

FINAL CAPSTONE REPORT



**University
of Manitoba**

**Elmer's
MANUFACTURING**

1/6th Scale Grain Cart

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Executive Summary

This project aimed to design and build a 1/6th scale HaulMaster 2500 grain cart for Elmer's Manufacturing. A grain cart is an agricultural vehicle designed to transport grain from the field to a storage truck or facility. This vehicle features several subsystems including the tank, mainframe, auger, and hitch which all aid in the main functions of the grain cart. The scaled-down grain cart will be used as a showpiece by Elmer's Manufacturing to allow for easy visibility of internal features and will help to reduce hesitancy in farmers regarding purchasing new machinery. The grain cart will also be used to increase convenience in software testing done by Elmer's Manufacturing. The final 1/6th scale grain cart is required to closely resemble the full-scale HaulMaster 2500, in both aesthetics and functionality.

The first project objective was to redesign the grain cart by scaling down subsystems and creating them on Autodesk Inventor, a 3D computer-aided design (CAD) software. This led to challenges associated with changing load capacities, unscalable components, and manufacturability. Features that could not be scaled-down were replaced with components – such as sensors and actuators - that fit the redesigned model. All subsystems were scaled down to closely resemble the full-scale model. The mainframe features a redesign of the undercarriage and steering system, and all moving components besides the steering system, have been replaced with fixed pieces. The secondary project objective was to build and assemble the scaled-down grain cart. The team has fully completed the building of the scaled-down grain cart and has conducted tests to ensure they meet all target specifications discussed with the client, such as a dimension, weight, and mobility specifications. The final dimensions of the grain cart are 6.74'x3.43'x3.71' with a final empty cart weight of 308.8lbs.

For the continuation of this project, the team primarily recommends replacing the fixed pieces to be able to implement the moving components, integrating the electrical system to power the moving components, and optimizing and improving upon the build process.

In conclusion, this project successfully modelled and assembled a scaled-down version of the HaulMaster 2500 grain cart. This will support Elmer's Manufacturing in software testing and demonstrating their product's features, helping farmers gain confidence in adopting modern agricultural technology.

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Introduction

Elmer's Manufacturing designs and manufactures innovative farm equipment to meet the demands of the agricultural industry [1]. Their focus is on developing user-friendly, durable, and low-maintenance products to optimize farming operations. A significant challenge in the industry is farmers' reluctance to adopt modern equipment due to financial constraints, limited infrastructure, and concerns about usability [2]. Addressing these challenges requires support and education to help farmers navigate technological advancements.

The purpose of this project is the designing and building of a 1/6th scale HaulMaster 2500 grain cart as a showpiece and software testing platform for Elmer's Manufacturing. The scaled-down model provides an accessible way to demonstrate the grain cart's features, helping farmers better understand new technology and gain confidence in adopting modern equipment. Additionally, it will facilitate software testing in a more convenient and controlled environment compared to the full-size model, which requires significant space to operate and modify.

This section summarizes the purpose of this project regarding how it benefits Elmer's Manufacturing and their customers, and background information about the details of the project.

1.1 Background

A grain cart is an agricultural vehicle designed to transport grain from the field to a storage truck or facility. Grain carts are usually towed by a tractor, enabling continuous operation alongside a combine (harvester) [3]. Grain carts feature a large storage tank, an auger for unloading, and wheels for mobility. The HaulMaster 2500, shown in Fig. 1, was released in 2024 and is the second largest grain cart produced by Elmer's Manufacturing, with a capacity of 2500 bushels. The HaulMaster line of grain carts are described by the company as "the largest grain carts in the industry" [4].

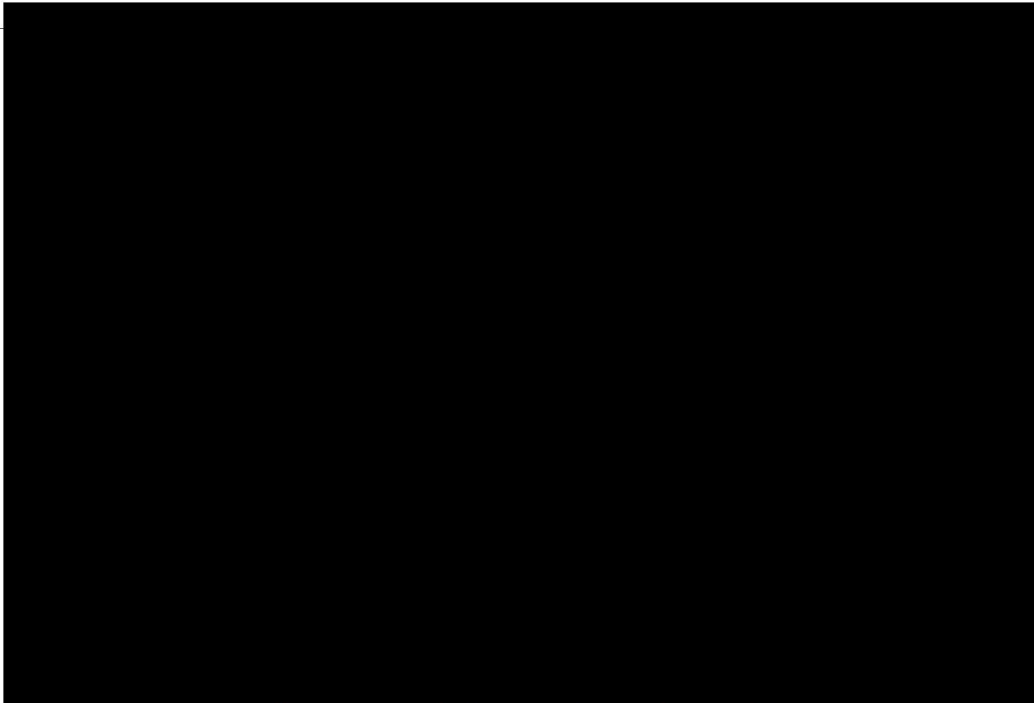


Figure 1. HaulMaster 2500 grain cart [5].

As an innovative and new product, farmers are hesitant to invest, and product demonstrations are imperative. Product demonstrations for full-scale grain carts are logistically challenging and can be impossible in certain space constraints, especially for indoor agricultural shows. In addition, software testing is inconvenient on a full-scale grain cart, requiring a large-sized tractor to move the cart and power the hydraulics. A solution to these problems is to design and build a 1/6th scale grain cart that can be transported to indoor agricultural shows easily, so its features are seen by individuals in the farming industry while also being a practical software testing platform.

1.1.1 Challenges with Downscaling

Although creating a 1/6th scale grain cart solves this problem, the scaling down of machines causes four main design issues: (1) Loss of strength, (2) Loss of detail, (3), Unscalable systems, and (4) Manufacturing and construction limitations.

The strength of structural components often does not scale down proportionally to size. For example, the cross-sectional area is important in the load-bearing capacity of members, which scales down at the squared rate of a size reduction.

Small features such as grooves and latches can also be lost in a scale-down due to manufacturing tolerances, so alternatives to these features must be explored.

Off-the-shelf components such as sensors and actuators cannot be scaled proportionately, as well as the software processor used by Elmer's Manufacturing in their equipment.

Elmer's Manufacturing designs solely with a set range of sheet metal thicknesses and manufacturing processes that can only cut and bend to a certain size and width. These limitations prevent a direct scaling of the full-size model. Due to the sheet metal options available, many components of the grain cart will be thicker than needed. In addition, scaled-down models are more difficult to assemble due to smaller parts and tool-use spaces, so considerations need to be made regarding construction.

1.1.2 Comparison to existing scaled-down models

Existing miniature farm equipment models are typically scaled down to about $1/8^{\text{th}}$ to $1/16^{\text{th}}$ of the full size, as they are primarily designed as toys [6]. In these models, all parts are reduced by the same scale, and functionality is not a requirement. There is currently no documented $1/6^{\text{th}}$ scale grain cart with the same functionality as a full-size grain cart. However, there are other scaled-down agricultural machines in similar scales. The Prairie Farm Report [7] showcases a series of $1/5^{\text{th}}$ scale John Deere farm equipment, with one of the highlights being a $1/5^{\text{th}}$ scale combine that uses an auger to unload grain into a grain cart. The design presents important design principles for downscaling agricultural equipment. It maintains full functionality, even though some parts cannot be scaled directly. It also demonstrates how unscalable systems can be adapted to fit the new scale. As another example, ASABE hosts an annual international $1/4$ scale tractor student design competition, in which many $1/4$ scale tractors are made. The building of these tractors showcases the importance of designing for manufacturing and assembly [8].

2 Problem Definition

Elmer's Manufacturing requires a simplified means of showcasing their grain carts to farmers during peak purchasing months and a more efficient software testing platform. Current practices in both software testing and showcasing are time-consuming and labor-intensive, as they involve transporting and operating the full-scale equipment. Given its size, this also makes it challenging for farmers or Elmer's testing personnel to view all the internal features. A scaled-down or alternative demonstration method enhances visibility and accessibility at agricultural

showcases and increases the ease of software testing. The scale-down process includes designing a complete CAD model of a 1/6th scale grain cart, ordering parts, and assembling the 1/6th scale grain cart. The major function of the full-scale grain cart is discussed in Section 2.1, with the key functions highlighted in Section 2.2.

