Capstone Design Report #1
Drywall Cart Re-Design

ME 4182 – A

2/9/2022

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EXECUTIVE SUMMARY

Drywall is one of the most used materials in construction. It is used in the construction of interior walls and ceilings. Most general contractors do not provide themselves with this material; however, they hire subcontractors to deliver it. These subcontractors deliver the required amount of drywall at the specified location of the general contractor. Sometimes these locations can be at the top floor of an apartment building or upstairs in a residential house. GMS or Gypsum Management & Supply Inc has used the same drywall cart for forty years to transport drywall to the desired location. GMS has recorded a number of work-related injuries that involve the use of this cart. As a result, GMS is exploring alternative solutions to reduce the number of injuries related to the transport of drywall. With support from GMS, the team's sponsor, the team is attempting to replace the current cart with an updated version that would reduce the number of injuries.

To meet the needs of GMS, the team is working on an improved drywall cart that can safely transport up to sixteen sheets of drywall in various construction environments. The main safety concerns in the current design are the cart being overloaded and tipping over and the caster wheels puncturing the floor. The team's overall objective is to design a cart that would prevent these situations from happening. In doing so, the design will concentrate on the stability and maneuverability of the cart along with the ability to support and secure the payload.

With the current cart in mind, the team has identified certain attributes of its design that have potentially led to injury. One of which is the use of caster wheels, which force the laborers to both direct and move the cart at the same time. By doing both, the laborers can cause the cart to flip over and lead to serious injuries. These injuries have led to GMS losing close to a million dollars annually.

In order to solve these problems, the team came up with multiple potential design concepts. After analyzing the pros and cons of all the concepts, one design was settled on. This design was very similar to the original cart, but it implements a steering system on two of the wheels. Horizontal forces are the catalyst that causes the carts to fall over and cause injuries, and the steering system would eliminate the employees' need to apply that force to turn the cart. Additionally, an external safety mechanism is a part of the design, which will prevent the cart from falling over in the case that it does lose its balance. By using evaluation matrices and other design selection tools, this design was concluded to be most likely to fulfill all of the needs of GMS.

NOMENCLATURE

- **A-Frame-** a support structure shaped like the letter A
- **Caster wheels** -an undriven wheel that is designed to be attached to the bottom of a larger object to enable that object to be moved. Allows rotation around the vertical axis.
- **Tipping moment**-the critical point in a situation, process, or system beyond which a significant and often unstoppable effect or change takes place. Measured in lb-ft.
- **L-frame**- a support structure shaped like the letter L

GLOSSARY

TERM	DEFINITION
GMS	Acronym for: Gypsum Management & Supply Inc.
DFM	Acronym for: Design for Manufacturability
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, it was estimated that approximately 26 billion square feet of wallboard products were sold in the U.S [1], accounting for nearly 95 percent 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 Gypsum Management & Supply Inc. or GMS, whose main function serves to source and deliver large quantities of drywall to staging sites for construction projects across the United States. The most labor-intensive aspect of the delivery process is manually transporting stacks of drywall from the on-site delivery truck to respective rooms or staging areas within the worksite by using a standard drywall cart. Unsurprisingly, this process is also where the majority of worker-related accidents or injuries occur, and where the greatest dollar amount in damages due to worker's compensation is spent. In fact, GMS reports roughly 90 injuries per year related to accidents involving the drywall cart, totaling in damages worth approximately $1 million per year as well as losses in productivity due to injured workers. Further, because nearly every major commercial material supplier in the U.S. uses the same standard drywall cart design, there exists a widespread need for improvements to the safety of the wallboard delivery process, especially relating to the drywall cart itself.

GMS has sponsored this Capstone Design Project in an effort to pursue a solution for the drywall cart that specifically addresses and improves worker safety. GMS currently employs the industry-standard DC-2020-P drywall cart manufactured by Adapa, shown in Figure 1, which is a rudimentary L-frame cart with four caster wheels. The current cart requires two operators to move due to a full load weighing around 1 ton. Workers are only able to maneuver a loaded cart by pushing on the drywall itself because of the large scale of drywall panels, which can measure up to 8'x16'. Because the cart must also be narrow in order to navigate through tight spaces and thresholds, the cart is prone to flipping. GMS suggests that the most common accidents consist of broken bones in the legs, feet, or chest as a result of a fully loaded cart flipping over and crushing the operator. Under the sheer weight of a loaded cart, it is commonplace for one of the caster wheels to puncture through the flooring, causing a weight imbalance and subsequent flipping. The caster wheels may also fail if they come into forceful contact with debris or uneven substrates as a result of the immense stress applied by the weight and momentum of a moving cart. Other common worksite hazards such as wet or weakened flooring, debris, and uneven substrates also complicate the use of a drywall cart, increasing the potential for injury.

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

The goal and scope of this design project is to develop a fully realized drywall cart design that can safely and efficiently transport drywall throughout various worksite conditions. This will be done by minimizing the potential risks of injury that exist with the current design while also ensuring that maneuverability is not sacrificed. Beyond safety, GMS requires that the cart be durable, usable on multiple surfaces, able to be lifted by one person, easy to maneuver in tight spaces, have a high tipping stability, have an ergonomic design, and more. These user needs were evaluated in tandem with engineering design specifications using a House of Quality to determine importance level. In addition, four essential functions were defined that the drywall cart must be able to perform in order to satisfy the user needs: maneuver through tight spaces, load and unload drywall, support and secure drywall sheets, and roll over uneven surfaces. These functions make up the basis for the function tree and morphological chart which were used during the ideation process to facilitate the generation of preliminary design concepts. Chosen from a selection of 5 alternative designs, the selected design concept comprises: an angled L-frame vertical support attached to a rectangular base frame, a two-wheel drive steering system consisting of two free caster wheels and two controllable fixed-axis wheels, and retractable rubber end-stop support arms that extend the length of the drywall disposed over the cart.

2 MARKET RESEARCH

To gather market information to aid in the process of designing a safer and more stable drywall cart for Gypsum Management and Supply (GMS), our team has taken a variety of approaches. So far, we have interviewed two of our stakeholder groups: GMS and worksite employees who use the carts. GMS has provided us insight into the size of the drywall cart market, liabilities associated with the operation of such carts, the current competition in the market, desired functions that current products in the market do not provide, and more. The worksite employees provided insight into how the carts are actually operated on the job, functions/characteristics that the current carts could use improvement on or are missing, and functions/characteristics of the current carts they deem acceptable. We have also read drywall cart research available on the internet, which has better quantified the financial liabilities and the breakdown of injuries associated with drywall cart operation and given more insight into the effects of poor cart maintenance. A final market research method the team has implemented is collecting information on the current state of drywall carts in the market from members of an online drywall forum via an anonymous survey; the survey has recently been made available on the internet, so no impactful insights can be drawn from it until later in the design process when more submissions have been collected.

