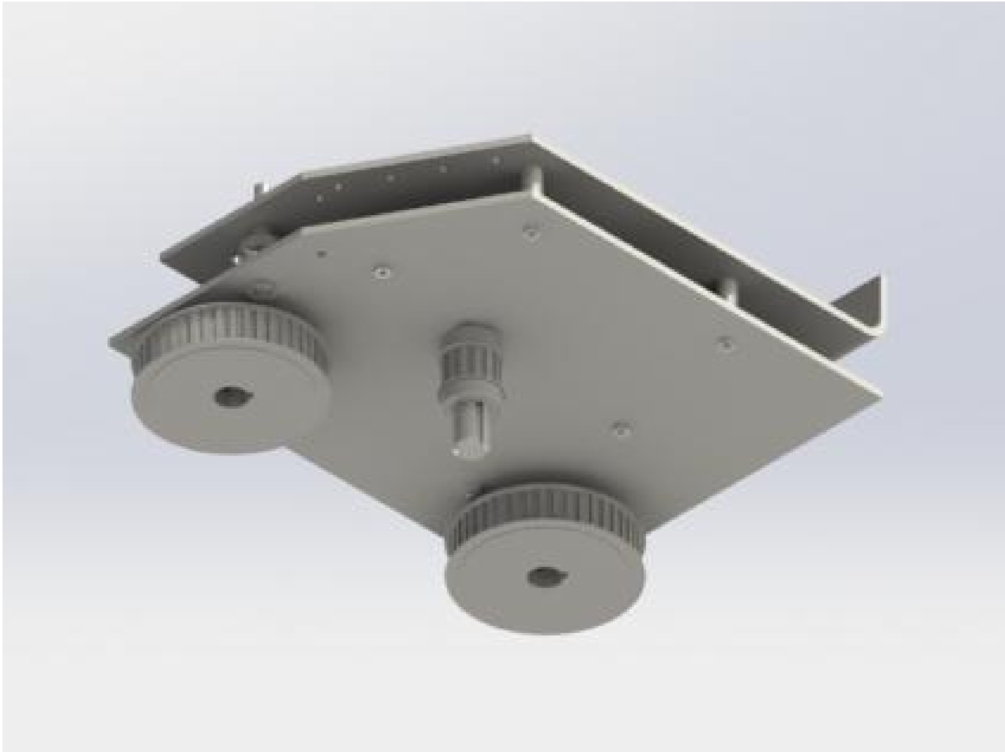


Figure 8: Pulley System

9.5 Kickstand

The final kickstand design, shown extended in Figure 9, consists of an arm that swings out to a 45° angle to support the drywall cart and its payload. Hand calculations were performed to validate each component of the subsystem. Table 3 lists the various stresses, specifications, strengths, and factors of safety for each component. For more detail on these calculations, please see Table B4 and Figures B3, B4, B5, B6, B7, B8, and B9 in Appendix B.

Figure 9: Rendering of deployed kickstand

Table 3: Loads, specifications, strengths, and factors of safety for kickstand components

Component	**Loads**	**Specifications**	**Strength**	**Factor of Safety**
Connecting Pin	Shear force = 707 lbf	D = 0.25 inches L = 4 inches AISI 4140 Steel	Shear strength = 10000 lbf	14.1
Center Rod	Axial load = 1010 lbf Von Mises = 36.1 ksi	Slenderness ratio = 85.7 > $(L/k)_{crit}$ (long column)	Buckling load = 14900 lbf S_y / 2 = 37.5 ksi	14.8 1.04
Swinging Arm	Axial load = 707 lbf	Slenderness ratio = 85.7 > $(L/k)_{crit}$ (long column)	Buckling load = 5820 lbf	8.23

9.6 Mounting Bracket

The final part to be validated was the mounting bracket for the kickstand, which was done through FEA. The results of the FEA analysis can be seen in Figure B10 in Appendix B. The bracket was modeled as a 0.25 inch sheet metal component made from AISI 1020 low carbon steel and reached a maximum stress of 16 MPa. Since the yield strength of the material was 352 MPa, this gave a factor of safety of 22. Thus, our mounting bracket should be able to easily withstand the forces that we anticipate our kickstand to undergo.

10. Industrial Design

The most important aspect of our final design from an industrial design standpoint was the effort we put into making it look as similar to the existing cart as possible. When we were surveying workers about the current cart design, many of them seemed reluctant to change to something new. In order to make our new design more palatable, we decided to try to make our design seem as familiar as possible. We did this by making three key design decisions that were aimed at keeping our product's aesthetics as close as possible to that of the current cart design, as can be seen in Figure 10.

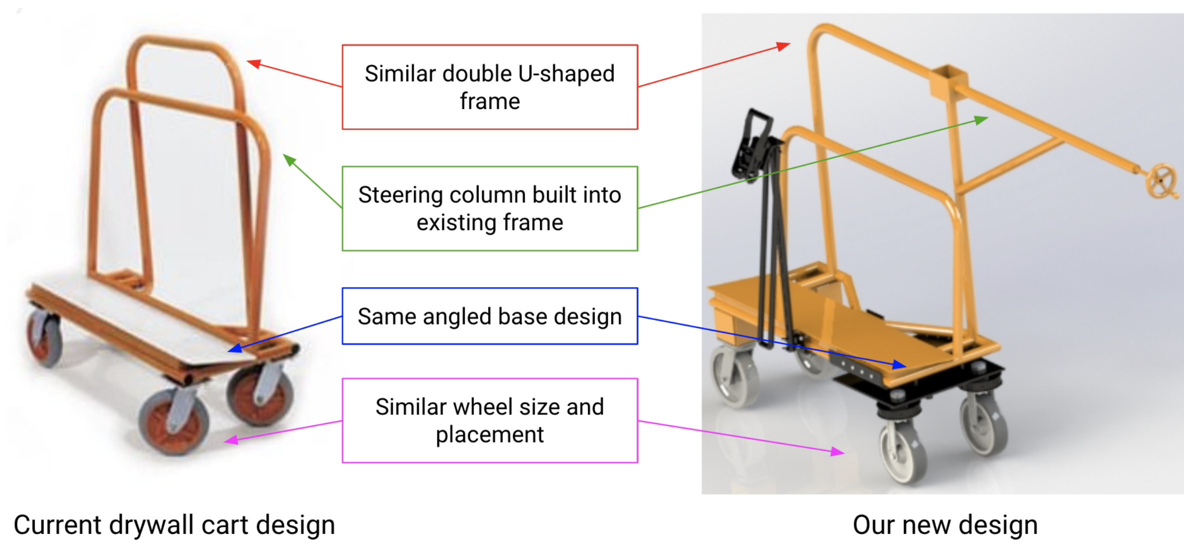


Figure 10: Comparison of the current drywall cart and our new design

First, we decided to use the same double U-shaped design with an angled base that the current cart employs. This decision was also a practical one, as we decided early on that this design also maximized the cart payload and minimized the height of the center of mass of the cart. However, this choice was also a good one from an industrial design standpoint, as the load and unloading procedures will be essentially the same for both designs. Second, we built our steering mechanism into the existing cart frame as much as possible. For example, we used the vertical part of the tubing to hold a shaft and we built our bevel gear box straight into the existing frame. This prevents the steering from appearing too novel and intimidating, as all the gearing is contained within the same original frame. Third, we used the same number of wheels as the existing design. While this may seem trivial, we did have several multi-wheel concepts during ideation phase, but all were eventually rejected due to their novelty. With these changes we hope to make the adoption of our product go as smoothly as possible.

11. Societal, Environmental and Sustainability Considerations

As our product is primarily designed for commercial use, it will not have any societal impacts other than the prevention of injuries. In order to quantify environmental considerations, we used CES Edupack's Eco Audit tool to determine how much energy our design would cost relative to the current cart, as seen in Figure 11.

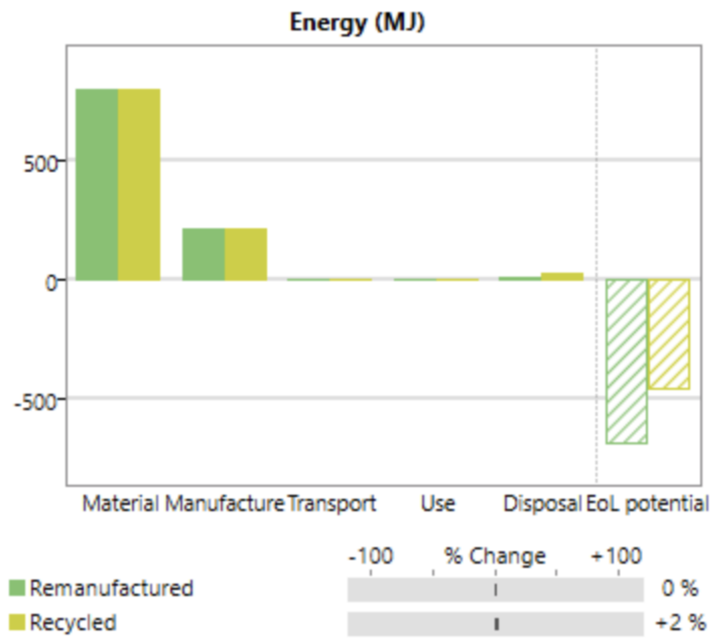


Figure 11: Eco Audit report on remanufacturing versus recycling the Adapa cart

We determined that by remanufacturing the current Adapa cart, we would save 240 MJ of energy relative to simply recycling the cart, 20 MJ of which come from disposal and 220 MJ of which come from additional end of life potential. While we do not recommend that our product should be produced by remanufacturing old Adapa carts, it is worth noting that this process would result in substantial environmental impact savings. The rest of our additions, including the kickstand, new wheels, and gearing system, cost an additional 450 MJ of energy to produce.