2.1 Full Scale Design Overview – Parts and Systems

Elmer's Manufacturing offers a full-scale Tandem HaulMaster 2500 grain cart project information brochure which provides a detailed overview of the grain cart's main functions, key components, and mechanisms that ensure its efficient operation [9]. Each part plays an essential role in maintaining the cart's functionality. The overall grain cart assembly is shown in Fig. 2.



Figure 2. Elmer's Manufacturing Inventor model of the HaulMaster 2500 grain cart [9].

The subsystems and components of the grain cart are outlined and summarized below:

Mainframe: The mainframe of the grain cart serves as the backbone, providing structural support and carries the weight of the tank and grain, as well as houses the drag auger. The mainframe also has trapdoors at the bottom to allow for drag auger cleaning and gates that can open and close to restrict or allow grain flow from the tank into the drag auger as shown in Fig. 3.

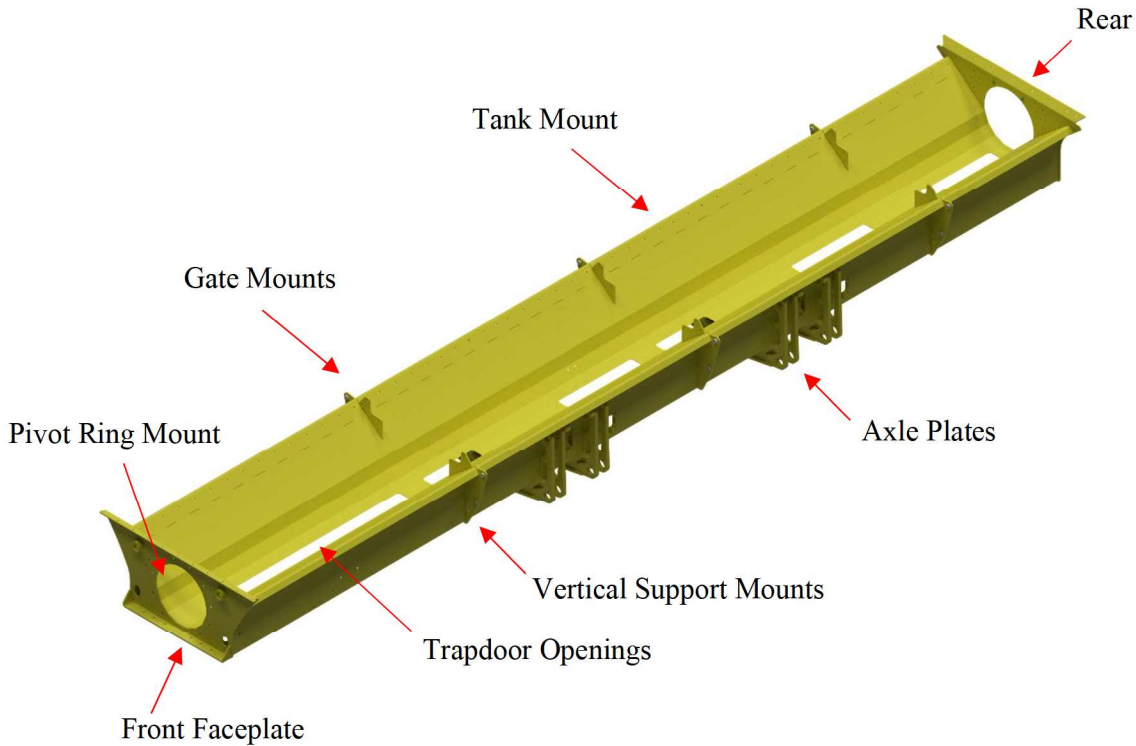


Figure 3. Mainframe features of the HaulMaster 2500 [10].

Undercarriage system: The grain cart utilizes an inline tandem system. This configuration consists of four wheels, with a front and rear wheel on each side, allowing for improved weight distribution across the cart.

Auger System: This mechanism unloads grain from the cart using a spiral screw. The grain cart includes both a drag (horizontal) auger and an unload (vertical) auger. The drag auger, which is integrated with the tank, moves the crops to the front and into the unload auger. The unload auger is positioned at the front of the grain cart and lifts the contents moved by the drag auger for discharge. The unload auger is divided into two sections and can fold and unfold. Additionally, it has a spout on the top of the upper section that can move in two directions. The auger system is shown in Fig. 4.

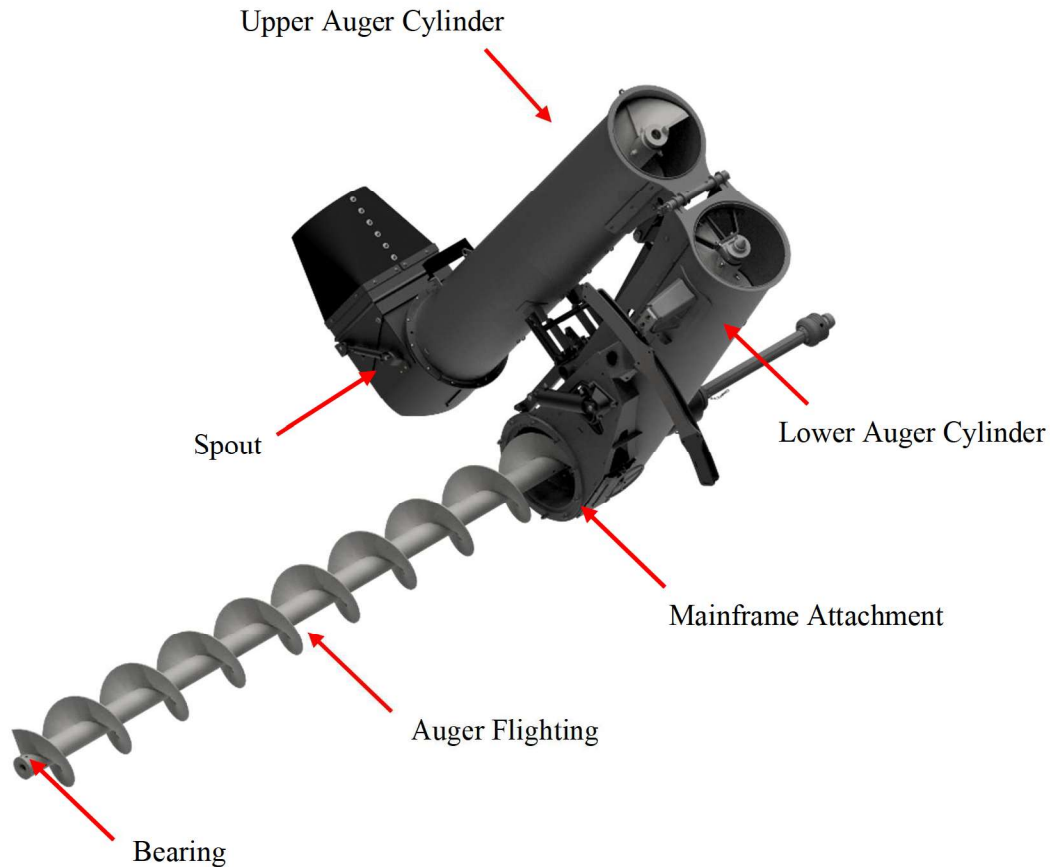


Figure 4. Auger system features of the HaulMaster 2500 grain cart [10].

Tank: The tank is designed for storing and transporting harvested grain. It features sloping plates, an opening at the top, and is connected to the mainframe at the bottom.

Gates: The gate system is designed to control the flow speed of harvested grain into the drag auger. The gate system opens and closes to regulate the flow of crops. The system is positioned above the drag auger and consists of a hood that acts as a canopy and arms connected to a supporting structure to facilitate its operation.

Hitch: The hitch, located at the front of the tank and mainframe, connects the grain cart to a tractor. It also measures the weight supported through the hitch into the towing device or other support mechanism (tongue weight).

Sensors and controllers: The grain cart uses load sensors in the undercarriage and hitch to measure the load in the tank, as well as angle sensors to sense the folding auger angles. A controller collects data from these sensors.

2.2 Key Features for 1/6th Design

The key features included in the 1/6th scale design, as emphasized by the client, are as follows.

1. Fully functional auger system that moves grain, with unload auger that can fold and pivot*.
2. Inline tandem undercarriage with ability to steer
3. System to measure the weight of the grain cart's tank supported by the undercarriage and hitch in real time*.
4. Trapdoors on bottom of mainframe for drag auger cleaning.
5. Maintains overall aesthetics that resemble full-scale design.
6. Utilize the same controller for sensors and moving components as the full-scale design*.

*Note: Not all these key features were within the scope of the BIOE4950 project. The client removed all electrical components, including the rotating, pivoting, and folding ability of the auger system and the powering of the load sensors from the BIOE4590 project scope due to time constraints and lack of available electrical expertise. The controller was also removed from the BIOE4950 project scope. The design allows for future upgrades to achieve full functionality of the auger and load sensors when time and electrical personnel become available to the client.