Based on discussions with GMS, the drywall cart manufacturer Adapa monopolizes the market for such carts due to a lack of competition, and is used by all of GMS's major competitors within the U.S. However, a quick internet search for drywall carts reveals a range of manufacturers in the market besides Adapa. In fact, a relatively small-scale research study our team read cited two drywall cart manufacturers that were encountered during research of Tamarack Materials, Inc., which happens to be a subsidiary of GMS: Adapa and Sonny [4]. And so, Adapa clearly does not monopolize the drywall cart market, or even the sub-portion of the market covering GMS's needs, but it produces what construction material suppliers, like GMS, deem to be one of the best drywall carts currently available in the U.S. market. For the purposes of delivering GMS a satisfactory product, surpassing Adapa's cart in terms of durability, stability, price, safety, and other factors should suffice; however if time permits, our team should strive to produce a device that surpasses other leading dry wall carts on the market in the same categories to ensure we provide GMS with the best product possible and that we have a product that could seriously compete in the entire U.S. market. It is important to note that the market for drywall carts includes not only national construction materials suppliers like GMS but also construction materials suppliers and building contractors of all sizes throughout the U.S. Furthermore, while the U.S. is currently the leading consumer

of drywall in the world, having “more than 97%” of its structures built using drywall, and thus the current target market for our product, other regions such as Western Europe and Asia-Pacific are adopting the use of drywall at rapid rates, so there is potential for this product to compete in markets across the globe in the future [5].

In terms of demographics, the primary beneficiaries/users of drywall carts in the U.S. are middle-aged white men, seeing that roughly 88% of construction workers in the U.S. are men, roughly 59% of U.S. construction workers are white, and the average age of construction workers in the U.S. is 38 [6]. The price of drywall carts currently available in the market vary greatly. Even when just comparing carts of similar size, load capacity, and functionality to/with the Adapa DC-2020-P, GMS’s drywall cart of choice, prices range from the low $200’s to upper $600’s with the Adapa cart coming in at $650, as quoted by GMS. Safety and durability are paramount as our team designs a drywall cart, so we would sell our cart closer to the high end of the aforementioned range. However, drywall carts are relatively simplistic in terms of materials, design, and manufacturing, so it should be feasible to produce a cart of equal or better quality than the Adapa ones used at GMS and sell the product for significantly less at $500 — we would simply mark up our product price from the cost-to-manufacture by less than the competition does, while still leaving room for substantial profit margins.

The inner workings of the construction industry are sheltered from public view, and so a successful go-to-market strategy would entail first receiving approval of our product from GMS to a point where they have adopted the use of our cart throughout their entire business. Once the cart has gained traction within GMS, our team would cooperate with GMS to push the product throughout the construction industry. In terms of current competition, variations of one drywall cart style dominate the market for the specifications we are designing our cart upon – though other drywall cart designs do exist as will be discussed under the prior art analysis. The style is a cart with a slanted base, as shown in Figure 1, to lower the center of gravity of the drywall [3]. As mentioned earlier, these carts can sell from anywhere between the low $200’s to upper $600’s. And so since the designs are so similar, it can be assumed that differences in sale price are attributed to build quality, stability, durability, brand recognition, maneuverability, and similar factors. Considering the Adapa cart sells at the extremely high price of $650 and boasts praise from both the online drywall community and large construction materials suppliers like GMS, it would certainly be reasonable to sell our design at $500 if we are able to engineer a superior product, for this should leave plenty of room for markup in the sale price beyond the manufacturing cost while still delivering our product at a significantly smaller price compared to products of similar quality and functionality.

Aside from the research summarized so far that essentially defines the market for the type of drywall cart our team is engineering, we also encountered findings that will directly affect the design we move forward with. In a research study conducted upon Tamarack Materials, Inc., which happens to be a subsidiary of GMS local to Minnesota, the company racked up roughly half a million dollars in workers' compensation between 2001-2004 [4]. On a similar note, GMS reports roughly 1 million dollars in workers' compensation per year to this day, so clearly there is a need to produce a more stable cart from both the perspective of reducing corporate financial liability and to provide workers with a less hazardous work environment based on the copious amounts of money being spent to compensate workers due to harm. Also cited in the study was that roughly 60% of manual materials handling (MMH) claims involved 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 [4]. And the study also noted that more than 57% of all MMH claims involved strains or sprains, hence overexertion of muscles to properly transport materials, which could easily be caused by a lack of stability and excessive vibration in drywall carts during transportation, causing worksite employees to compensate for the instability using their own strength [4].

Based on these findings and our discussions with GMS and worksite employees about the lack of stability present in the Adapa carts both during stationary loading and transportation of drywall, our team should focus on developing several features in our design. We should make the contact surfaces of the cart more ergonomic along with connecting the wheels to the cart base in a more secure fashion and lowering the cart's base, hence its center of gravity, to make handling the cart easier for users and to reduce the frequency and intensity of random vibrations and sudden deviations in motion from the operation of our drywall cart. Furthermore, our team may wish to investigate incorporating a self-lubricating wheel system into our design, for stiff wheels due to a lack of maintenance have been referenced in the aforementioned research study as one of the most impactful causes of resistance to smooth motion when operating drywall carts, and no drywall cart on the market currently possesses this capability [4].

3 Relevant Prior Art

There are multitudes of material transport carts currently available on the market for nearly every use imaginable. Such applications include Hand Trucks for moving low-weight stock or equipment, Pallet Trucks for transporting heavy palletized loads, Platform Carts for moving large-scale materials, Panel or A-Frame carts designed for moving material boards, and several more. Since there are a wide range of alternatives, the scope of this prior art search was not limited specifically to drywall transportation devices. Instead, the focus of this study was to identify prior art relevant to mechanisms or components of existing cart designs that particularly teach towards improving the safety of the four required operational functions defined by the customer.

3.1 The Classic Drywall Cart

The current market standard for drywall carts is manufactured by Adapa, who supplies carts for GMS as well as for a large percentage of the commercial material supply industry. Shown in box A of Table 1, the Adapa cart design is an A-Frame wheeled cart comprising: a rectangular base frame, an angled floor platform upon which the drywall rests, a vertical support frame on one side for laterally supporting the drywall, and four hard-rubber 6-inch caster wheels for the cart to roll. The cart frame is typically made entirely of steel tubing welded together, and the angled floor platform includes a thin top sheet made of Teflon to reduce friction while loading and unloading. Similar renditions of this cart include wider base frames as well as larger, 8-inch caster wheels. Because this cart design is currently employed by GMS, it will be used as a baseline design to help inform the desired safety improvements that are the goal of this project. The lack of caster wheel brakes is a notable design flaw which causes a need for an external wheel chock to keep the cart stationary while loading and unloading. Also, the lack of a support or guide rail along the free edge of the angled floor platform creates a risk of the drywall falling off the cart if it is loaded improperly. Despite its operational safety hazards, the industry standard drywall cart design is easy to manufacture and low in cost. As such, manufacturability and overall cost will be important factors in determining a viable design improvement moving forward.

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

Flatbed carts, troll carts, and centered A-frame carts also exist as viable alternatives for transporting panels, however these designs are typically employed in small-scale settings such as a DIY home renovation or by individual contractors. Flatbed carts differ from the classic drywall cart design in that the platform the drywall rests on are parallel to the ground, not angled. These carts may also be referred to as platform carts and can either have a number of vertical support frames to support and partition panels laying vertically or have no vertical supports so that drywall lays flat on the base frame closer to the ground. An example of a flatbed cart can be found with Patent Number *US-20070085287*, shown in box B of Table 1. This patent teaches to a flatbed panel cart, comprising: a central trough for the drywall to rest on, four vertical support bars for lateral support, and four outriggers securely attached to the vertical support bars that individually mount to caster wheels so that the wheel axes sit in line with the base of the central trough. The notable aspect of this design is in the way the drywall platform rests in-between the caster wheels, as opposed to on top of the caster wheels as in the classic drywall cart design. Positioning the drywall load in-between the caster wheels is advantageous because it minimizes the height of the drywall disposed above the cart, and thereby lowers the center of gravity of the load to prevent tipping.