12. Manufacturing

Due to the many unique components within our design, several different manufacturing processes will be required to manufacture it. Each piece of the frame must be produced through hydraulic pipe bending due to their severe 90˚ bends. These pieces must then be welded together. The kickstand subsystem also requires pipe bending for the swinging arm rod and creation of the sheet metal parts such as the bottom plate mounting bracket and the top plate. Since bending steel pipe longer than 4 feet becomes difficult with a hydraulic tube bender, the two 90˚ bends on the swinging arm should be made on a separate 8 inch long tube and then welded to longer piping to achieve the required length. The sheet metal would be purchased at the required gauge and then punched to make the holes and pressed using a hydraulic brake press for the bends required by the design.

The most difficult subsystem to manufacture is the gear assembly underneath the cart. The sprockets and pulleys that allow the operator to turn the cart's wheels using the steering wheel can be purchased from outside sources or manufactured via forging. Creating the components in house would likely decrease the cost per part, resulting in significant cost savings since the bill of materials, shown in Table C1 of Appendix C, states that the gear assembly is the primary source of cost in our design. However, this would also require investment in heavy machinery, which may not be advantageous if only a few carts are manufactured. Another advantage of manufacturing the gears would be that the required holes could be drilled prior to hardening the components. This increases tool life and saves time, making the manufacturing process more efficient. After drilling, the sprockets and pulleys would be carburized in order to harden them to increase their durability and strength.

13. Risk Assessment, Safety, and Liability

We completed a full failure modes and effects analysis (FMEA) during the final stages of our design process, which can be found in Appendix A as Table A3. This analysis showed that our most important failure modes were the kickstand mechanism not deploying over rough terrain and the cart tipping in the direction opposite to the kickstand.

We found that although our prototype kickstand deployed extremely reliably during testing on flat ground such as concrete, carpet, or wood, it did not perform as well on rougher terrain such as grass or dirt. This was because the kickstand was designed to deploy at exactly a 45˚ angle with respect to the cart and a 90˚ angle with respect to the ground to maximize the strength of the kickstand components. However, if the ground on which the kickstand landed was at a slightly lower elevation than the cart, this resulted in the kickstand reaching a less than 90˚ angle with respect to the ground. This in turn led the reaction force from the ground to contribute to pulling the cart over, as can be seen in the free body diagram in Figure 12 below.

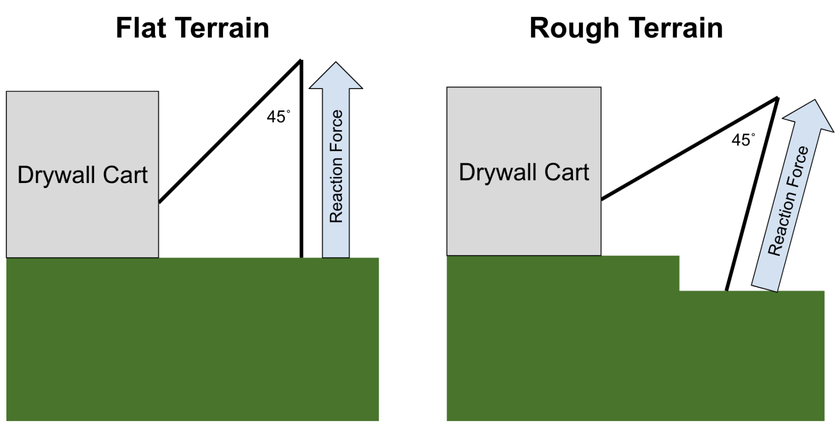


Figure 12: Free body diagram depicting the change in direction of the reaction force when the kickstand is used in rough terrain

Our second failure mode was the cart tipping in the direction in which there is no kickstand to support it. We chose not to account for this in our design due to some accident report data that we received from GMS that stated that close to 80% of all drywall cart accidents occur on the open side. Thus, while it is possible for the cart to tip in the direction opposite the kickstand, we decided that it was unlikely enough to not be considered.

14. Patent Claims and Commercialization

We are not currently pursuing any patent claims on our design, but our sponsor GMS has plans to commercialize this product in the future. They would like to be able to manufacture and sell this cart to other drywall distributors as an alternative to the widely popular current Adapa cart design. We estimate that this product would retail for between $1500 and $2000 in the US market, which is around 3 times more than the Adapa cart. This presumably means that they will eventually file a US patent covering the work laid out in this report. A Canadian patent may also be required as GMS does operate in Canada as well as within the United States.

15. Team Member Contributions

Ryan Grajewski (Team Leader):

- Ordered and maintained receipts of all prototype parts
- Led team communications with GMS sponsors
- Joint-lead on all prototyping efforts with Will Hagler, including machining, assembly, painting, and troubleshooting
- Coordinated team meetings with machining expert
- Performed functionality testing of kickstand
- Performed failure analysis calculations of the kickstand, and FEA of mounting bracket

Graham Brantley (Writing Lead/Materials Lead):

- Editor of executive summary, introduction, market research, prior art, codes and standards, customer requirements, design concept ideation, and selected design concept, engineering analyses and experimentation sections, and manufacturing sections
- CAD of the shafts and bevel gears
- Materials selection for the frame, shafts, and bevel gears
- Engineering feasibility calculations for the frame, shafts, and bevel gears
- Writer of industrial design, societal impact, risk assessment, patent claims, and future work sections

Will Hagler (Prototyping Lead):

- Joint-lead on all prototyping efforts with Ryan Grajewski, including all machining, assembly, painting, and troubleshooting
- Performed functionality testing of kickstand
- Led machining efforts for the steering system sub-components and assembly prior to putting the mechanism on hold
- Writer of engineering analysis for the gear and timing belt system
- Certified for specific machines in the MMM

Garrett Rodino (CAD Lead):

- Combined subassemblies in a full CAD assembly
- Added components to the CAD as they were added to the prototype
- Created exploded and parts drawings for each individual CAD part
- Compiled drawings and views into a comprehensive fabrication package with subassemblies and grouping the parts associated with those subassemblies together

Nischal Bandi (Analysis Lead):

- Aided all prototyping and troubleshooting efforts including part procurement
- Secondary editor of final report
- Responsible for CAD and geometric calculations related to the emergency kickstand's center rod, swinging arm, top plate, and pin
- Aided in failure calculations for components of the emergency kickstand
- Wrote majority of engineering analysis for emergency kickstand components

16. Conclusion and Future Project Deliverables

As a culmination of the ideation, engineering analysis, and prototyping efforts taken by our team, we were able to produce a working prototype with one of the three main additions we plan to implement in our final design: the emergency kickstand. Not only does the kickstand addition aid in fulfilling the primary design objective of improving cart safety by acting as a failsafe in the event of a cart beginning to tip, but it also performs very closely to the specifications we designed it for (e.g. halting the cart when it has reached a 45° angle). Along with the progress made towards developing an effective emergency failsafe, we also made significant progress towards implementing steering functionality into the cart through the addition of a system of gears, shafts, pulleys, etc. While our team did face some challenges, such as machinability restrictions due to the cart's steel frame, we did make detailed CAD models to aid in the future implementation of the system.

Testing was performed to ensure that our design met our target specifications. We validated all of our components via FEA analysis and hand calculations before trying to implement them in our prototype. We managed to test the kickstand extensively, demonstrating that it had an 85% effective deployment rate. Additionally, we found that our cart could withstand 2000 Nm of torque before tipping, which was substantially more than our target value of 408 Nm.

The next steps required to take our design to market are to optimize our design, to determine a manufacturing strategy, either creating components in house or sourcing cheaper components from other companies, and then to patent our design. This work will need to be undertaken by our sponsor, Gypsum Management and Supply, as all of the contributors to this report currently have plans for after graduation that do not include this project. After the patenting process is complete, the product will need to be marketed and then sold, probably around the $2000 price point.