2.3 Target Specifications

The target specifications for the 1/6th scale grain cart are listed in Table 1, which includes a specification number, description, criteria, and the verification procedure section for each specification. The results from these verification procedures as well as the procedure details can be found in Section 4 of this report.

Table 1. Target specifications

Spec.	Description	Criteria	Verification Procedure
S1.1	Length	< 7.15 feet	Sect: 4.1.1
S1.2	Height*	< 3.56 feet	Sect: 4.1.2
S1.3	Width*	< 3.36 feet	Sect: 4.1.3
S2.1	Empty Weight	< 1200 lbs	Sect: 4.2.1
S2.2	Empty Tongue Weight	< 200 lbs	Sect: 4.2.2
S3.1	Straight Travel Distance	> 36 feet	Sect: 4.3.1
S3.2	Turn Radius	< 4 feet	Sect: 4.3.2
S4.1	Total Cost	< \$7500 CAD	Sect: 4.4

*The dimensions are for when the auger is in the unfolded, 30° pivot position.

It should be noted that the straight travel distance criteria of 36 feet was chosen as this equates to five full lengths of the scaled-down grain cart which was determined to be a sufficient representation of the grain cart's ability to move forward. The turn radius of less than four feet was chosen as this is the average width of a hallway [11] this would ensure easy movement of the grain cart indoors. The dimension and weight criteria were set by scaling down the full-size grain cart by 1/6th. The cost criteria was set by the client.

2.4 Client Deliverables

The team is required to design and assemble all components of the grain cart required by the client using Autodesk Inventor 2023. The key client deliverables include a complete Inventor model of individual parts, subassemblies and final 1/6th scaled cart assembly which is sent to Elmer's Manufacturing for production. Additionally, the team provides a finalized Bill of materials (BOM) with vendor information for all purchased components and delivers a fully assembled physical grain cart upon project completion. The client also requests a change log seen in Appendix A documenting any parts or systems that didn't fit due to manufacturing or design issues, the identified problem, the modification made during the assembling, supporting images and recommended actions for future reproduction of individual parts or the full system.

2.5 Constraints

The project constraints consisting of technical limitations and project bounds are listed in Table 2 along with their constraint number and associated implications.

Table 2. Project constraints

Constraint	Description	Implications
C1	Project timeframe is limited to 7 months	Project progress is closely monitored and compared with Gantt chart.
C2	Project must be feasible for under \$7500 CAD	Team will track expenses in a budget sheet to ensure costs are kept below budget.
C3	Parts must be manufacturable by Elmer's or purchasable elsewhere	Design consists of materials approved by Elmer's or found on industrial supply websites that ship to Canada.
C4	Empty cart weight must be less than a pickup truck's tow capacity (13,300lbs) [12]	Weight of parts is monitored and tracked in an excel file to keep total mass below the maximum capacity.
C5	Model must fit HaulMaster Connect and Pro devices	Parts are designed to prioritize the fitting of their respective devices.
C6	Must be powered by a standardized power source (120VAC, 12VDC) plugged into a power outlet at events	All moving components will use motors using the power provided by the standardized sources.

3 Design Solution

The 1/6th scale grain cart was designed using Autodesk Inventor to closely resemble the full-scale design, with some simplified part geometry in all subsystems, and significant undercarriage modifications. All the modelled parts can be seen in Appendix B. The moving components and sensors for the gate movement, auger rotation, spout movement, and load sensing were changed to fit the scaled-down design. Near the end of the design process all motion – besides wheels rolling and steering – and electrification of sensors, as well as the gates to control flow of grain into the drag auger, were removed from the scope of the project due to time constraints. The model was adjusted by the client to remove the motion mechanisms, and this adjusted model was manufactured and built. This section compares the scaled-down design with the full-scale design, showing both the initial scaled-down model designed to have auger movement and the as-built design. The comparisons and changes between the full-scale design, initial design, and as-built design will be explained in the following sections specific to the subsystems: 3.1 Mainframe, 3.2 Undercarriage Design, 3.3 Auger Design, 3.4 Tank Design, and 3.5 Hitch Design. To highlight

what these changes are, details of the full-scale design are explained as well. The final version of the CAD model featuring the as-built design is shown in Fig. 5.



Figure 5. As-built scaled-down CAD model.

3.1 Mainframe Design

The mainframe is responsible for serving as the structural backbone of the entire grain cart, connecting the undercarriage to the auger system and the tank. The main components of the mainframe consist of front and back faceplates, a chute for the drag auger, side rails that allow for attachment to the undercarriage, and three tank connection plates that appear at intervals along the length of the mainframe. Fig. 6 shows a side-by-side of the as-built scaled-down mainframe and the full-scale mainframe.

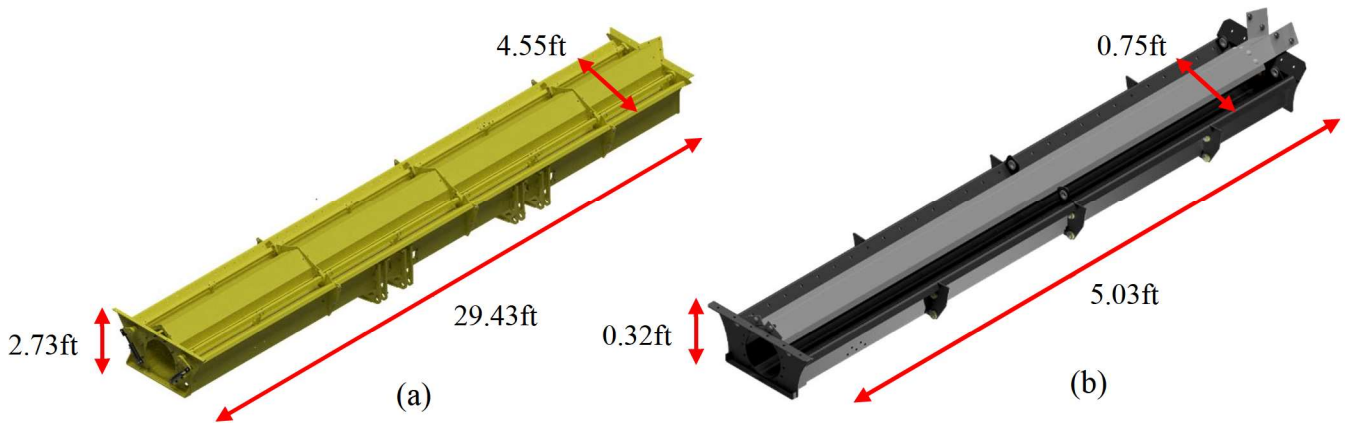


Figure 6. (a) Full-scale mainframe and (b) as-built scaled-down mainframe.

The mainframe also includes a hood that runs the length of the drag auger chute and covers a majority of the auger. This hood mounts onto the tank at the front and a mounting bracket with slotted holes at the rear to allow for some inaccuracy in the manufacturing of the hood. In the full-scale model there are gates that raise and lower to control flow of grain into the cart, controlled by hydraulic cylinders at the front face plate. A labelled as-built image of the mainframe model can be shown in Fig. 7.

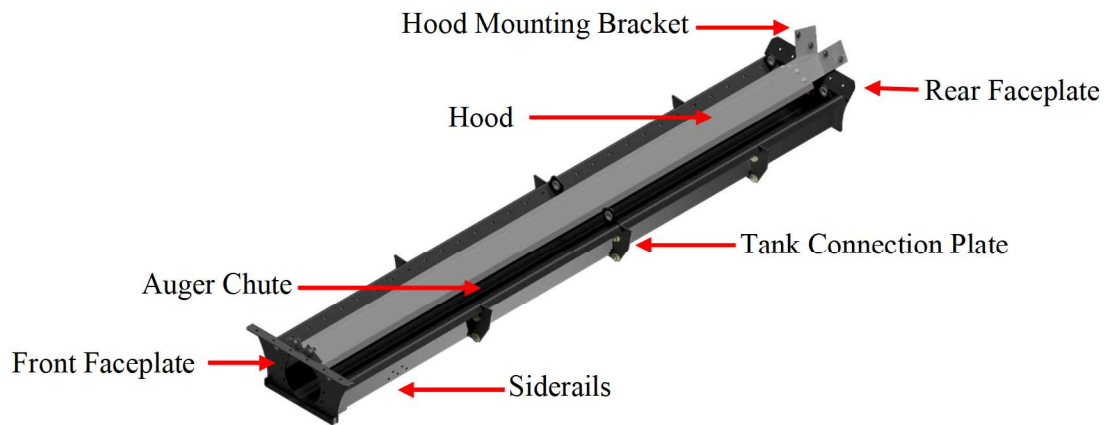


Figure 7. As-built scaled-down mainframe.

These gates were added to our initial design and were intended to be controlled with the 11 lb IP65 Micro linear actuator [13]. They were designed to follow the same mechanism concept as the full-scale model. The initially designed gate control mechanism is shown in Fig. 8.