Troll carts are similar in design, though they typically employ two central vertical support posts and an H-frame base so that drywall rests on two support beams rather than a continuous floor platform. Telpro is a major manufacturer of the troll cart – their design is shown in box C of Table 1. What makes their design unique is their collapsible vertical support beams that can lay flat so as to create a flatbed dolly. Also, by using the H-frame base which only allows two contact points to support material, the troll cart is inherently able to handle more versatile materials such as large, rounded objects or tables. The advantages of the troll-cart design is that it is typically lower in weight, can be made from lighter weight materials such as aluminum, and lends itself to including useful functions like folding or collapsing for storage and transportation purposes.

The centered A-frame cart is very similar in design to the classic drywall cart, except with the addition of a second angled floor platform on the other side of the vertical A-frame. Vestil is one manufacturer of this type of cart – their design is shown in box D of Table 1. Centered A-frame carts are typically reserved for transporting plywood or wallboard that is lighter and smaller in size than drywall, and because material can be placed on either side of the vertical a-frame, the base must inherently be wider and thus sacrifice maneuverability through tight spaces. However, one advantage of this design is

that it can transport a greater capacity of material at one time. Also, with material on both sides of the A-frame, the center of gravity is positioned central to the frame itself so as to reduce risks of tipping.

3.3 Swiveling Carts

Swiveling carts provide useful mechanical functions that allow the user to manipulate the orientation of drywall on the cart, typically between a vertical or angled position to a horizontal position. Some embodiments of the swivel cart also include combined rotable motion in the horizontal and vertical planes so as to allow for the ability to easily fit a fully loaded cart onto an elevator. Shown in box E of Table 1, Patent Number US-20030127834 is an example of a swiveling drywall cart. This embodiment comprises: an upper and lower frame, a lift assembly between the upper and lower frame, and two extendable support arms that span the length of the drywall so as to secure both ends of the material while swiveling. Shown in box F of Table 1 is Patent Application Number 20100059952, the Haley Material Handling Cart, which is a swivel cart utilizing an X-frame base that attaches to four caster wheels at each end point and supports a single central beam attached to the lift assembly. The swiveling action of these carts is pertinent to this design problem as it addresses the maneuverability function in a unique way; altering the orientation of the drywall while transporting through tight spaces can allow for easier movement through thresholds. Also, the mechanical lift assembly used to alter the orientation of the drywall enables possible alternative applications such as increasing or decreasing the angle of tilt of the vertical support frame. This is advantageous because lowering the tilt angle will lower the center of gravity and reduce tipping, while increasing the angle will still allow for the ability to maneuver through thresholds.

3.4 Wheel Brakes

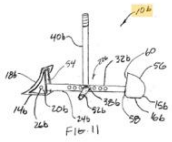
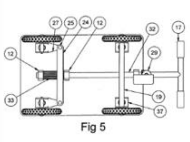
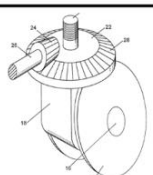
Being able to keep the cart stationary while loading and unloading drywall is a vital function for the drywall cart. Since caster wheels are used in nearly every rendition of the drywall cart, there is currently a lack of an integrated brake design that can keep the cart still. Some caster wheels come with clamp brakes, shown in box G of Table 1, that stop the rotational motion of the wheels, but these brakes do not address the rotation of the caster itself about the vertical axis. This still allows for a certain degree of wobbliness that can make loading and unloading unwieldy. The current alternative is to employ an external chock behind a wheel to secure the cart, and this is typically achieved by having a worker wedge his foot behind a wheel instead. There are some products available on the market that address this problem. Patent Application Number US-20080073162 is a design for an integrated wheel chock system that is designed to immobilize two wheels via a mechanical lever action. This design teaches towards any

form of integrated wedge mechanism that can be engaged to brake a wheel with a fixed axis. Shown in box H of Table 1, a second embodiment of an integrated brake system is found in Patent Number US-6508479B1, which comprises an integrated chock design that can be engaged using a convenient squeeze-action handle. This design is useful to because it teaches towards a user-controlled mechanism used to engage and disengage the brake from a comfortable position, making it easier control while actively moving the drywall cart. Both of these designs, however, are intended for fixed-axis wheels, and because caster wheels have an added degree of rotation, these two prior arts are informative but do not constrain design options for this project.

3.5 Steering/wheels

One design consideration that addresses the maneuverability functions is being able to control the navigation of the cart via steering systems. Currently, the classic drywall cart is navigated by workers who push and pull the load entirely by acting on the drywall itself, rather than the cart. There exist a few cart steering systems for uses on smaller-scale carts that employ gear trains and mechanical linkages to control the direction of the wheels. Shown in box I of Table 1, Patent Number US-20070085285 teaches towards a series of gears under the base of the cart that attaches to a vertical steering bar similar to a bike handlebar. While this design is informative on how to construct a gear train for wheel control, additional innovation would be required in order for a steering mechanism to be comfortably used by workers while still being able to push and pull the cart from the disposed distance of drywall that extends beyond the cart. Shown in box J of Table 1, Patent Number US-5964471 teaches towards a mechanical linkage other than a gear train, that controls steering by changing the direction of the base frame that connects the two caster wheels to the vertical frame. This design patent is unique in that it is capable of providing steering to a cart with caster wheels, though it may constrain the design options for this project.

Table 1: Prior Art References

 **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	 **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 some OSHA filings and company guidelines concerning the operation of drywall carts that should be considered when designing such a cart. One OSHA filing describes a scenario in which a drywall cart was altered to store materials with no incline angle so that they sat vertically. In the specific incident, the cart was left loaded −to roughly 1,400 pounds− for a week, and in the process of trying to move the cart to unblock his work path, an employee tipped it over, fracturing his leg. And thus, the filing highlights that leaving drywall carts loaded when not in use, altering carts from their intended method of operation, and operating heavily loaded drywall carts alone all contributed to the tipping of the cart, so they should be avoided to prevent a hazardous work environment [7]. On a similar accord, the safety and handling guidelines for drywall carts at the company Island Acoustics call for operating carts with at least 2 workers, not modifying carts, not overloading carts, not using carts in a manner inconsistent with the manufacturer's suggestion, not using damaged carts, and not storing carts in non-designated areas or with materials loaded, all of which bolster the aforementioned OSHA guidelines. These set of guidelines also call for: keeping drywall carts stable and stationary during loading, generally by chocking the wheels with a piece of wood; keeping the center of gravity of the cart low by stacking items such that they are progressively lighter the higher up on the cart; and securing particularly bulky payloads with straps [8]. Again, these OSHA and company guidelines/suggestions do not officially limit the design/operation of drywall carts, but they do clarify best practices for operating such carts, which can help in determining features cart manufacturers may want to consider incorporating in their products. For example, drywall cart manufacturers as a whole should consider adding dedicated footbrakes and sidewalls into their designs to provide more secure methods of holding loaded materials and the overall cart stable than using a separate piece of wood and straps.