Appendix A: Design Process Tools

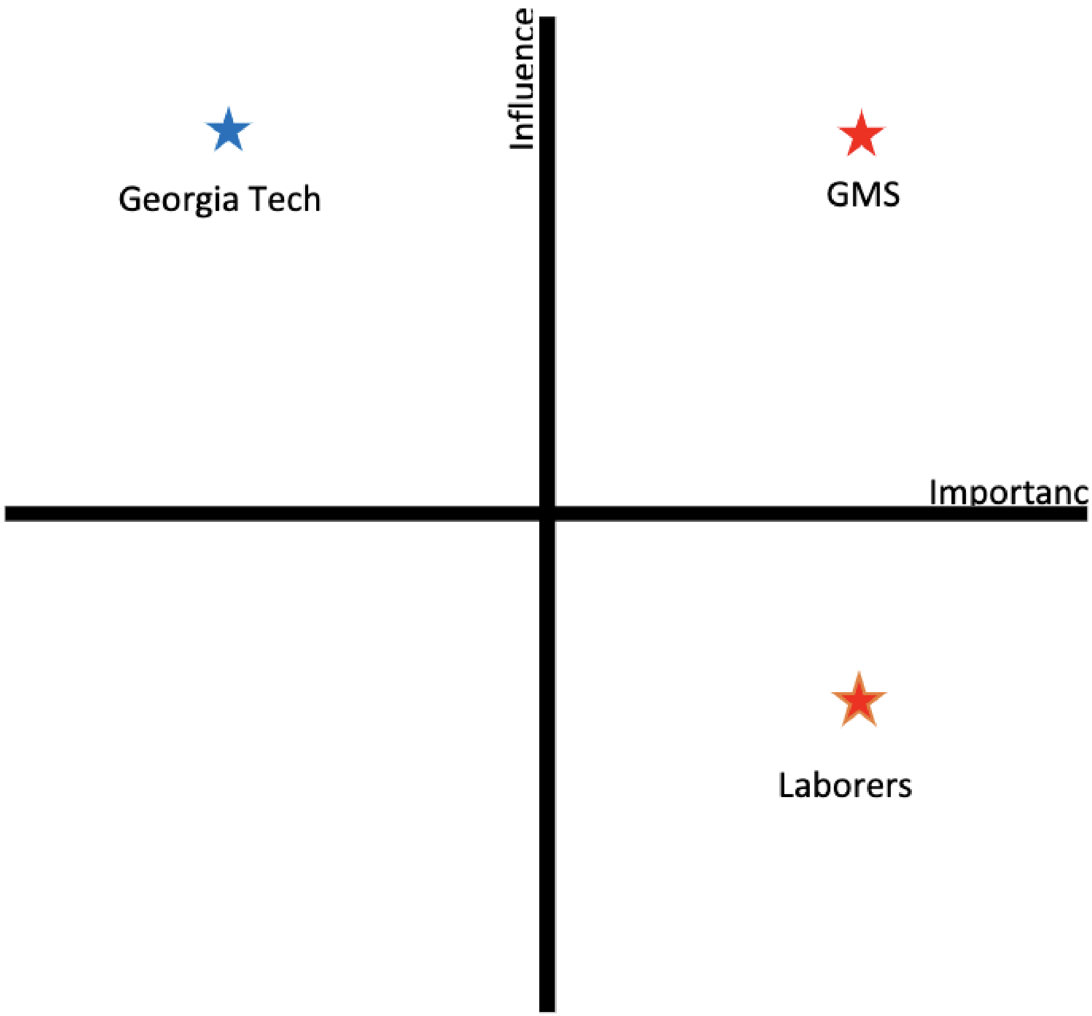


Figure A1: Stakeholder Analysis Overview Chart with relevant stakeholders and their relative importance and influence

Table A1: Specifications sheet

`				Issued:	1/31/2022	
			For:	**Page:**	**1**	
			Specification	**Drywall Cart**		
No.	**Date**	**D/W**	**Requirements**	**Responsible**	**Source**	**How Validated**
General						
Cost	1/31/2022	W	Total Manufacturing Cost between 350-450$	Everyone	Sponsor	Cost Analysis
Schedules	1/31/2022	D	Finished by Expo	Everyone	GT	Is it done?
Physical Characteristics						
Size	1/31/2022	D	Fits within Doorframe and small hallways (30-32 in.) Length < 16'	Everyone	Standard	Testing
Maneuverability	1/31/2022	D	0 turn radius	Everyone	Sponsor	Testing
Material	1/31/2022	D	Lightweight, strong, cheap material	Everyone	Sponsor	Material Optimization
Change of Direction	1/31/2022	D	Smooth turning, no wheel hangups	Everyone	Sponsor	Testing
Mechanical						
Stiffness	1/31/2022	D	No flex during use	Everyone	Standard	Testing
Weight	1/31/2022	D	Max weight of 90 lbs.	Everyone	Sponsor	Scale
Strength	1/31/2022	D	Supports a minimum of 2500-3000 lbs	Everyone	Sponsor	Modeling/Hand Calcs
Performance						
Manufacturable	1/31/2022	W	Must be manufacturable using simple machining equipment	Everyone	Sponsor	Prototyping
Repairable	1/31/2022	D	Must be modular in design for ease of repair	Everyone	Sponsor	DFMA Analysis
Durable	1/31/2022	D	Infinite Life Assumption (10^6)	Everyone	Sponsor	Modeling/Hand Calcs
Safe	1/31/2022	D	Design must be safe within operating ranges	Everyone	Sponsor	Testing/Modeling
Operation	1/31/2022	D	Must be within OSHA guidelines	Everyone	GT	Testing
Assembly	1/31/2022	D	Modules assembled using standard fasteners	Everyone	Sponsor	Prototyping
Ergonomics	1/31/2022	D	Must be easy to load and unload	Everyone	Sponsor	Sponsor feedback

Table A2: Concept evaluation matrix. Concept #1 (2 wheel drive + angled A-frame + external kickstand) was selected as the best design concept moving forward.

		Drywall Cart Design Concepts									
		Concept #1		Concept #2		Concept #3		Concept #4		Concept #5	
		2WD + Angled A-Frame + External Kickstand		4WD + Angled A-Frame + Internal Kickstand		Caster Wheels + Angled A-Frame + Suspension + Footbrake		Caster Wheels + Flatbed + Footbrake		Caster Wheels + Angled A-Frame + Internal Kickstand + Side Guards + Footbrake	
											
User Needs	Importance	Score (1-5)	Product	Score (1-5)	Product	Score (1-5)	Product	Score (1-5)	Product	Score (1-5)	Product
Low cost	5	2	10	1	5	2	10	5	25	3	15
Safe to use	10	4	40	5	50	3	30	1	10	3	30
Can use on multiple surfaces	9	4	36	3	27	4	36	1	9	1	9
Durable	7	4	28	1	7	3	21	5	35	2	14
Lightweight	6	3	18	3	18	3	18	5	30	2	12
Not complex	4	3	12	1	4	4	16	5	20	3	12
Highly maneuverable	10	5	50	4	40	5	50	5	50	5	50
Same capacity as current cart	7	3	21	3	21	3	21	5	35	3	21
Stable	10	5	50	5	50	3	30	1	10	3	30
Easy to use	3	2	6	1	3	5	15	5	15	4	12
Easy to repair	5	3	15	1	5	4	20	5	25	2	10
Looks nice	1	3	3	3	3	3	3	5	5	3	3
Portable by 1 person	5	3	15	3	15	3	15	3	15	3	15
Can fit in truck	10	5	50	5	50	5	50	4	40	5	50
Total Scores		354		298		335		324		283	
Rank		1		4		2		3		5	

Engineering Requirements	Total width (in)	Total length (in)	Total height (in)	Total weight (lbs)	Total cost ($)	Number of cycles until failure (unitless)	Load capacity (lbs)	Tipping moment (lb*ft)	Failure system response time (ms)	Impact yield stress (ksi)	Turning radius (ft)	Number of parts (unitless)	Minimum safety factor (unitless)	Longest time to replace part (min)	Maximum corrosion rate (mpy)	Minimum surface roughness (milli in)	Time to learn to operate (hours)	Number of controls (unitless)	Height of center of mass (ft)	Maximum speed (mph)	Packing density (units/ft^3)
Total width (in)																					
Total length (in)																					
Total height (in)																					
Total weight (lbs)	⊕	⊕	⊕																		
Total cost ($)				+																	
Number of cycles until failure (unitless)																					
Load capacity (lbs)				+																	
Tipping moment (lb*ft)	⊕		⊖	+			+														
Failure system response time (ms)								+													
Impact yield stress (ksi)						+															
Turning radius (ft)	-	⊖																			
Number of parts (unitless)				+	⊕	-				-											
Minimum safety factor (unitless)					⊕	⊕	+	+	-	⊕											
Longest time to replace part (min)				+								⊕									
Maximum corrosion rate (mpy)					⊖	-				-		+									
Minimum surface roughness (milli in)					⊕	+							+		⊖						
Time to learn to operate (hours)												+									
Number of controls (unitless)					+						-	⊕		+			⊕				
Height of center of mass (ft)			⊕					⊖													
Maximum speed (mph)				-													+		-		
Packing density (units/ft^3)	⊖	⊖	⊖																		
Direction of Improvement	o	o	o	↓	↓	↑	↑	↓	↓	↑	o	↓	↑	↓	↓	o	↓	↓	↓	o	↑
Importance (1-10)																					

Figure A2a: House of Quality (correlation matrix)

		Engineering Requirements																				
Customer Requirements	**Importance (1-10)**	Total width (in)	Total length (in)	Total height (in)	Total weight (lbs)	Total cost ($)	Number of cycles until failure (unitless)	Load capacity (lbs)	Tipping moment (lb*ft)	Failure system response time (ms)	Impact yield stress (ksi)	Turning radius (ft)	Number of parts (unitless)	Minimum safety factor (unitless)	Longest time to replace part (min)	Maximum corrosion rate (mpy)	Minimum surface roughness (milli in)	Time to learn to operate (hours)	Number of controls (unitless)	Height of center of mass (ft)	Maximum speed (mph)	Packing density (units/ft^3)
Low cost	5	○	○	○	○	◎							○				Δ		Δ			
Safe to use	10								◎	◎	Δ			◎		○	○			◎	○	
Can use on multiple surfaces	9																					
Durable	7						◎				◎					◎			○			
Lightweight	6	○	○	○	◎																	
Not complex	4												◎		○			○	◎			
Highly maneuverable	10	○	○	○	○				Δ			◎								Δ	Δ	
Same capacity as current cart	7							◎														
Stable	10	Δ	Δ	Δ	Δ				◎					Δ						◎	○	
Easy to use	3				○				○									◎	○			
Easy to repair	5												◎		◎							
Looks nice	1																					
Portable by 1 person	5	○	○	○	◎																	
Can fit in truck	10	◎	◎	◎																		◎
Targets		12	50	48	90	450	10^6	3000	300	10	72.5	0	20	2	3	1	1	1	2	2	3	0.1
Absolute Importance		178	178	178	163	45	63	63	199	90	73	90	96	100	57	93	35	39	71	190	70	90
Relative Importance (%)		8.24	8.24	8.24	7.54	2.08	2.92	2.92	9.21	4.16	3.38	4.16	4.44	4.63	2.64	4.30	1.62	1.80	3.29	8.79	3.24	4.16
Rank		4	4	4	6	19	16.5	16.5	1	11	13	11	8	7	18	9	21	20	14	2	15	11