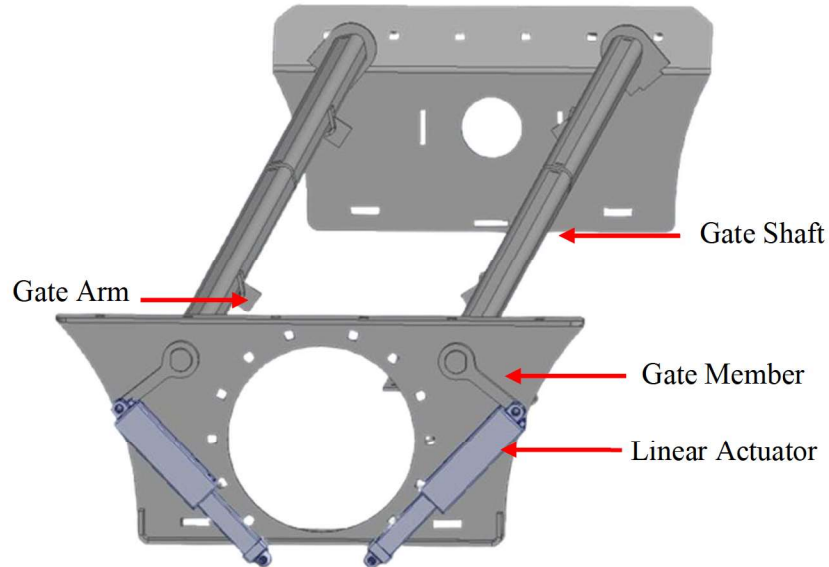


Figure 8. Gate control mechanism.

Two linear actuators that are secured via pin connections to a stationary bracket on the auger on one end and a member connecting to the gate shaft on the other end. As the actuators extend and retract, the members connecting to the shafts rotate about the pinned connection to the actuators. This causes the gate shafts to spin, as the gate members are attached to the gate shafts via set screws and a flat key which acts as a fixed connection. As the gate shafts rotate, they lower and raise gate arms that - on the full-scale model- are attached to a plate which spans the length of the mainframe and blocks or unblocks flow of grain between the auger chute and auger hood into the drag auger. In the scaled down model, there was not enough space to include the actual gate plates, but the gate shafts and gate arms were designed to show how the mechanism works. For the as-built model, the gates were cut from the project, however there are holes in the front faceplate, supports at the middle tank connection plate, and a rear support bracket for gates to be added in the future.

Another key feature of the mainframe are trap door cutouts that span the bottom of the drag auger chute. In the full-scale model, these trap doors are controlled by a rod that runs along the length of

the mainframe and can be rotated via a hand crank to simultaneously open all trap doors. Due to space limitations, these trap doors on both the initial and as-built scaled-down design are welded to bars that are bolted into a mounting bracket on either side of the trap door, which can be unbolted to allow the trap door to swing open. This allows any grain stuck in the auger to be cleaned out. An isolated view of a trap door on the as-built model with a support bar and mounting brackets is shown in Fig. 9.

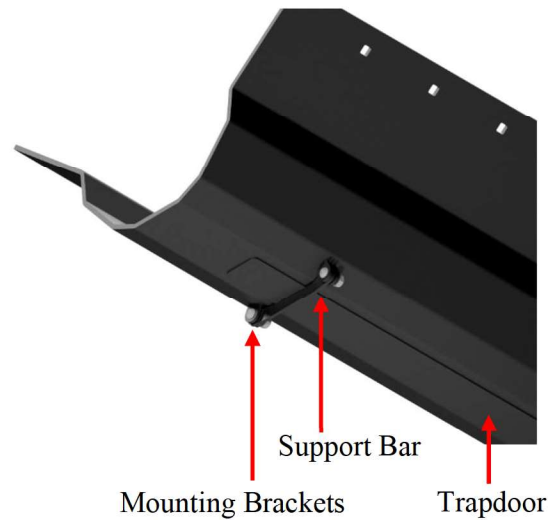


Figure 9. Trapdoor mechanism on as-built mainframe.

The scaled-down mainframe maintains the aesthetic and function of the full-size model, with slight modifications including a simplified hood, simplified trapdoor system, reshaped rear faceplate, and conceptual but non-functional gates. The only difference between the initial design and the as-built mainframe is the lack of gate bars or linear actuators. Besides this, the design did not have to change for manufacturing.

3.2 Undercarriage Design

The purpose of the undercarriage is to connect the wheels to the mainframe, as well as provide a way to measure the weight of the tank and any grain within the tank. On the full-scale model of the grain cart, each of the four wheels is independently connected to the mainframe via a wheel shaft that is attached to a steering system shown in Fig. 10(a). This steering system is attached to the mainframe through a truss-like support frame and suspension cylinder. The wheel shaft in the

full-scale model is a custom-made load cell that measures the force being transferred through each tire into the ground. This design is shown in Fig. 10(b).

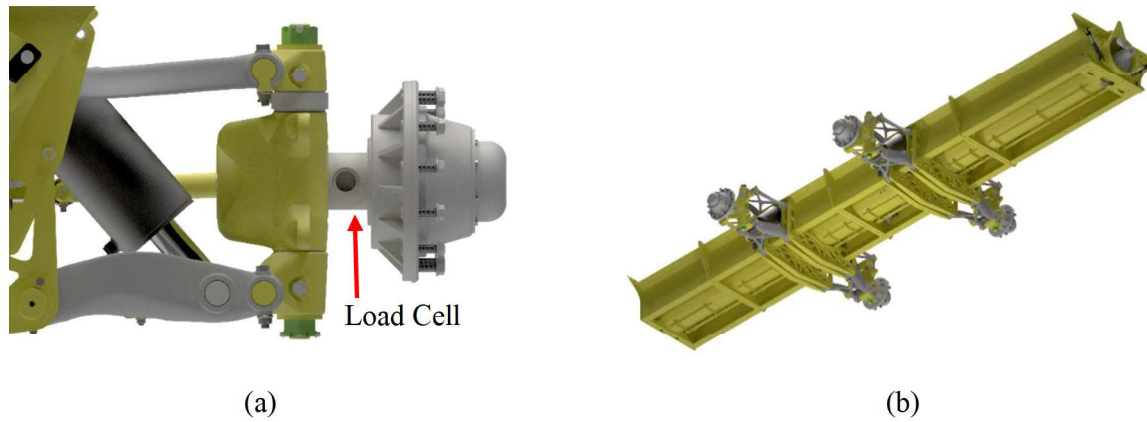


Figure 10. Full-scale undercarriage a) side view and b) isometric view.

This design was not feasible or necessary for the scaled-down model, due to the complexity of the support frames, the fact that suspension is not required in the smaller model, and the lack of access to custom load cells. Instead, a simplified design was implemented, and in the case of the undercarriage, there is no difference between the initial design and the as-built model.

The important functions retained in this simplified design are having sufficient strength to support the smaller grain cart, providing areas to sense the weight in the tank, and being able to provide passive steering with all four wheels while ensuring the two front wheels are aligned and the two rear wheels are aligned. The front view of the redesigned undercarriage is shown in Fig. 11(a) and the top view is shown in Fig. 11(b).