5 Customer Requirements and Engineering Design Specifications

5.1 Stakeholder Analysis

The stakeholders of this project have been identified and categorized based on importance and influence. Importance is defined as the relative value this project will provide to each stakeholder. The influence is defined as the stakeholder's willingness and ability to guide the projects requirements. As seen in Figure 2, GMS is the key stakeholder due to the impact that this drywall cart has had on their business. GMS's input in this project will be vital in our team's ability to put this redesign cart into the market. Since the Georgia Tech provides high influence, but low importance, they will not be considered as key stakeholders. However, the laborers provide a lot of importance due to their firsthand experience and will be considered as key stakeholders.

Table 2 provides a detailed analysis of the stakeholders interested in the drywall cart redesign. Figure 2 shows an overview of the stakeholder analysis on a 2x2 map.

Table 2: Stakeholder Analysis

Stakeholder	Interests	Impact/Effect	Importance	Influence
GMS	Reduce injury damage and insurance costs Potential to sell new cart; revenue	Reduce insurance and workers' compensation liability.	Improve safety of working conditions when loading, operating, and unloading drywall carts.	High influence. These stakeholders initiated the project, have pledged to compensate all costs, and have the final say on implementation.
Worksite Employees	Reduce workers needed to load, operate, and unload cart. Increase stability of cart; safety	Shortens time taken for employees to complete jobs. Gives employees more confidence in safely completing job.	The safety of the workers on the jobsite is of very high importance since they are the ones that are presently being injured.	Medium influence. Jobsite workers are the direct beneficiaries of the design. However, worker approval is not as influential on the project as that of the other stakeholders who can directly affect/judge the project's success.
Georgia Tech	Team makes forward progress on project. Team collaborates to ideate/produce a full design.	Determines our grade in the class and how we are evaluated.	The outlook of the project is not of entirely high importance to GT since they are only concerned with our team's performance.	High influence. This stakeholder ultimately evaluates the efforts of the team in terms of grades. Graduation is on the line.

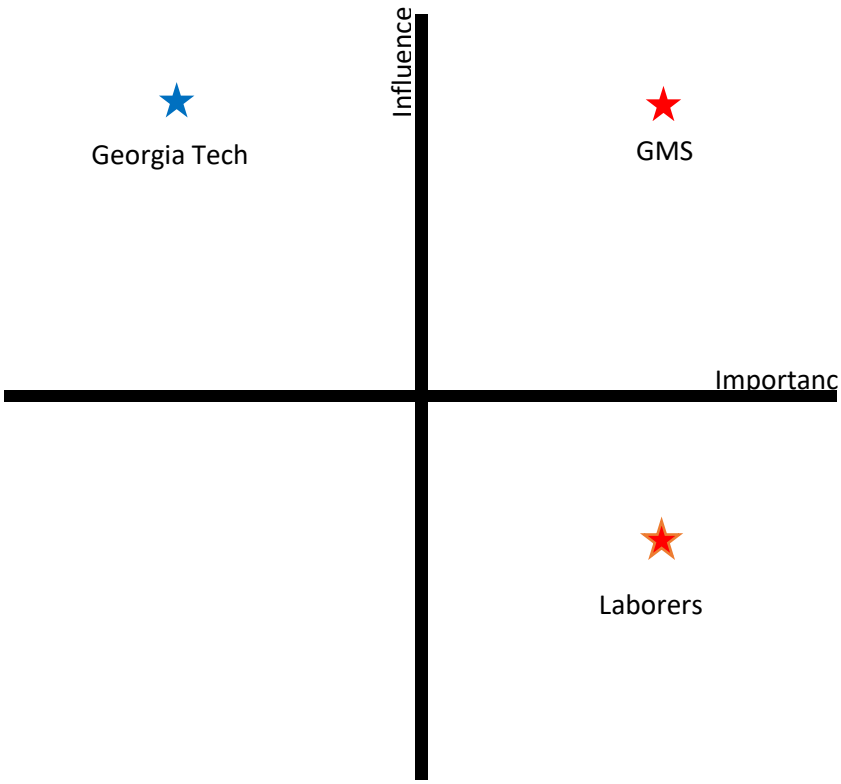


Figure 2: Stakeholder Analysis Overview Chart with relevant stakeholders and their relative importance and influence

One interesting takeaway from interviews with construction workers and calls with the GMS corporate sponsors is that these two key stakeholders often have conflicting views when it comes to desired outcomes for a drywall cart redesign. For example, when asked about the primary causes for accidents involving the drywall cart, many workers replied with the assertion that any injuries on the job were instigated by careless user error and that the current cart design is just fine. The GMS sponsors replied on the contrary when asked the same question, suggesting that the cart itself and worksite conditions were to blame. This difference in perspectives is not a new issue – companies in all industries experience resistance or hesitation from workers when it comes to adopting new technologies. Moving forward, it will be critical to find that middle ground between corporate GMS and their employees in order for a new cart design to be adopted fully.

5.2 Customer Requirements

Based on the team's interactions with the key stakeholders, customer requirements for the drywall cart have been identified as shown in Table 3.

Table 3: Customer requirements

Category	Customer Requirements
Function	a) Hold and support product load b) Move easily over multiple surfaces c) Remain Stationary during loading and unloading d) Navigate through narrow thresholds e) Easily lifted by one person
Geometry	a) Similar shape to previous design
Cost	a) Use manufacturing processes similar to previous design b) Cost similar to previous design
Reliability	a) Weatherproof b) Does not tip during use

The customer requirements can be broken down into user needs and functions. From discussions with the key stakeholders, it is evident that our design must be safer than the previous model, which means it should not tip over or fall through soft substrates while supporting the product load. The design must be usable on multiple surfaces, easy to maneuver, and easily lifted by one person. Also, the cart must be durable and resistant to harsh weather conditions due to its use on various construction sites. Finally, the cart should be in the same price range as the previous model (600$).

5.3 Engineering Requirements

Based on the customer requirements discussed above, the team identified important engineering requirements. Although some of these customer requirements are implicit, the team has assigned numeric target values for some of the requirements. Shown in Table 4, the specification sheet shows the important specifications of the drywall cart, the sub team responsible for ensuring each specification, and the methods to validate the desired target values that have been assigned.

`				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 4: Specification sheet

The size of the cart is to be designed to fit within doorframes and small hallways of width 30-32 in. This will be validated by testing and measurements. For maneuverability, the cart must have a zero-turn radius to ensure it can navigate through tight spaces, which will be validated by testing. The max weight of the cart is to be 90 lbs., so the laborers can hoist it into a truck bed. The current cart design is capable of holding up to sixteen sheets of drywall. In order to match the current cart's capabilities, the redesign must also do the same. In terms of weight, the drywall cart must be able to support a minimum of 2,500 to 3,000 lbs. This will be tested by developing a force-analysis model based on hand calculations. With the cart supporting this required load, it is important that its frame remains stiff while in operation. The requirement for stiffness is that it must not flex/bend while operating. This will be validated by testing the material strength. To prevent the cart from tipping while in use, the cart's tipping moment and center of mass must be in a reasonable range. This will be validated by modeling and hand calculations.