Figure A2b: House of Quality (relationship matrix and engineering requirement rankings)

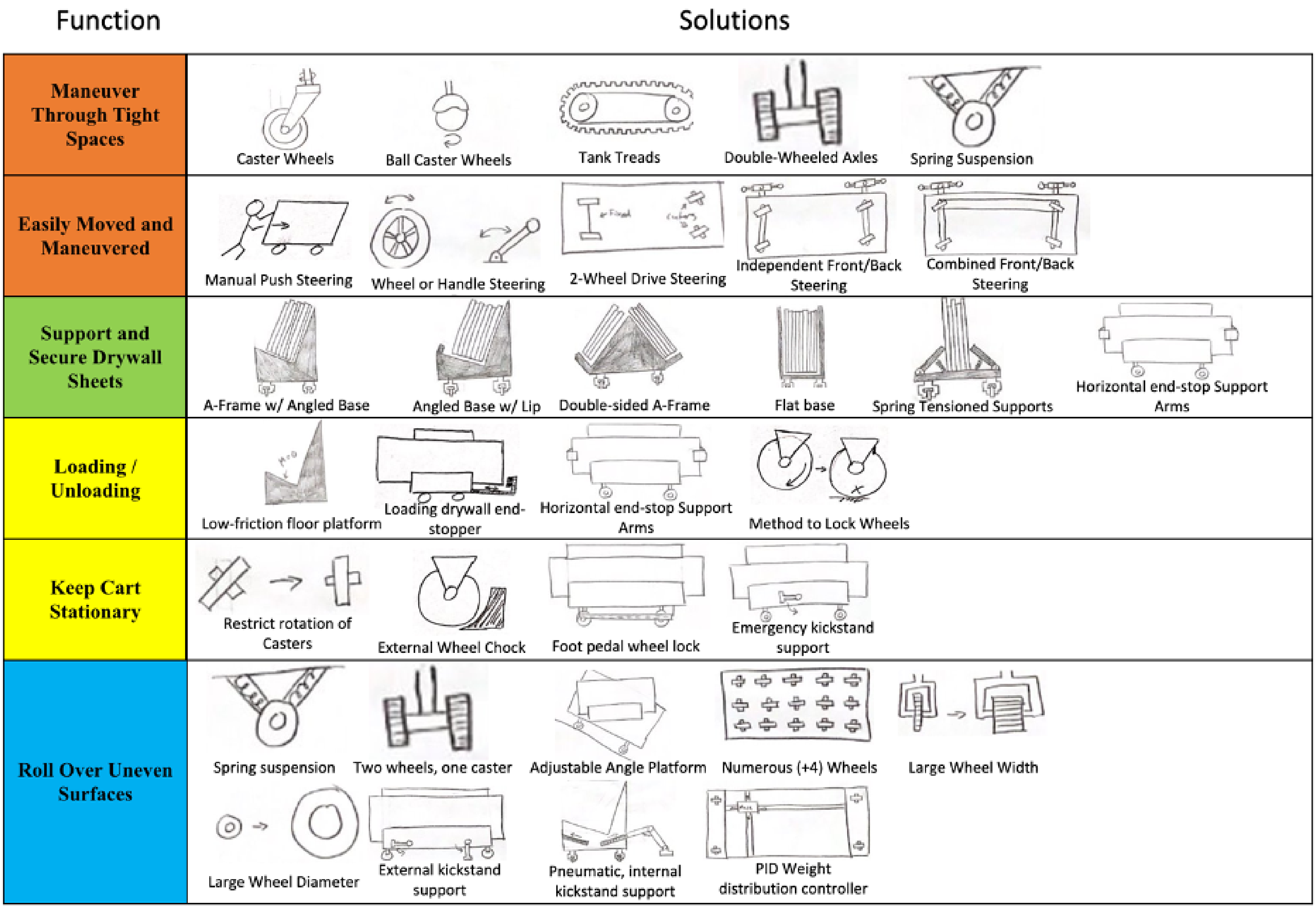


Figure A3: Morphological chart with sketches of each component concept design

Table A3: FMEA analysis of our cart design

Failure Mode	**Severity (1-5)**	**Potential Causes**	**Frequency of Occurrence (1-5)**	**Reasoning for Frequency**	**Score**	**Rankin g**
The kickstand mechanism fails to deploy	5	• Rough terrain causes the kickstand to not reach a 45˚ angle	2	In testing our kickstand reliably deployed, but there may be cases in which it will fail in rough terrain	10	1
Cart falls in direction opposite from the kickstand	5	• The drywall is pushed towards the frame with extreme force • Rough terrain substantially tilts the cart	1	Only 20% (1/5) of injuries involve the drywall tipping towards the cart [GMS]	5	2
A user's hand gets caught in gears	3	• Covering panels are absent • User puts hand into bevel gear box	1	All gears should be covered at all times per our design	3	3
The cart's wheels puncture the floor	1	• Very weak flooring • Overloading the cart	2	While we did make the wheels softer and wider to avoid this problem, we cannot control jobsite surface conditions	2	4
Gears get stuck	1	• Lack of lubrication • Debris gets inside the gearing system	1	The gears should work fine so long as the panels are still present to protect them	1	5

Appendix B: Calculations

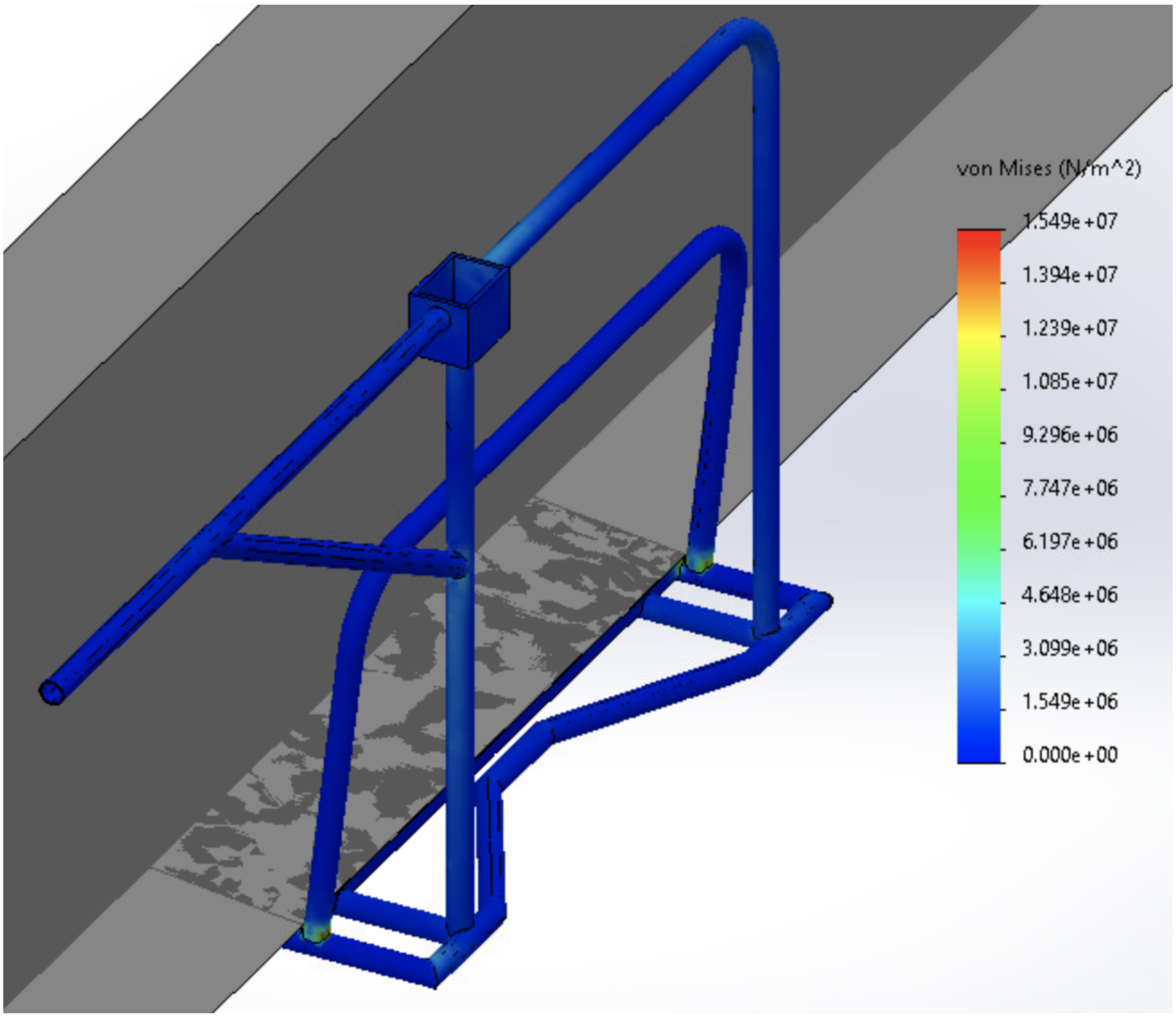


Figure B1: FEA analysis of the frame under the maximum load of 3000 lbs of drywall. Drywall was modeled as a rigid 96" x 192" x 8" block. Frame was meshed with a blended curvature-based mesh with a maximum element size of 3" and a minimum element size of 0.15".