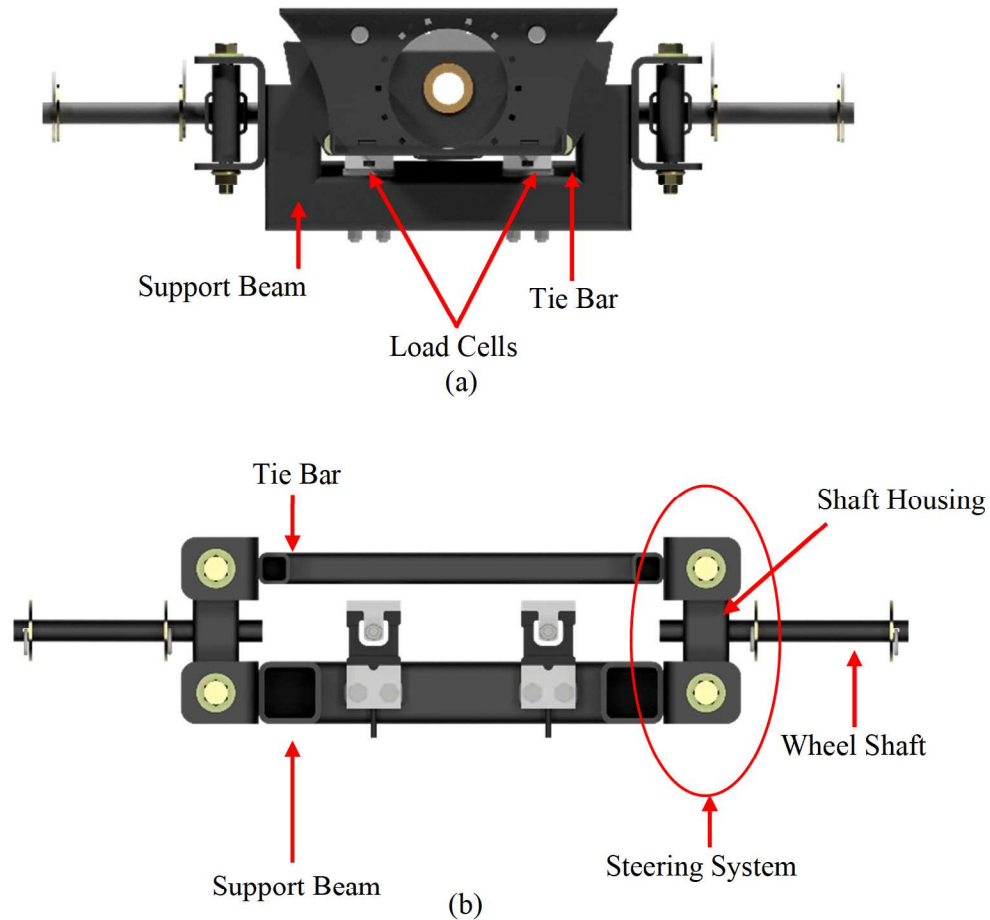


Figure 11. (a) Front view and (b) side view of redesigned undercarriage

Although the undercarriage does not closely resemble the full-scale design, this portion of the grain cart is hidden under the tank and mainframe and is not crucial to the grain cart aesthetics. The scaled-down undercarriage consists of a central support beam that travels underneath the mainframe at the location of the front and back tires. This central support beam is attached to the mainframe via two horizontal flanges, which are not shown in Fig. 11(a) and Fig.11(b) as they are covered by the faceplate. At each of the four connection points (two on the front undercarriage, two on the rear), a load cell is placed between the support beam and mainframe. The details of this load cell can be found in Appendix C. Calculations justifying the choice of support beam thickness and load cell can be found in Appendix D.

The support system has a steering system on either side which then attaches to a shaft that connects to the wheel. On the opposite side of the steering system from the support beam, a tie bar runs between adjacent wheels. The tie bar is not attached to the mainframe and is used to ensure

alignment between wheels. The reason that the support beam and tie bar are dropped down in the middle is to pass under the mainframe while keeping the low profile of the grain cart, a selling point for the HaulMaster 2500. As the tires begin to steer, the shaft housing rotates about the kingpin in the front steering knuckle, which is fixed. The straight travel steering is shown in Fig. 12(a) and the turning motion is shown in Fig. 12(b).

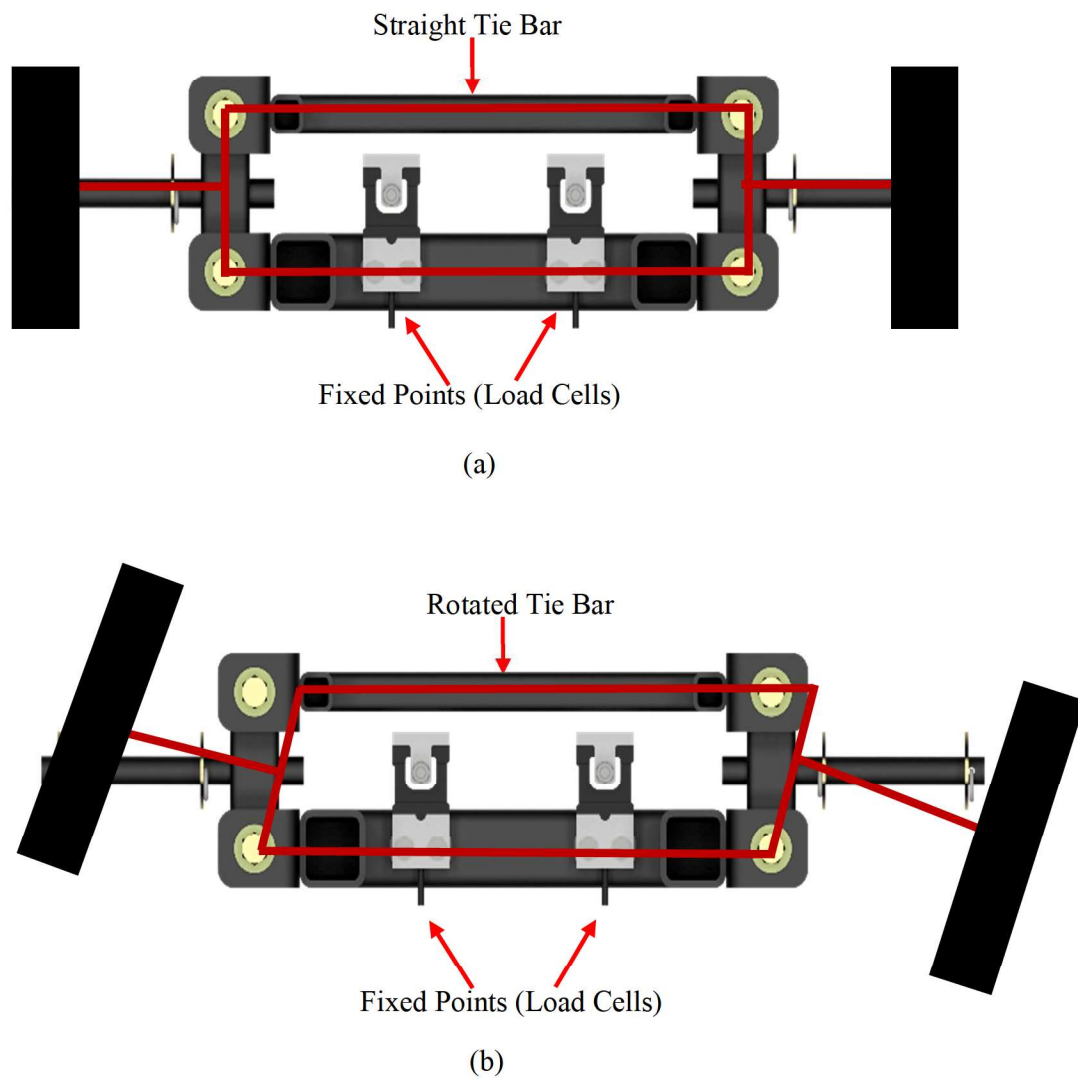


Figure 12. Undercarriage steering (a) straight travel (b) turning.

The rotation of the shaft housing causes the wheel shafts to shift from being on the same axis, as they stay perpendicular to the wheel shaft housing. The tie bar spanning between the two steering

systems moves freely as the shaft housing rotates to ensure wheel alignment. This same design is used in both the front and back wheels of the grain cart. Overall, the undercarriage maintains all the key functionalities of the full-scale undercarriage by supporting the tank and mainframe, allowing the grain cart to travel and steer, and providing a location for load cells to be placed to measure the weight of the tank.

3.3 Auger Design

The auger subsystem consists of the mainframe attachment, auger cylinder, the drag auger, the unload auger, and the spout. These components are shown on the as-built model in Fig. 13.

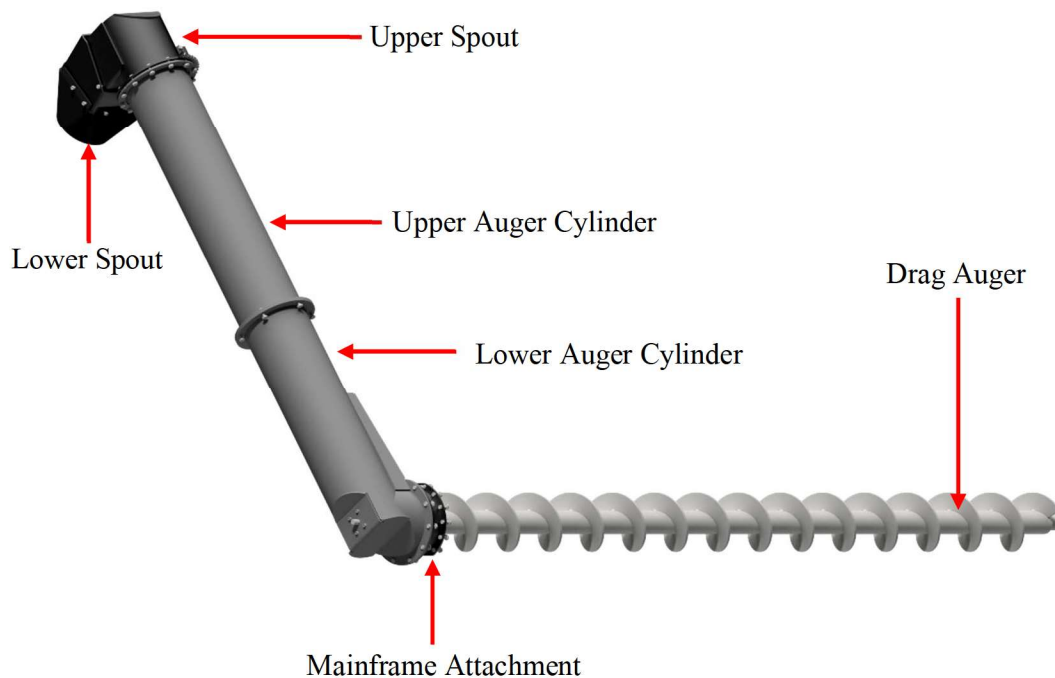


Figure 13. As-built auger.