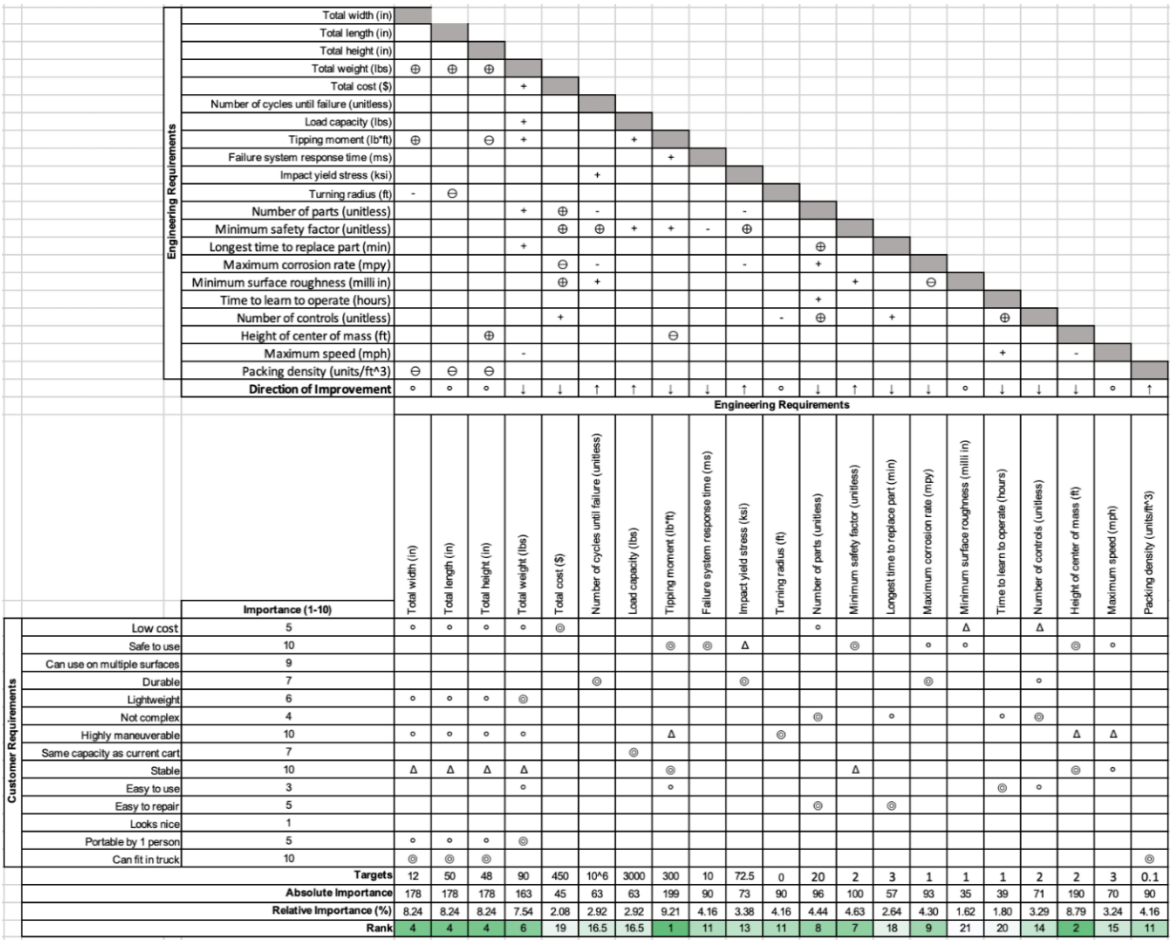
The drywall cart needs to be affordable with regards to DFM using manufacturing process suitable for small-scale batch sizes of about 60 units. This will be ensured by using readily available and simple machining equipment. The cart needs to be easily assembled and disassembled for ease of repair. This will be ensured by using a modular design with the use of standard fasteners.

5.4 Constraints for Engineering

Several constraints that will influence the design principles and decisions have been identified. Due to the narrow thresholds the cart must pass through, it is evident that the new design must be similar in size to the Adapa design. In addition to size, the standard loading and unloading capabilities will have to be considered. GMS has requested that this cart must be able to perform on uneven surfaces and differing substrates. Due to this requirement, the cart is prone to wear and misuse and must be easily repairable. The cart must provide the laborers with a safe and stable way of loading and unloading the payload. All of these constraints will influence the design choices in the mechanical design.

5.5 House of Quality

After collecting the customer requirements and design specifications through meetings and job site visits, a House of Quality, shown in Figure 3, could be made that would distinguish the importance of each customer requirement as well as the relationship between the engineering requirements and the customer requirements. Another important aspect of the House of Quality is the correlation matrix which notes how the engineering requirements affect each other. After this analysis, it was found that the most important customer requirements were the safety of use, maneuverability, and the stability of the drywall cart. Additionally, the tipping moment and the height of the center of mass were the engineering requirements found to be of highest relative importance. Using this data, better criteria can be drawn for the design concept ideation process, helping to uncover which design fulfills the customer and engineering requirements. The target values included on the House of Quality were mainly collected through the site visit with the sponsor. Additionally, through meetings with the sponsor and research on prior art, the other target values that were not collected on-site were determined.



Engineering Requirements	Direction of Improvement
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	○ ○ ○ ↓ ↓ ↑ ↑ ↓ ↓ ↑ ○ ↓ ↑ ↓ ↓ ○ ↓ ↓ ↓ ○ ↑

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 2: House of Quality with relationship and correlation matrices for engineering and customer requirements

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 4.

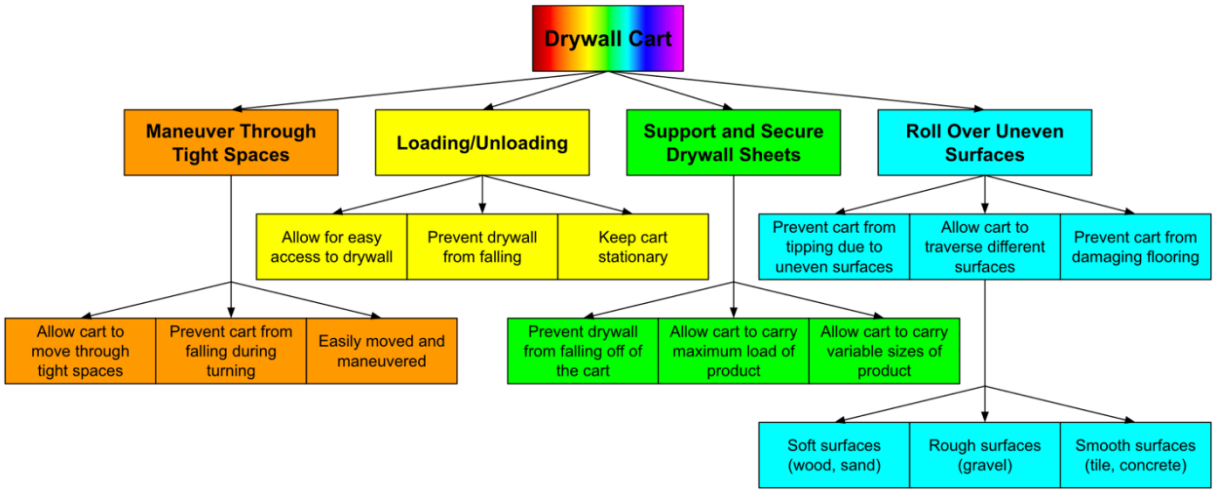


Figure 3: Drywall cart Function Tree showing 4 main functions and their sub-functions

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. For example, the concept of the end-stop support arms could be used as a mechanism to support and secure the drywall on both ends while also acting as an aid during loading and unloading so the drywall gets centered on the cart with ease. A Morphological Chart, shown in Figure 5, was used to compile each individual component idea into sub-function categories for the purpose of facilitating alternative design generation.