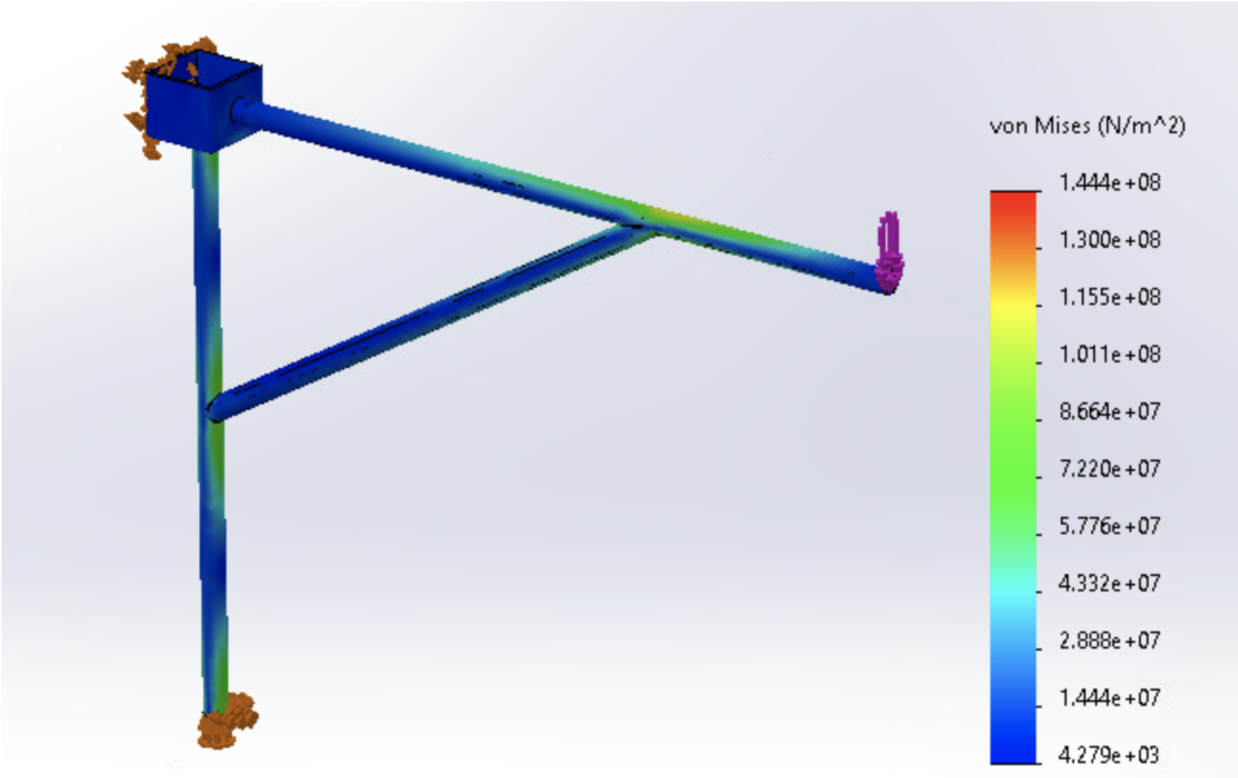


Figure B2: FEA analysis of the steering column under an unusually large load of 100 lbf at the steering wheel, simulating someone pressing down on the steering wheel with a large amount of force. Only a section of the cart was used to reduce computation cost.

Equations B1 and B2: Equations used to calculate torsion and bending stresses in shafts

$$\sigma_{Torsion} = K_{fs}\frac{16T}{\pi d^3},\ \sigma_{Bending} = K_f\frac{32M}{\pi d^3}$$

Table B1: List of variables used and calculated through our shaft analysis

Variable	Value
K_{fs}	(assume no notches) 1
K_f	(assume no notches) 1
d	0.5 in
L	44.0 in
$T_{horizontal}$	10.00 Nm

$M_{horizontal}$	8.89 Nm
$T_{vertical}$	20.00 Nm
$M_{vertical}$	0.00 Nm
$\sigma_{t,horizontal}$	24.9 MPa
$\sigma_{b,horizontal}$	44.2 MPa
$\sigma_{t,vertical}$	49.7 MPa
$\sigma_{b,vertical}$	0.9 MPa
σ_{yield}	310.0 MPa
$FS_{horizontal}$	7.01
$FS_{vertical}$	6.24

Equations B3 and B4: Equations used to calculate contact and bending stresses for bevel gears

$$\sigma_{Contact} = \frac{\sigma_{c,lim} Z_{NT} Z_{W}}{K_{\theta} Z_{Z}}, \ \sigma_{Bending} = \frac{\sigma_{b,lim} Y_{NT}}{K_{\theta} Y_{Z}}$$

Table B2: List of variables used for bevel gear analysis

Variable	**Value**
$\sigma_{c,lim}$	1200 MPa
$\sigma_{b,lim}$	150 MPa
Z_{NT} = stress-cycle factor for pitting resistance	1.52
Z_W = hardness ratio factor	1
K_θ = temperature factor	1
Z_Z = reliability factor	1.22
Y_{NT} = stress-cycle factor	1.20

for bending strength	
$Y_Z = Z_Z^2$	1.50

Equations B5, B6, B7, and B8: Equations used to calculate factors of safety for the gearing system

$$\sigma_{bending} = \frac{(W^t K_o K_v K_s P_d K_m K_b)}{FJ}, \sigma_{contact} = C_p\left(\frac{W^t K_o K_v K_s P_d K_m C_f}{d_p F I}\right)^{1/2}$$

$$S_{F,bending} = \frac{S_t Y_N}{K_T K_R / \sigma,bending}, S_{H,contact} = \frac{S_C Z_N C_H}{K_T K_R / \sigma,contact}$$

Table B3: Input and output values for gear train calculations

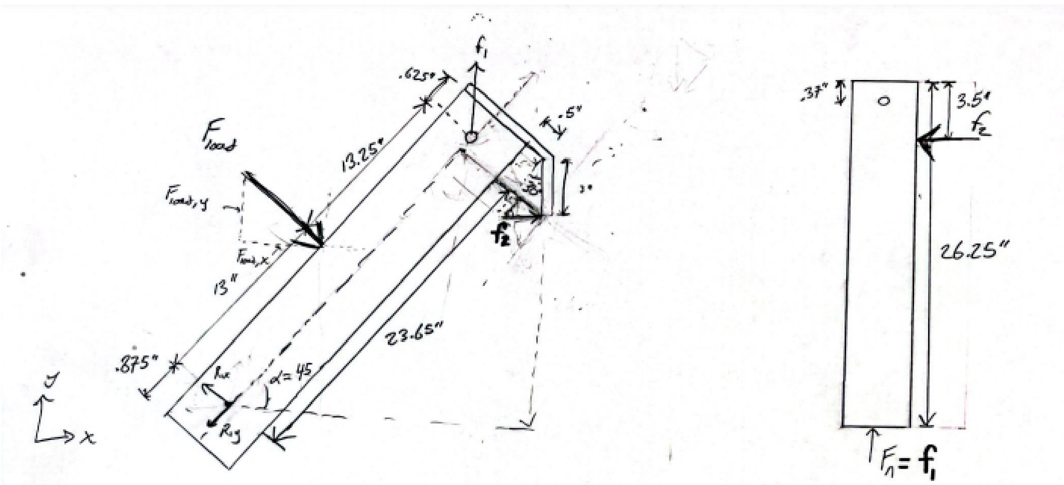
Factors	**Pinion**	**Gear**
[T] - Input Torque (ft-lbf)	14.75	29.5
[n] - Angular Velocity (rpm)	15.0	7.50
[V] - Gear Velocity (ft/sec)	0.157	0.196
[d_p] - Diametral Pitch	10	
[m_G] - Gear Ratio	2	6
[N_p] - Number of Teeth	17	102
[Φ] - Pressure Angle (˚)	20	
[P_d] - Pitch Diameter (in)	1.70	10.2
[W^t] - Transmitted Load (lbf)	208	
[K_o] - Overload Factor	1	
[K_v] - Dynamic Factor	1.0041	1.0036
[K_S] - Size factor	1.12	1.13

[K_m] - Load Distribution Factor	2.28	
[K_b] - Rim thickness factor	1	
[F] - Face Width (in)	1	
[J] - Geometry Factor for bending strength	0.20	
[C_p] - Elastic Coefficient (ksi)	2.30	
[C_f] - Surface Condition factor	1	
[C_H] - Hardness Ratio Factor	1	
[I] - Geometry factor of pitting resistance	0.107	0.121
[K_T] - Temperature Factor	1	
[K_R] - Reliability Factor	0.850	
[S_T] - Bending Strength at 10^7 cycles and 0.99 reliability (carburized and hardened grade 1 steel) (ksi)	28.3	
[S_C] - Contact strength at 10^7cycles and 0.99 reliability (carburized and hardened grade 1 steel) (ksi)	93.5	
[Y_n] - Stress Cycle factor for bending strength	1	
[Z_n] - Stress cycle factor for pitting resistance	1	
[σ_b] - Bending Stress (ksi)	26.8	4.09
[σ_c] - Contact Stress (ksi)	51.4	43.4
[S_F] - Bending Safety Factor	1.24	1.35

[S_H] - Contact Safety Factor	2.43	2.53

Table B4: List of forces and corresponding magnitudes apparent in emergency kickstand