The entire unload auger assembly is attached to the mainframe by the mainframe attachment piece. A right-angle gear box is positioned at the bottom of the lower auger cylinder where it connects both the drag and unload auger together to enable the movement of grain from the tank of the grain cart to the spout. A cross section of the auger's connection to the mainframe in the as-built is shown in Fig 14, highlighting the gear box positioning.

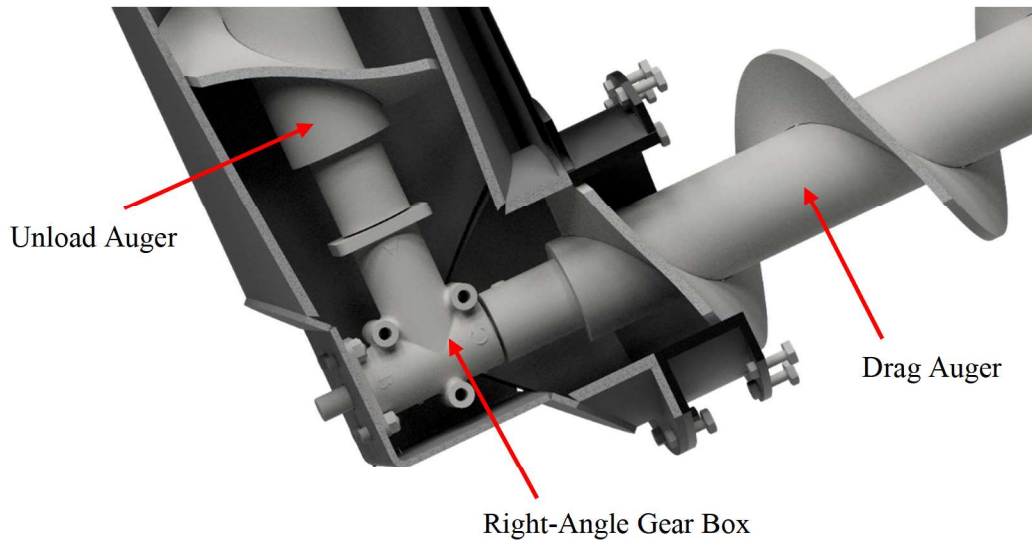


Figure 14. Cross-section of auger connection to mainframe.

A third shaft sticks out the front of the lower unload auger cylinder to allow a motor placed at the front of the drag auger to run both augers at once. The selection and implementation of this motor was removed from the scope of the project and is not included in the as-built model.

The upper auger cylinder is attached to the upper spout by two floating flange pieces that clamp a smaller flange at the top of the upper auger cylinder. This clamping allows for the spout to rotate about the auger cylinder. The connection between the spout and upper cylinder is shown in Fig. 15. There are two floating flange pieces that are bolted to the upper spout, however, only one of the floating flange pieces is visible so this connection can be clearly seen.

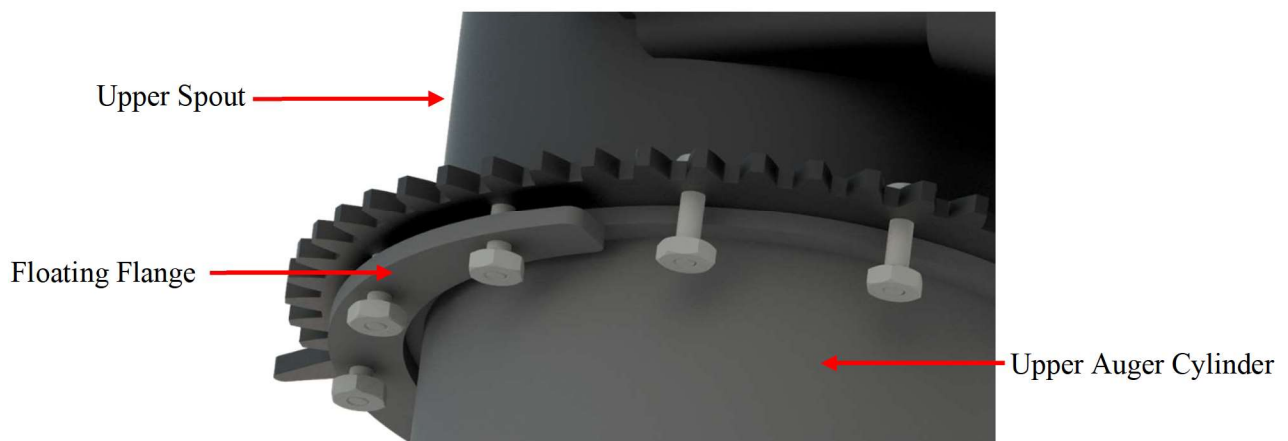


Figure 15. Connection between spout and upper cylinder

The spout consists of the upper and lower spout components. A gear profile was welded on the backside of the auger spout where it can later be connected by separate gear to a motor for automated movement of the spout. The lower spout was designed to be made using rubber material, with a lofted flange profile cut out and bolted on to the upper spout attachment to match the same profile of the lower spout on the full-scale grain cart.

In the full-scale model, the spout is able to tilt up and down to direct the flow of grain leaving the unload auger. On the full-scale model, a hydraulic cylinder controls this, however on the as-built scaled-down model there is a metal bar in its place which has multiple bolt holes in one end. The as-built auger spout is shown in Fig. 16.

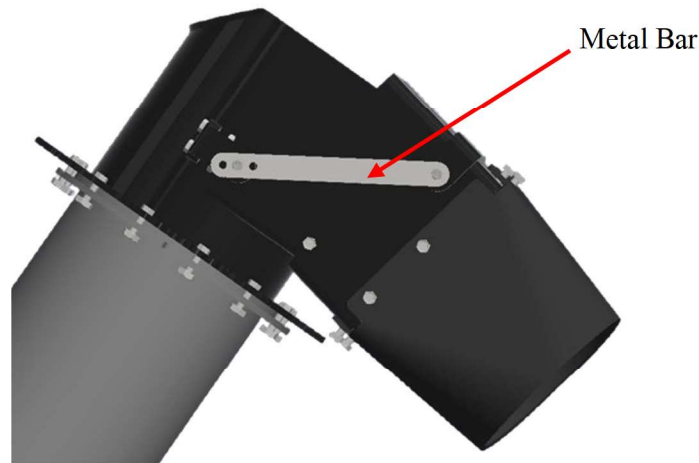


Figure 16. As-built auger spout.

The screw holding the left side of the metal bar in Fig. 16 can be removed, allowing a new hole on the bar to be aligned with the mounting bracket, and then put back in. This adjusts the tilt of the auger spout, showing a simulation of what could be done automatically in the full-scale grain cart

In the full-scale model, the auger can pivot as shown in Fig. 17.



Figure 17. Pivoting of full-sized model.

The pivoting is achieved by hydraulic cylinders which are attached on one end to a floating pivot ring at the mainframe connection and are fixed to the lower auger. This pivot ring operates in the same way as the floating flanges seen on the connection between the upper auger cylinder and the spout. In the initial design, a similar mechanism was designed to pivot the unload auger using the 169lb IP65 Mini Linear Actuator [14], however this was cut from the scope of the project for the as built model. Instead, the lower auger cylinder is bolted solidly onto the mainframe in the as-built design.

Additionally, in the full-scale model, the auger also has the ability to fold to allow for easier travel and storage. This folding can be seen in Fig. 18.



Figure 18. Folding of full-sized model.

This folding is achieved in the full-scale model by another hydraulic cylinder which is attached to a fold linkage that pulls the auger down when the cylinder retracts. The initial design of the scaled-down model had a fold linkage like that of the full-scale model, and this fold linkage can be seen in Fig. 19.

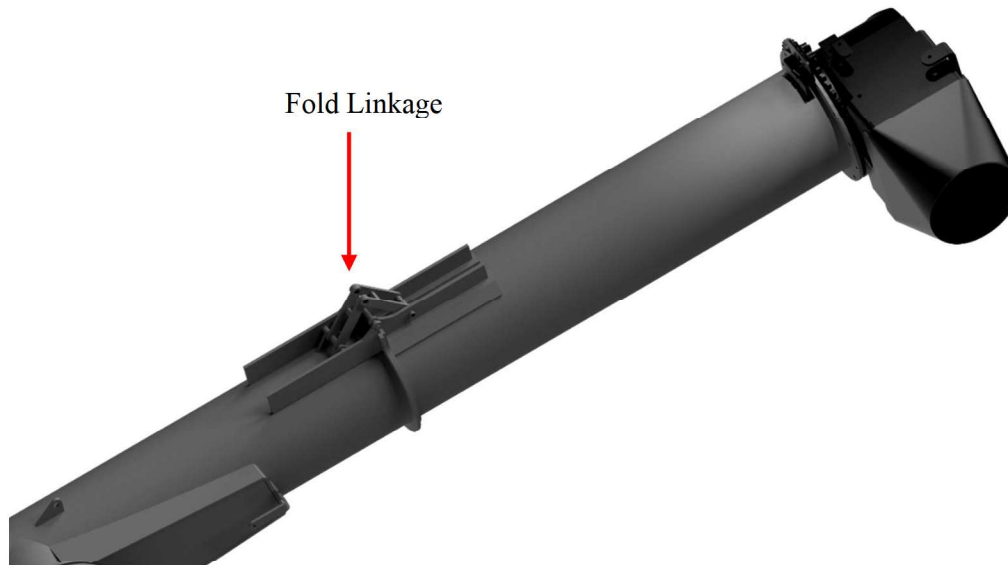


Figure 19. Folding mechanism of initial scaled-down auger

This linkage was designed to be controlled by a 112lb Progressive Automations IP65 Mini Linear Actuator [14], and when conceptually tested in inventor, successfully folded the auger. The linkage and actuator were cut from the scope of the project, and the lower auger cylinder and upper auger cylinder are simply bolted together in the as-built model.