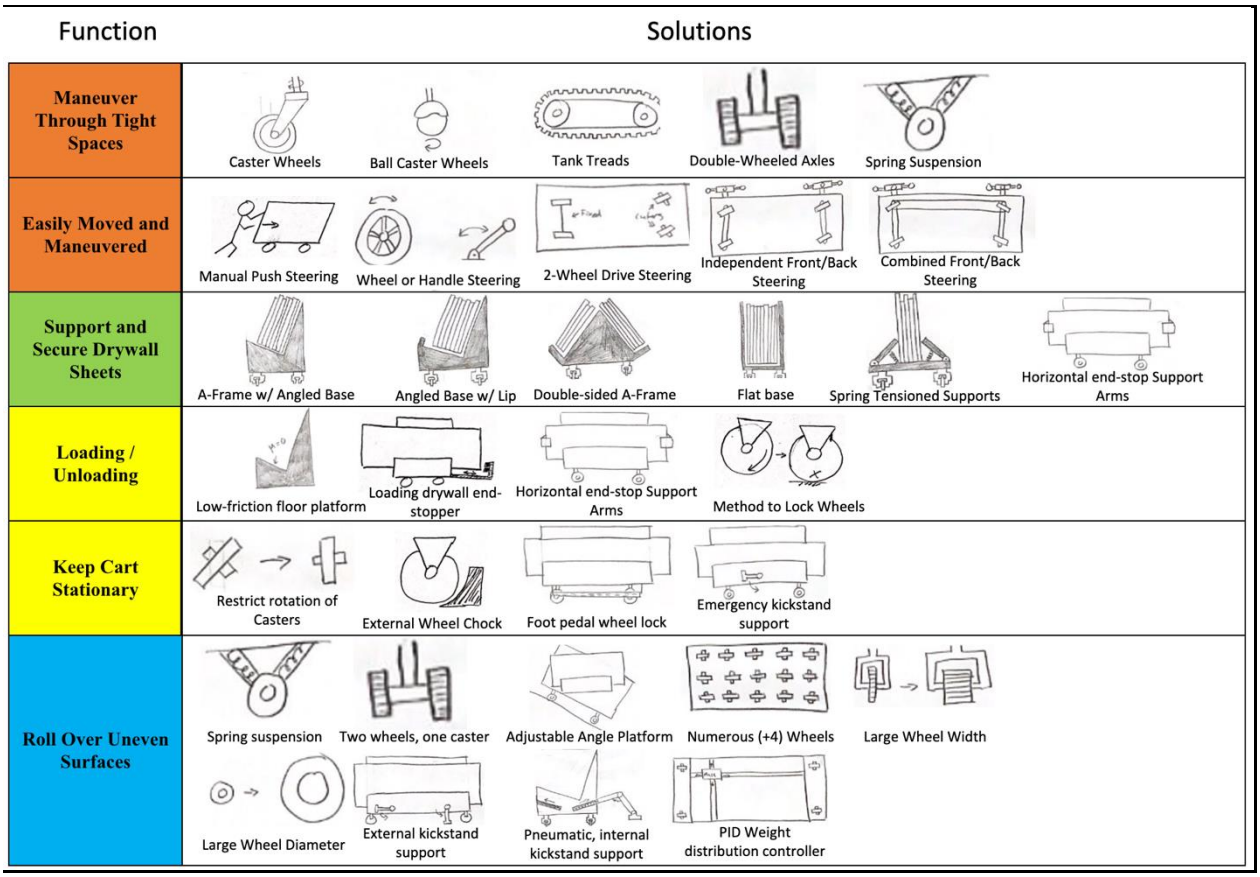


Figure 5: Morphological chart with sketches of each component concept design

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.

1. A 2-wheel drive steering cart with an angled base A-frame and an external kickstand

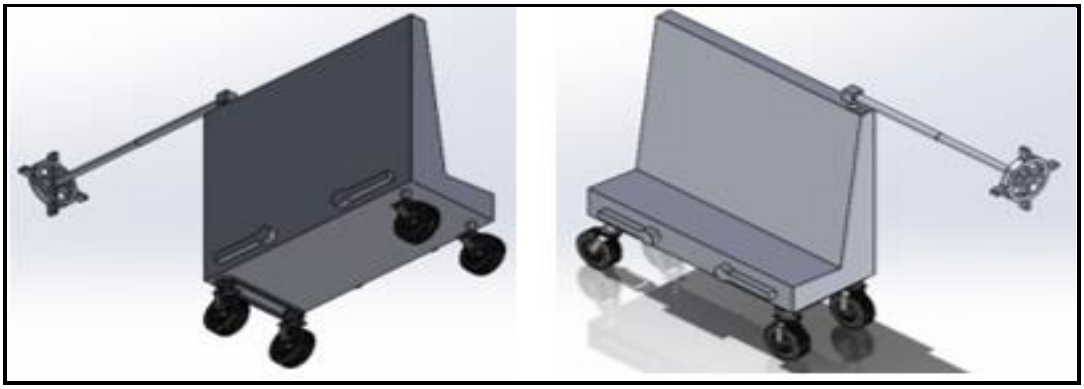


Figure 6: Design #1 concept art. This design uses a 2-wheel steering system plus casters to help maneuver the cart around tight corners and has a backup external kickstand safety mechanism.

The design in Figure 6 attempts to balance the need for control over the drywall cart's wheel direction with the desire to keep our cart as simple and easy to operate as possible. It does this by having a front set of wheels that are turned by a wheel and a back set of free-spinning caster wheels. A front facing steering wheel was chosen as the operator input of choice to allow the worker at the front of the cart to have easy access to both the drywall and the steering. The frame of the cart is a conventional A-frame design, as it both maximizes the capacity of the cart and minimizes the height of the center of mass of the loaded cart. Finally, an external emergency kickstand was added in order to provide safety in the event that an accident does occur. An external design was chosen in order to allow for easy maintenance and repair, as well as to lower the complexity of the design.

2. A 4-wheel drive steering cart with an angled A-frame base and an internal kickstand

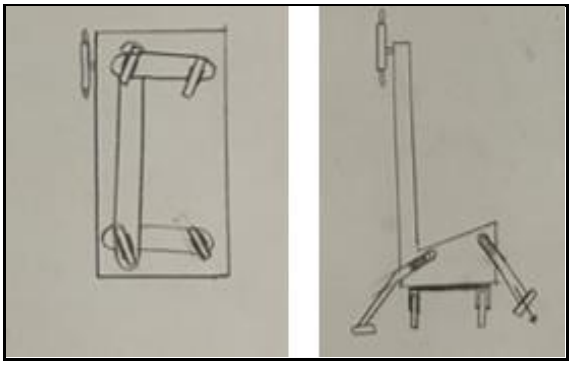


Figure 7: Design #2 concept art. This design uses a 4-wheel steering system to allow for a 0˚ turn radius and uses an internal backup kickstand to prevent tipping

This design maximizes the control that users have over the cart's direction, but correspondingly increases the complexity of the design and its use case. A 4-wheel steering system was chosen to allow the front worker to control the entire system from a single wheel. The frame of the cart was once again chosen to be a conventional A-frame design in order to maximize load and minimize the height of the center of mass. An internal emergency kickstand was included in order to make the design as sleek and safe as possible.