Force	Value	Description
F_{load}	2000 lb	perpendicular to center support rod
F_1	1414.2 lb	reaction force from swinging rod
F_2	15.6 lb	reaction force from top plate on swinging rod
R_{1x}	1011.02 lb	x-component of connection hardware reaction force
R_{1y}	1011.02 lb	x-component of connection hardware reaction force



$$\Sigma F_x = -R_{1x} + F_{load} + f_2\cos(45) - f_1\cos(45) = 0$$

$$\Sigma F_y = R_{1y} + f_1\sin 45 + f_2\sin(45) = 0$$

$$\Sigma M_R = -F_{load}(13") + f_1\cos(45)(26.25") + f_2\cos(45)(1") - f_2\sin(45)(23.65") = 0$$

$R_{1x} = R_1\cos(45)$ $\quad F_{load} = 2000\text{ lb}$

$R_{1y} = R_1\sin(45)$ $\quad F_{load,x} = 2000\cos(45) = 1414.2\text{ lb} = F_{load,y}$

$R_{1x} = -1429.8\cos(45) = 1011.02\text{ lb}$ (↖)

$R_{1y} = -1429.8\cos(45) = 1011.02\text{ lb}$ (↙)

$\therefore R_1 = 1429.8\text{ lb}$

$F_1 = 1414.2\text{ lb}$ (up ↑)

$F_2 = 15.6\text{ lb}$ (right →)

Figure B3: Free body diagram of emergency kickstand assembly depicting main forces

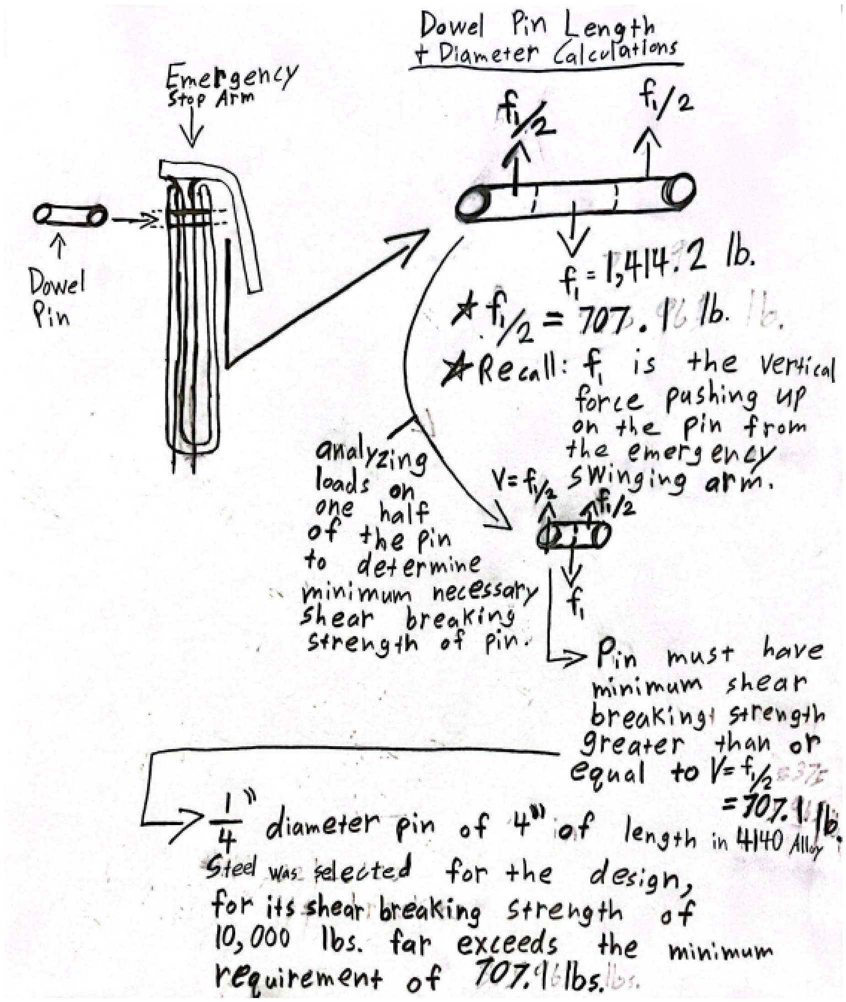


Figure B4: Connecting pin shear and dowel pin specifications

Long or Short Column?

long: $\frac{L}{K} > \left(\frac{L}{K}\right)_1 = \sqrt{\frac{2C\pi^2E}{S_y}}$ | $K = \sqrt{\frac{I}{A}}$ $\quad I = \frac{\pi}{64}(d_2^4 - d_1^4)$

$A = \frac{\pi}{4}(d_2^2 - d_1^2)$

Center Support Rod

$d_2 = 1''$ $\quad d_1 = 5/8''$ $\quad L = 27.75''$ $\quad I = \frac{\pi}{64}((1in)^4 - (5/8 in)^4) = .0416\ in^4$

$A = \frac{\pi}{4}((1)^2 - (5/8)^2) = .4786\ in^2$ $\quad K = \sqrt{\frac{.0416\ in^4}{.4786\ in^2}} = .2948\ in$ $\quad S_y = 75{,}000\ psi$

$\frac{L}{K} = 94.1278\ in < \left(\frac{L}{K}\right)_1 = \sqrt{\frac{2(1)\pi^2(27{,}900\ ksi)}{(75{,}000\ psi)}} = 85.69$

∴ Long Column:

$P_{crit} = \frac{C\pi^2EI}{L^2} = \frac{1(\pi^2)(27{,}900{,}000)(.0416\ in^4)}{(27.75)^2} =$

$\boxed{P_{crit} = 14875.2\ lb}$

→ greatest axial force is $R_1 \sin 45 = 1{,}011.02$ lb.
→ will not buckle ✓

Swinging Support Rod

$d_2 = 3/4''$ $\quad d_1 = 3/8''$ $\quad L = 26.25''$ $\quad I = \frac{\pi}{64}((3/4)^4 - (3/8)^4) = .0146\ in^4$

$E = 27{,}900{,}000\ psi$ $\quad S_y = 75{,}000\ psi$ $\quad A = \frac{\pi}{4}((3/4)^2 - (3/8)^2) = .3313\ in^2$

$K = \sqrt{\frac{.0146\ in^4}{.3313\ in^2}} = .2096\ in$

$\frac{L}{K} = 125.22\ in > \left(\frac{L}{K}\right)_1 = \sqrt{\frac{2(1)\pi^2(27{,}900\ ksi)}{75000\ psi}} = 85.69$

∴ Long Column:

$P_{crit} = \frac{C\pi^2EI}{L^2} = \frac{1(\pi^2)(27{,}900{,}000\ psi)(.0146\ in^4)}{(26.25)^2}$

$\boxed{P_{crit} = 5{,}818.8\ lb}$ → greatest axial force is $f_1 = \frac{1414.2\ lb}{2} = 707.1$ lb. (2 rods for swinging arm)
→ will not buckle ✓

Figure B5: Center rod and swinging arm buckling load

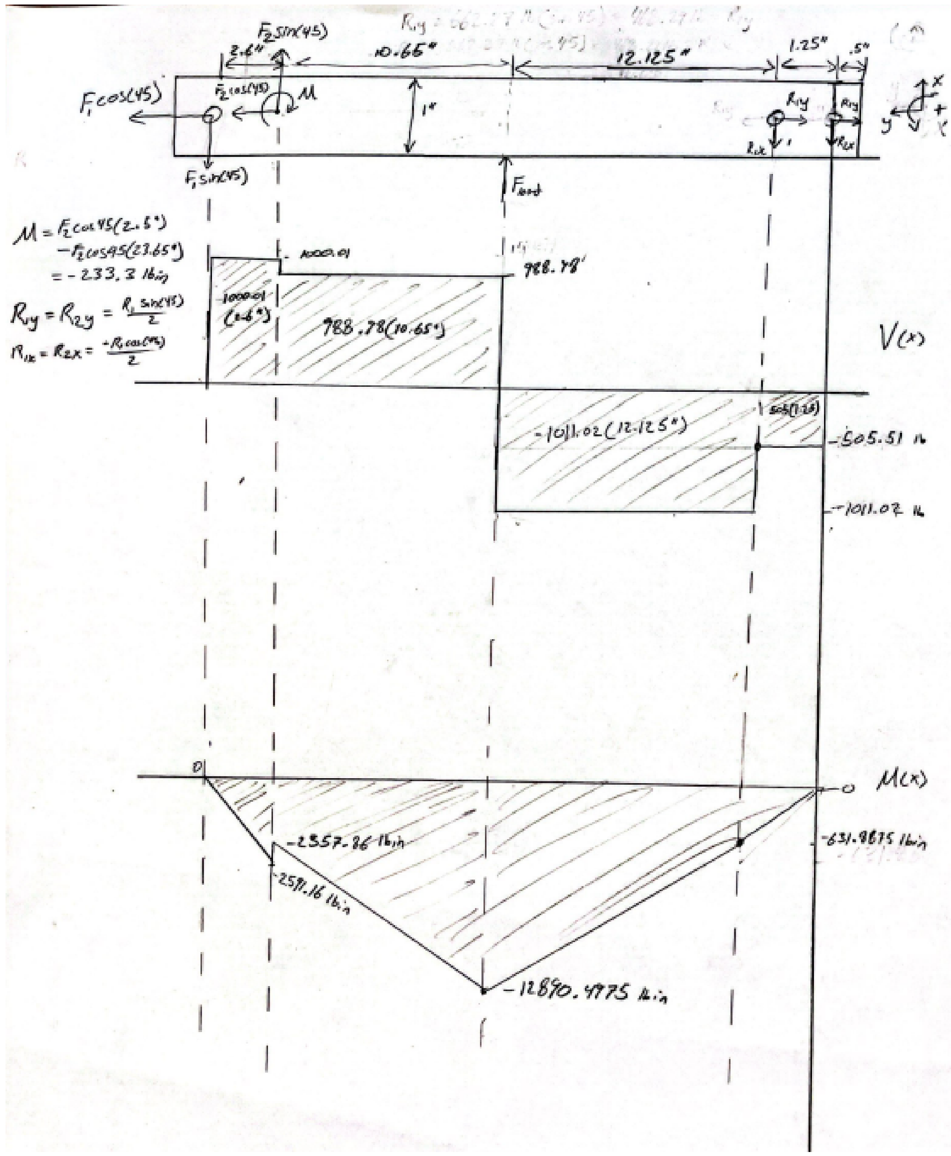


Figure B6: Shear force and bending moment diagrams of emergency kickstand center rod