The initial design of the auger replicated the movement mechanisms of the full-scale grain cart, however due to time constraints the rotating of the auger flighting itself as well as the folding and pivoting of the unload auger were cut from the scope of the project, and the as built model is bolted together and stationary. The as-built model aesthetically resembles the full-scale model very closely. The comparison between the full-scale and as-built model are shown in Fig. 20.

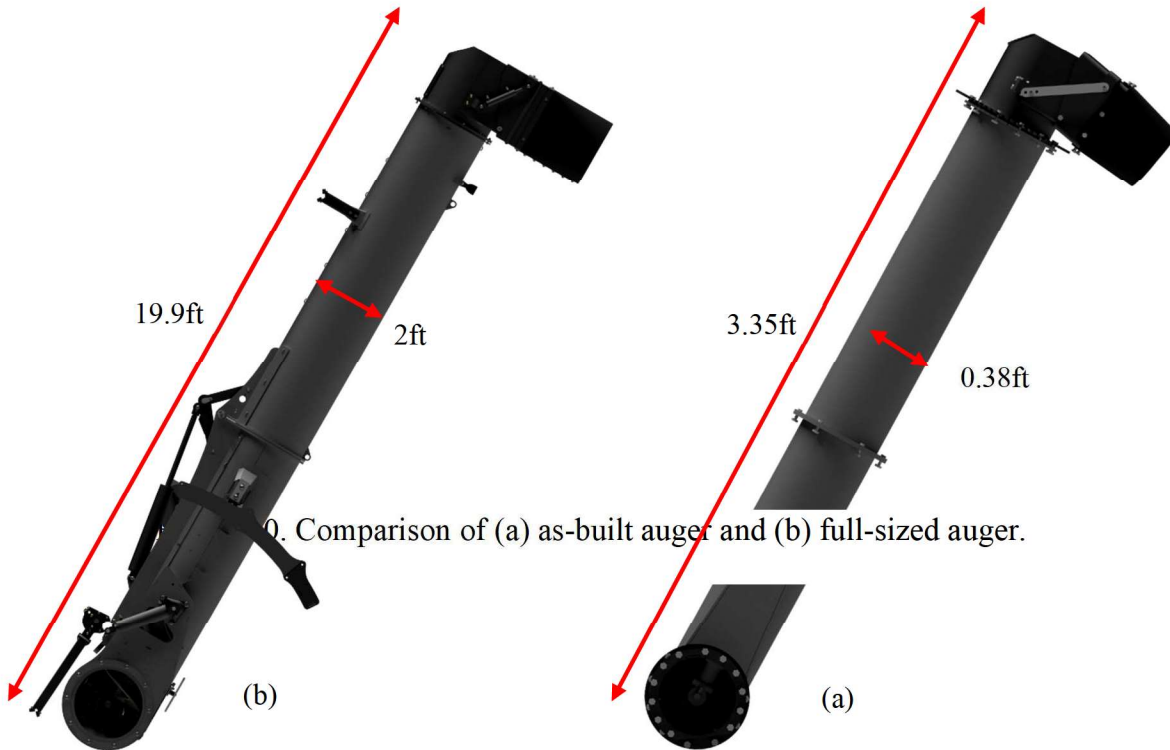


Fig. 20. Comparison of (a) as-built auger and (b) full-sized auger.

3.4 Tank Design

While the tank walls of the full-scale design are divided into several sections due to its size, as it exceeds the maximum dimensions for commercially available materials, the smaller dimension of the 1/6th grain cart allowed each tank wall to be a single laser-cut sheet metal part, unlike the sectioned walls of the full-scale cart. The full-scale and scaled-down tanks are shown in Fig. 21 (a) and (b).

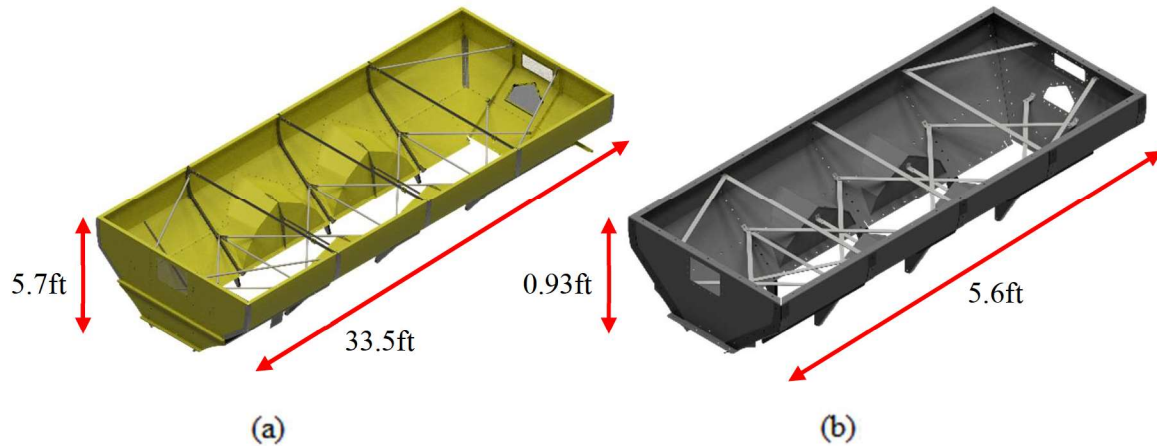


Figure 21. (a) Full-scale and (b) scaled-down tank assembly.

Another significant difference in the 1/6th grain cart is its reduced load capacity compared to the full-scale model. The full-scale tank requires internal steel bars for structural support due to its large volume, as shown in Fig. 21 (a). However, the scaled down cart carries a lighter load eliminating the functional need for these bars. Instead, the internal cross bracings is included purely for aesthetic purposes to replicate the appearance of the full-size model. The tank also features extension pieces that hold the grain cart's retractable top cover. Although the folding cover is outside the scope of this project, these extensions are included in the scaled-down version to maintain the aesthetics of the full-size model, as shown in Fig. 22. The tank is attached to the mainframe using bolts and rivets through flanges on the front, back, and side, aligning with the tank walls.

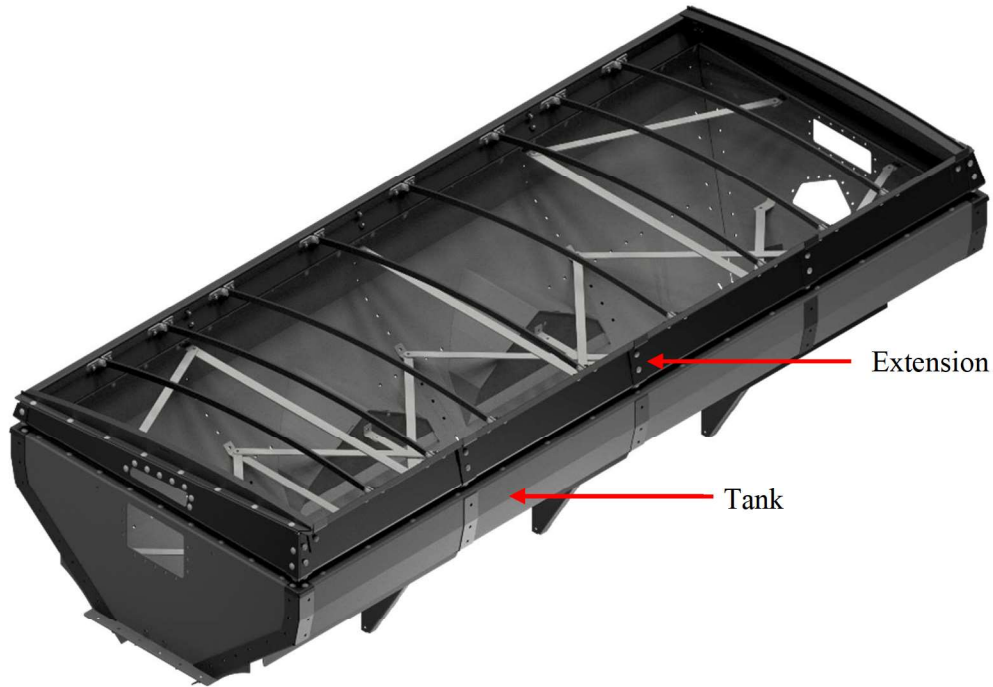


Figure 22. Scaled-down tank with extension pieces for top cover.

The tank is built exactly as designed with no changes from the CAD model to the physical model. The final design, including the extension, is shown in Fig. 22.