3. A caster-wheel directed cart with an angled A-frame base, suspension, and a footbrake

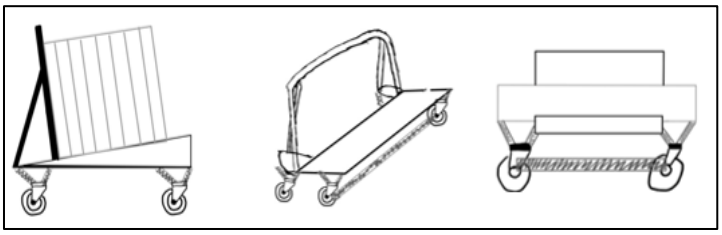


Figure 8: Design #3 concept art. This design uses caster wheels with a suspension system for easy traversal of rough terrain in combination with a footbrake to make loading and unloading safer for workers.

This design combines the traditional A frame with suspended caster wheels and a foot braking mechanism. The braking mechanism is designed so that a worker may press down on the foot-action pedal while loading or unloading drywall in order to keep the cart stationary. The suspended caster wheels would provide more stability to the cart as it maneuvers over uneven surfaces. The caster wheels would also provide simplicity for the workers' ability to maneuver the cart. While this design encompasses the traditional design with increased stability by use of a suspension system, it lacks support to prevent the cart from tipping. In addition to support, the springs would add another reliability factor when factoring in the durability of the cart.

4. A caster-wheel directed cart with a flatbed frame and a foot pedal brake

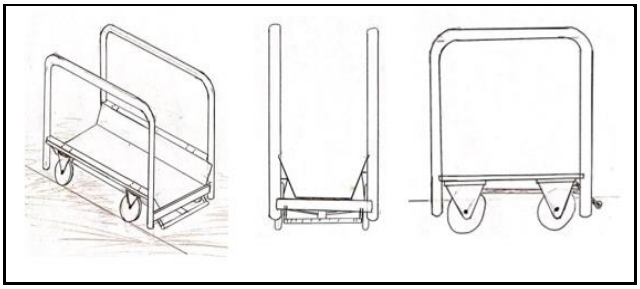


Figure 9: Design #4 concept art. This design uses its flatbed frame to allow for larger product loads and incorporates a footbrake to help with the loading and unloading processes.

This design combines the flatbed style frame with caster wheels and a foot pedal braking system. The foot-pedal braking system for this concept is repeated from concept #3. The trough design, where the wheels lay in line with the base platform as opposed to under it, is used to lower the center of gravity of the cart, decreasing risk of tipping. This design also allows for a greater capacity of drywall since there is no angle of title on the base platform. While the two vertical supports for this concept provide increased lateral support, they also hinder the unloading process by requiring the drywall to be unloaded from the narrow ends of the cart.

5. A caster-wheel cart with an angled A-frame base, internal kickstand, side guards, and footbrake

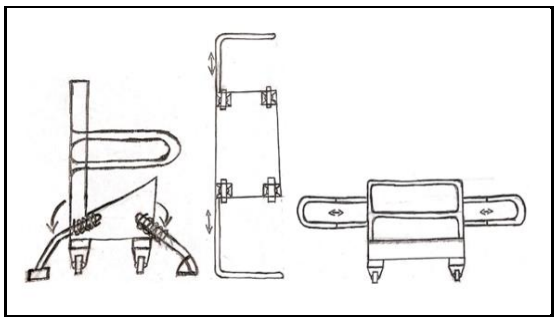


Figure 105: Design #5 concept art. This design uses the traditional caster wheel design to maintain the cart's maneuverability, while adding the internal kickstand, side guards, and footbrake to give users more tools to keep themselves safe

This design is very similar to the Adapa DC-2020-P that GMS currently uses in that it moves using a regular caster setup, and workers operate the cart through manual push. However, the design surpasses the Adapa cart in terms of stability and worker safety due to three key additions. The first additional component(s) are the adjustable side guards, which improve both worker safety and stability by ensuring that the payload cannot fall off the sides of the cart and injure workers and that the payload is held snug to minimize errant motion and vibrations during cart operation. The footbrake further improves cart stability during loading by eliminating any wobble workers could experience and fixing the rotation of the casters. Finally, the internal emergency kickstand provides a sleek method to prevent catastrophic damage/injury in the case of the cart suddenly tipping. Despite these significant improvements over the DC-2020-P, the design still falls short in terms of overall stability, safety, and ability to trek various terrains.

After choosing five design concepts, an evaluation matrix was 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, those scores were weighted accordingly so that a high score in a highly important customer requirement category would have a higher impact and so on. The results of the evaluation matrix can be seen in Table 5 below.

Table5: Concept evaluation matrix

		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	

7 SELECTED DESIGN CONCEPT AND JUSTIFICATION

Shown in Figure 6, the "2-Wheel Steering + External Kickstand" concept is the design that the team selected to work with moving forward. This design utilizes a steering system in the front set of wheels which allows the operator to steer the cart without having to apply a horizontal force to the cart which would possibly result in the cart tipping over and causing injury. Due to the steering system, not only is the operator safer, but they will also have much greater control over where the cart will go when it is pushed forward. The extended steering column also allows the operator to steer the cart as well as assist in the moving of the cart. Instead of having to walk in between applying force to the rear of the material to move the cart, the operator can quickly and effectively adjust the heading of the cart and then go back to pushing the cart in that desired direction.

Additionally, the design utilizes an external safety mechanism. This mechanism will be deployed automatically using a force sensor on the wheels to prevent tipping when two wheels on one side of the cart leave the ground. This external design allows for a quick reload in the case that the device is deployed in order to stop the cart from tipping. Once balance is restored, the “kickstand” arms can be quickly moved back into place so the cart can go on operating normally. So, not only does this cart apply preventative measures that should stop the cart from tipping over in the first place, but also will help to stop the cart in the event that it does tip over. The angled base allows for quick loading and unloading of the material. If it were a classic A frame, the operator would have to unload half of the cart, turn it around while it is very unstable due to weight distribution, and then unload the second half of the cart. Overall, the selected design shares some of the most productive aspects of the original design, while improving and adding different features in order to increase the safety of the cart.

This design was selected due to its success in the more important customer requirements for the cart as seen in the evaluation matrix in Table 5. For example, in the “Safe to Use” section the selected concept scored the second highest with a 4 out of the possible 5 points. In the categories with the most weight: “Safe to Use”, “Highly Maneuverable”, “Stable”, “Can Use on Multiple Surfaces”, and “Can Fit in Truck”, the selected design scored either 4 or 5 while all the other designs scored a 3 or less in one or more of those categories. Where the selected design separated itself from the second-place design was in the stability category where the selected design outperformed by 20 points. This is due to the increased stability that comes with the addition of steering. Since “Concept 3”, the second-place design, does not use steering, it relies heavily on the casters reorienting themselves rather than a steering column being

able to directly change the wheels' direction, causing the cart to lose a lot of stability. Through experience working with the original cart, it was found that the casters have very little control with reorienting themselves, which makes the stability very poor during situations where the cart must change directions dramatically. The only category in which the selected design does poorly is the "Easy to Use" section, which is due to the higher amount of training and coordination that comes with the steering system. Rather than being able to physically move the cart into its desired path, the steering wheel must be turned at the correct angle to turn the cart into the path.