Center Rod Support

axial

$$\sigma_{axial} = K_t \sigma_o = K_t\left(\frac{4F}{\pi(d_2^2 - d_1^2)}\right) \qquad \sigma_o = \frac{4(505.51\ lb)}{\pi(1^2 - (3/8)^2)} = 1056.2\ psi$$

interpolate $\frac{.9 - .625}{3.8 - K_t} = \frac{.9 - .59}{3.8 - 3.5}$

$$\rightarrow K_t = 3.533$$

$$\sigma_{axial} = 3.533(1056.2\ psi) = 3731.63\ psi$$

bending

$$\sigma_{bending} = K_t \sigma_o = K_t\left(\frac{32 M d_2}{\pi(d_2^2 - d_1^2)}\right) \qquad \sigma_o = \frac{32(631.8)}{\pi(1^2 - .626^2)} = 10560.7\ psi$$

interpolate: $\frac{.93 - .625}{3.6 - K_t'} = \frac{.93 - .6}{3.6 - 3.4}$

$$\rightarrow K_t = 3.41$$

$$\sigma_{bending} = 3.41(10560.7) = 36011.987$$

Shear due to bending

$$\tau_{xy} = \frac{2V}{A} = \frac{2(505.1)}{.4786\ in^2} = 2112.45\ psi$$

Von Mises Failure Theory

$\sigma_x = \sigma_{bending,\,x} = 36011.987$

$\sigma_y = 0$

$\tau_{xy} = 2112.45\ psi$

$$\sigma' = \frac{1}{\sqrt{2}}\sqrt{(\sigma_x - \cancel{\sigma_y})^2 + (\cancel{\sigma_y} - \cancel{\sigma_z})^2 + (\cancel{\sigma_z - \sigma_x})^2 + 6(\tau_{xy}^2 + \cancel{\tau_{yz}^2} + \cancel{\tau_{zx}^2})}$$

$$= \frac{1}{\sqrt{2}}\sqrt{(36011.987)^2 + 6(2112.45)^2}$$

$$\sigma' = 36104\ psi$$

$$\sigma' = 36104\ psi \leq \frac{S_y}{2} = \frac{75{,}000\ psi}{2}$$

✓ will not fail

Figure B7: von Mises stress analysis of kickstand

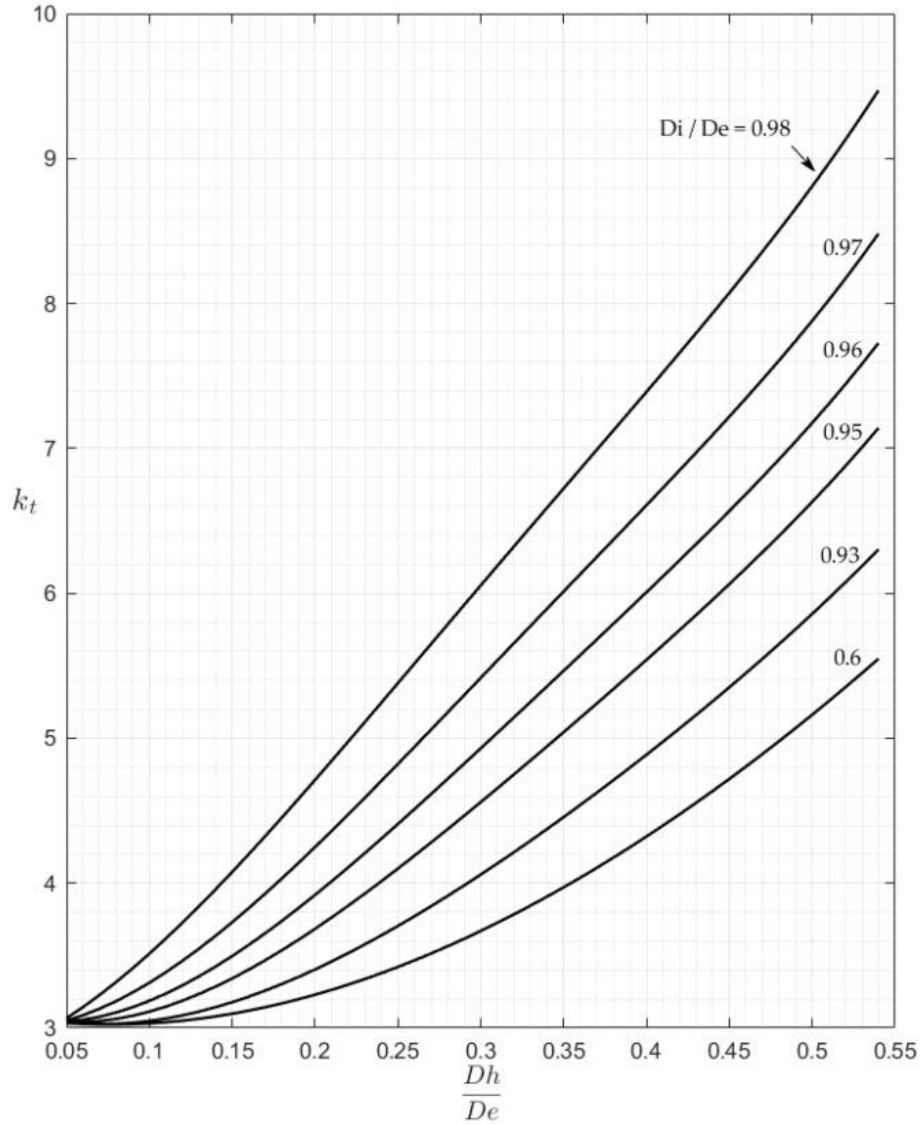


Figure B8: K_t (stress concentration) for bending stresses

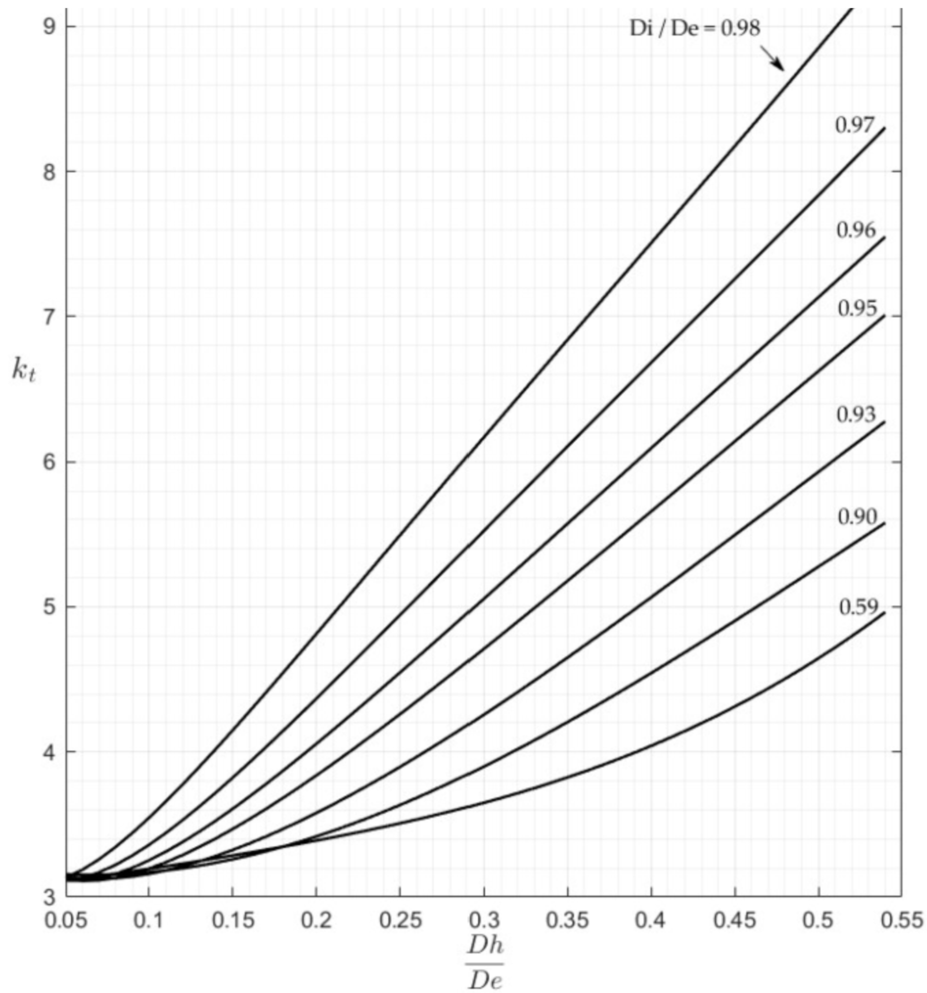


Figure B9: K_t (stress concentration) for axial stresses

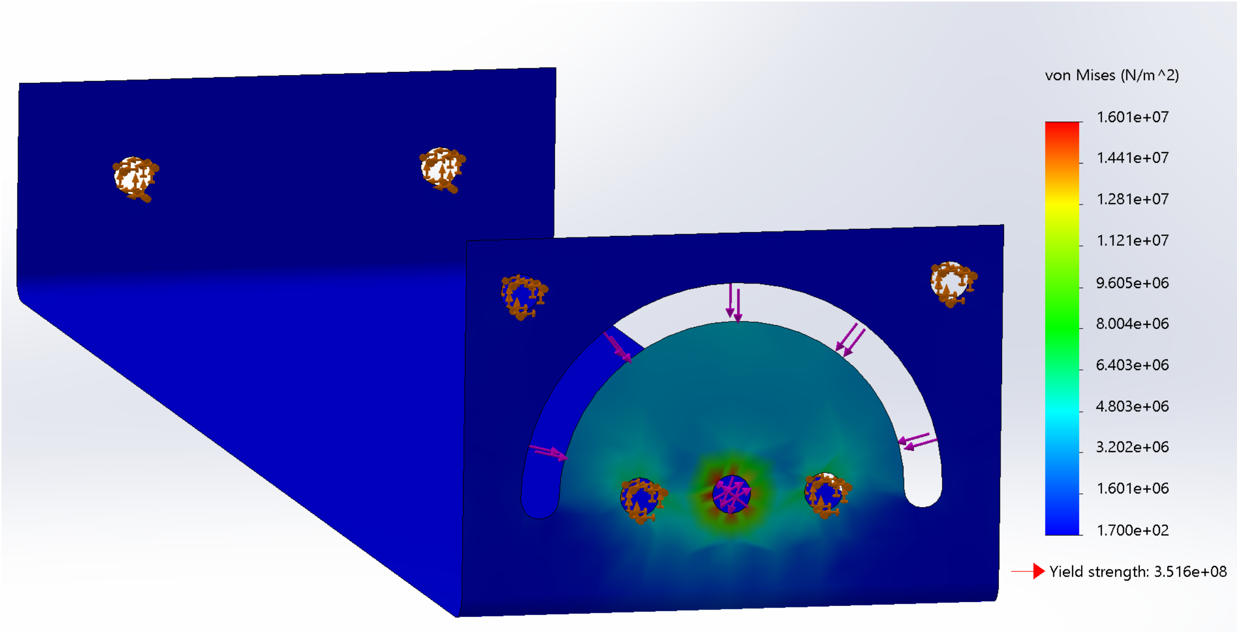


Figure B10: Results of FEA simulation on the mounting bracket for the emergency kickstand

Appendix C: Cost

Table C1: Bill of Materials

Bill of Materials					
Category	Part Number	Part Name	Quantity	Price Per Part ($)	Notes
Gears	6338K436	Oil-Embedded Flanged Sleeve Bearing	2	$5.63	Part from McMaster Carr.
	6338K417	Oil-Embedded Flanged Sleeve Bearing	2	$1.98	Part from McMaster Carr.
	1497K8	1045 Carbon Steel Keyed Rotary Shaft	1	$13.79	Part from McMaster Carr.
	92510A582	Aluminum Unthreaded Spacer	5	$3.88	Part from McMaster Carr.
	92620A552	Zinc Yellow-Chromate Plated Hex Head Screw	5	$0.87	Part from McMaster Carr. (pack)
	95462A029	Medium-Strength Steel Hex Nut	5	$0.08	Part from McMaster Carr. (pack)
	6280K641	Roller Chain Sprocket	1	$16.35	Part from McMaster Carr.
	6236K371	Roller Chain Sprocket	1	$94.40	Part from McMaster Carr.
	5906K572	Oil-Embedded Thrust Bronze Bearing	2	$7.32	Part from McMaster Carr.
	5906K514	Oil-Embedded Thrust Bronze Bearing	2	$2.32	Part from McMaster Carr.
	1497K144	1045 Carbon Steel Keyed Rotary Shaft	1	$18.48	Part from McMaster Carr.
	6435K18	Clamping Shaft Collar	2	$4.06	Part from McMaster Carr.
	6261K173	Roller Chain	3	$4.78	Part from McMaster Carr.
	6261K243	Adding Link for ANSI Number 40 Single Strand Roller Chain	1	$0.78	Part from McMaster Carr.
	6261K263	Add&Connect Link for ANSI #40 Single Strand Roller Chain	1	$2.13	Part from McMaster Carr.
	6484K358	L Series Timing Belt, Trade No. 420L100	1	$46.43	Part from McMaster Carr.

	98830A200	1018-1045 Carbon Steel Machine Key Stock	1	$1.63	Part from McMaster Carr.
	ATP44L100-A-NUK	L Type Timing Pulley	2	$136.66	Part from Misumi.
	ATP14L100-A-HUK	L Type Timing Pulley	1	$37.46	Part from Misumi.
	9414T11	Set Screw Shaft Collar	8	$1.98	Part from McMaster Carr.
	6383K34	Ball Bearing	4	$10.16	Part from McMaster Carr.
	8632T11	D-Profile Rotary Shaft	2	$32.86	Part from McMaster Carr.
	7767T28-7767T283	Low-Carbon Steel Round Tube	1	$15.06	Part from McMaster Carr.
Subtotal ($)				723.12	
Category	Part Number	Part Name	Quantity	Price Per Part ($)	Notes
Frame	7767T28-7767T283	Low-Carbon Steel Round Tube	10	$15.06	This is an estimation based on the volume of the frame and single tube. Volume of frame = 163.06 in^3. Volume of single tube = 17.42 in^3. Part from McMaster Carr.
	Source: https://www.performancecoating.com/powder-coating-cost/	Powder coat spray painting	3627.65	$0.07	This is an estimation based on the surface area of the frame and the cost of powder coating per square foot. Surface area of frame = 3627.65 in^2. Cost of powder coating = $10.00/ft^2 = $0.07/in^2.
Subtotal ($)				404.54	
Category	Part Number	Part Name	Quantity	Price Per Part ($)	Notes

Wheels	6033K71	Zinc Unthreaded-Hole Spoked Hand Wheel	1	24.17	Part from McMaster Carr.
	2498T56	Easy-Turn Wheel with 4-5/8" x 3-3/4" Plate	2	49.16	Part from McMaster Carr.
	2498T47	Easy-Turn Caster with 4-5/8" x 3-3/4" Plate	2	68.90	Part from McMaster Carr.
Subtotal ($)				260.29	

Category	Part Number	Part Name	Quantity	Price Per Part ($)	Notes
Kickstand	92510A767	Aluminum Unthreaded Spacer 1/2" OD, 3/4" Long, for 1/4" Screw Size	1	$2.03	Part from McMaster Carr.
	90492A150	Hairpin Cotter Pins for 3/16"-1/4" Pin Diameter, 3/64" Wire Diameter	1	$3.83	Part from McMaster Carr.
	91844A410	Zinc-Plated Steel Curved Washer for 1" Tube OD, 1/4" Screw Size, 0.28" ID, 1" OD	1	$25.01	Part from McMaster Carr. (pack)
	91257A548	Zinc Yellow-Chromate Plated Hex Head Screw Grade 8 Steel, 1/4"-20 Thread, 1-3/4" Long, Partially Threaded	1	$13.62	Part from McMaster Carr. (pack)
	90866A029	Zinc-Plated Steel Wing Nut 1/4"-20 Thread Size, 31/64" Base Diameter	1	$18.29	Part from McMaster Carr. (pack)
	92510A762	Aluminum Unthreaded Spacer 1/2" OD, 1/4" Long, for 1/4" Screw Size	1	$1.77	Part from McMaster Carr. (pack)
	7767T62	Low-Carbon Steel Round Tube, 0.188" Wall Thickness, 1" OD	1	$71.42	Part from McMaster Carr.
	7767T28	Low-Carbon Steel Round Tube, 0.065" Wall Thickness, 1-1/4" OD	1	$8.58	Part from McMaster Carr.
	3899T53	Pin-Release Shackle with Eye, 316 Stainless Steel, 1500 lbs. Capacity, Not for Lifting	1	$19.40	Part from McMaster Carr.
	9489T22	Routing Eyebolt with Nut - Not for Lifting Zinc-Plated with Bent-Closed Eye, 1/4"-20 Thread, 3" Shank	1	$4.28	Part from McMaster Carr. (pack)
	9491T14	Screw-In Hook with One Hex Nut, 0.210" Diameter, 1" Projection	1	$6.57	Part from McMaster Carr. (pack)

	15205A35	Spring Hinge, Self-Closing, Steel, 1-3/4" x 3/4" Door Leaf	1	$5.67	Part from McMaster Carr.
	9271K643	Torsion Spring, 120 Degree Left-Hand Wound, 1.102" OD, Packs of 1	1	$3.75	Part from McMaster Carr.
	9271K706	Torsion Spring, 120 Degree Right-Hand Wound, 1.102" OD, Packs of 1	1	$3.75	Part from McMaster Carr.
	92510A786	Aluminum Unthreaded Spacer, 5/8" OD, 1" Long, for 1/4" Screw Size	1	$3.17	Part from McMaster Carr.
	90145A857	18-8 Stainless Steel Dowel Pin, 1/4" Diameter, 8" Long, Packs of 1	1	$11.63	Part from McMaster Carr.
	53736	Hillman 110 ft. L Galvanized Steel 18 Ga. Wire	1	$11.99	Part from Ace Hardware
Subtotal ($)				214.76	

Categories	Subtotals ($)	Subtotal Percentages (%)	Notes
Gears	723.12	45.12	
Frame	404.54	25.24	
Wheels	260.29	16.24	
Kickstand	214.76	13.40	

Total ($)	Notes
1602.70	

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