Although the selected design is the best design resulting from the evaluation criteria, there are still potential hang ups that can be seen from the onset. For example, the feasibility of the steering system could pose a problem. At capacity, the cart will hold upwards of 2500 lbs and will be very difficult to steer especially without the help of a power steering assist. Additionally, the external kickstand system could prove to be incapable of deploying at a fast enough speed to prevent the cart from tipping and of supporting such a massive amount of weight. There is no doubt that the selected design will fit within the desired design specifications, but the feasibility of a steering system is the biggest concern in regard to the design's success. However, with this design being the most ambitious of all the team's generated concepts, if it is to fail, then the team will have a greater understanding of what direction the project must take in the future to maximize success.

8 TEAM MEMBER CONTRIBUTIONS

Ryan Grajewski (Team Leader): Company liaison, team meetings, team finances, team dynamics, mascot, Introduction & Background, Prior Art Analysis, Concept #4 Drawing, Conclusions and Future Project Deliverables

Graham Brantley (Writing Lead/Materials Lead): Editor, materials for prototypes and final product, team jobs during writing, Concept #1 Drawing, HOQ, Design Concept Ideation

Will Hagler (Prototyping Lead): Machine training, fabrication instructions, team jobs during prototyping, Concept #3 Drawing, Customer requirements and engineering design specifications, Executive Summary

Garrett Rodino (CAD Lead): CAD help, FEA analysis, CAD file manager, team jobs during modelling, Concept #2 Drawing, HOQ, Selected Design Concept and Justification, Executive Summary

Nischal Bandi (Analysis Lead): System modelling, component standards, FEA analysis, prototype analysis, Concept #5 Drawing, Market Research, Applicable Codes and Standards, Editing/Proofreading

9 Conclusion and Future Project Deliverables

To conclude, there is a glaring need for a redesign of the classic drywall cart due to worker related injuries that are causing commercial material supply companies to incur significant costs from lawsuits, workers' compensation payments, and lost productivity. Through field research, construction site visits, and key stakeholder interviews, it could be determined that the safety concerns with the current cart design are directly related to the cart flipping under the sheer weight of a full drywall load. Further investigation revealed that these accidents were often triggered by uneven and weakened substrates in the worksite, as well as the instability of the cart itself. GMS has sponsored this project with the purpose of addressing those safety concerns. The goal is to develop a novel drywall cart that significantly improves worker safety when operating the cart, while also maintaining maneuverability and efficiency so that the cart remains viable.

The "2-Wheel Steering + External Kickstand" concept was selected as the optimal drywall cart design for directly improving upon the safety concerns that exist with the current cart as well as addressing other customer requirements put forth by GMS. The selected design comprises a two-wheel steering system which speaks directly to the maneuverability requirement. Further, the emergency External Kickstand mechanism is designed as a failsafe mechanism that is intended to improve worker safety by reactively supporting and securing the cart if it were to start flipping. Also, the L-frame concept was carried from the current cart design as the advantages it provides to the loading and unloading process are significant compared to other alternatives.

While this integrated cart design was evaluated to be the most promising among the design alternatives, there still exists several striking implications that will define the design and prototyping phases of this project as it progresses. The two-wheel steering system presents the potential for a large improvement in stability, but an even larger potential for obstacles regarding feasibility. Moving forward, it will be important to conduct engineering analyses early in the evaluation phase to conclude the validity of using such a system. One foreseeable challenge is being able to physically turn the steering wheel under the weight of a full cart load without powered steering. There may come a trade-off where a successful design of the steering system also implies a significant addition of weight to the cart, making it difficult to push as well as lift. Further, the dynamic action of the emergency Kickstand Support mechanism also raises concerns of feasibility in terms of speed and strength. A fully loaded cart is half the weight of an average sized car, so being able to develop such a mechanism that can support that amount of weight while also

being compact enough to reasonably fit within the cart dimensions will be a challenge. It will be necessary to conduct a critical analysis of validity prior to progressing into the prototyping phase.

To outline the upcoming milestones in the development of this design, Figure 11 displays a Gantt Chart as a tentative schedule for the phases of production and expected deliverables for the next few months. The next major milestone for this project is conducting detailed engineering analyses for the purpose of proving the validity of the selected design concept. These analyses will entail force and weight balance calculations to determine tipping moment and stresses present in the selected design, FEA analysis, and fatigue failure analysis. The major conclusion to be made from those analyses would be the material selection for the frame of the cart, the gearing components, and the emergency kickstand supports. Beyond that, the next phase will entail extensive CAD work for modeling and prototyping each component of the selected design. Part of the CAD and prototyping phase will include outlining a professional fabrication package that provides details on the manufacturing of each design component. There is an expectation for this project that the final deliverable will be a physical, working prototype, and because of the expected time it will take to procure the materials and fabricate each component, there will need to be a large importance placed on establishing the final design concept early on.

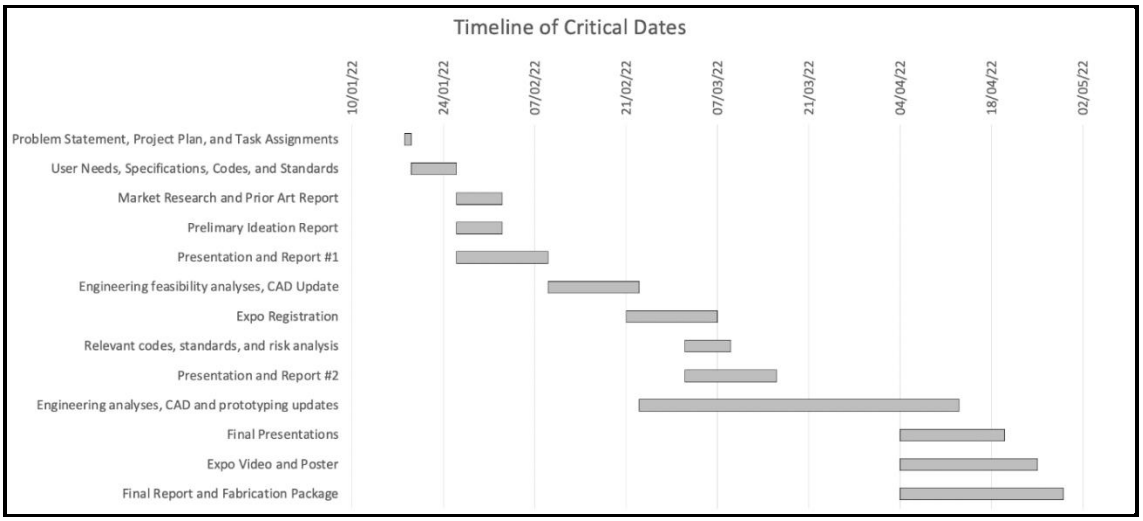


Figure 11: Gantt Chart outlining Future Deliverable Schedule

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