3.5 Hitch Design

Unlike the full-scale grain cart, which is designed to be towed by a tractor, the scaled version's hitch primarily provides support to ensure the cart does not tip forward and allows for brief towing by a forklift or other small motor vehicles. The aesthetics of the scaled-down hitch closely resembles that of the full-scale version. A comparison of both hitches is shown in Fig. 23 (a) and (b).

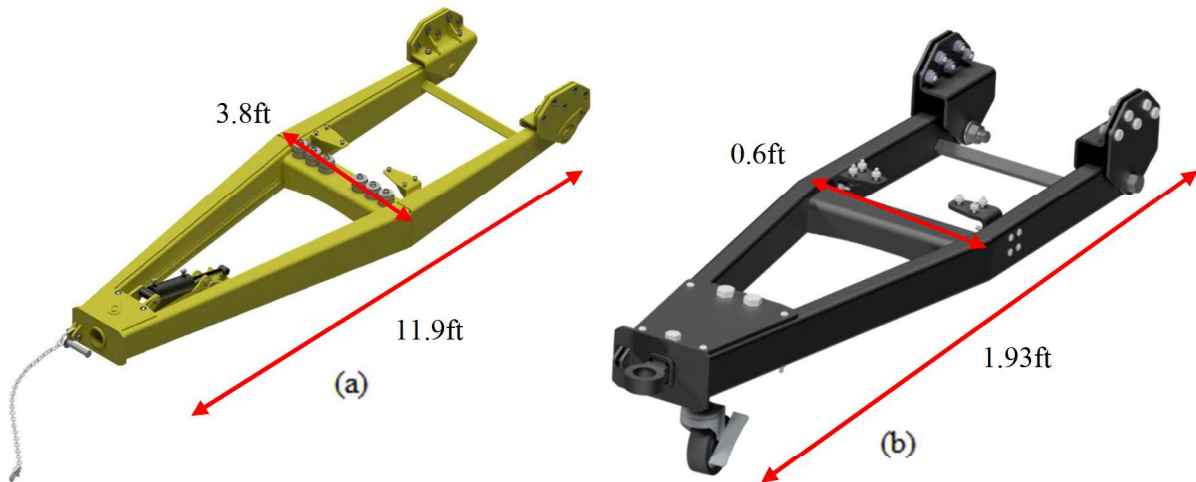


Figure 23. Comparison of (a) full-sized hitch and (b) as-built hitch.

The redesigned scaled-down hitch features a simple hitch ring for rope attachment, allowing it to be towed by any small towing machines. For support, the scaled down hitch has a fixed vertical shaft with a swivel wheel at the bottom replacing the hydraulic jack shown in Fig. 24. For support, the scaled down hitch has a fixed vertical shaft with a swivel wheel at the bottom replacing the hydraulic jack on the full-scale design. The wheel always remains on the ground simplifying operation by eliminating the need for setup or takedown. Additionally, the same load sensor used in the undercarriage is utilized in the hitch and integrated into this wheel shaft to measure the tongue weight of the grain cart. This is essential because, unlike the full-scale model, the scaled down hitch directly supports the front load rather than transferring it through the hitch ring. The labelled hitch can be seen in Fig. 24.

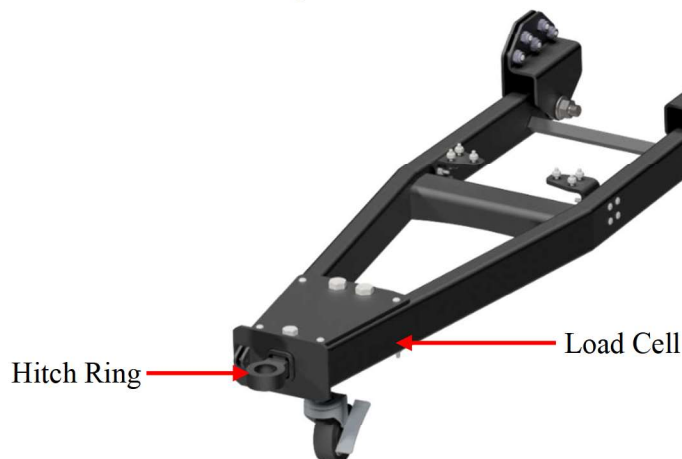


Figure 24. As-built hitch render.

The attachment points for the hitch to the mainframe maintain the original design. The scaled-down hitch is attached using a total of four mainframe mount plates and sliders bolted to the mainframe, shown in Fig. 25.

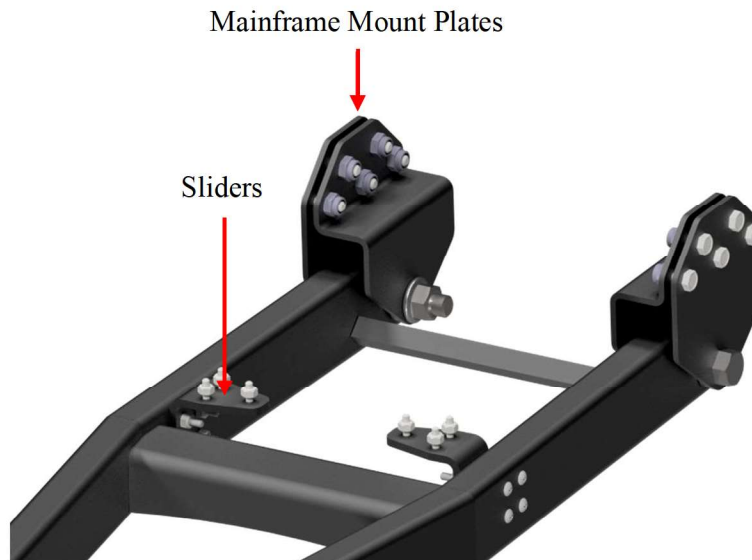


Figure 25. Close-up image of hitch mounting plates.

While the overall hitch dimensions adhere to the $1/6^{\text{th}}$ scale, certain components deviate slightly from precise scaling. One example is the hitch bars, which are slightly larger than exactly $1/6^{\text{th}}$ of the full-scale and are made of rectangular structural steel tubing instead of L-bars. This adjustment was made using materials from Elmer's existing inventory to reduce manufacturing and shipping costs. Additionally, the sheet metal parts of the hitch are not scaled down exactly, as reducing their thickness by a factor of six would greatly compromise structural integrity. The exact dimensions of the hitch parts are listed in Appendix B.

The hitch is built exactly as designed with no changes from the CAD model to the physical model. The final design of the scaled down hitch is shown in Fig. 24.

The subsystems of the $1/6^{\text{th}}$ scale grain cart are designed to closely resemble those of the full-scale model but are not exact replicas. Modifications are necessary due to manufacturability constraints, the feasibility of intended functions, assembly practicality, and material efficiency. These changes are made without compromising the overall appearance of the grain cart. This section outlined the major modifications that differentiate the full-scale cart from the redesigned $1/6^{\text{th}}$ scale version and

highlights any differences between the original design and the final built model, including client-implemented changes.

4 Verification Procedures and Results

This section describes the procedures and results used to verify that the 1/6th scale grain cart meets the target specifications. It outlines the methods and tools used to verify that the dimensions, weight, key functions, and cost of the scaled-down grain cart achieve the target values. Table 3 summarizes the target specifications from Section 2.3, their respective verification procedure, and the results

Table 3. Verification procedures results.

Spec.	Description	Verification Procedure	Results	Pass/Fail
S1.1	Length	Sect: 4.1.1	6.74'	Pass
S1.2	Height	Sect: 4.1.2	3.43'	Pass
S1.3	Width	Sect: 4.1.3	3.71'	Pass
S2.1	Empty Cart Weight	Sect: 4.2.1	308.8 lbs	Pass
S2.2	Empty Tongue Weight	Sect: 4.2.2	68.8 lbs	Pass
S3.1	Forward Movement	Sect: 4.3.1	36+ feet	Pass
S3.2	Turn Radius	Sect: 4.3.2	<4 feet	Pass
S4	Total Cost	Sect: 4.4	\$2,138.68 CAD	Pass

4.1 Dimensions Verifications (S1.1, S1.2, S1.3)

To verify the length, height, and width of the grain cart, a retractable tape measure and two 48-inch straight-edge rulers were used. Note the measurements were taken with the auger mounted, in its pivoted down position as the final scaled-down model does not have a folding auger and will therefore rest permanently with the auger in this position. Each dimension was measured three times, and the results were averaged, increasing accuracy and consistency in the measuring technique.

4.1.1 Length Verification (S1.1)

The length of the grain cart was determined by measuring its longest dimension. This dimension is shown in Fig. 26. The testing procedure was as follows:

1. Place one straight-edge ruler at the foremost point of the hitch, specifically the hitch ring, extending outward horizontally,
2. Place the second straight-edge ruler at the rearmost point of the tank body, extending it outward and parallel to the ground,
3. Hold the end of the tape measure at the extension of one straight-edge ruler and extend it to the other ruler. This will provide the measurement for the maximum length of the grain cart.



Figure 26. Length verification of the grain cart.

4.1.2 Height Verification (S1.2)

The height of the grain cart was determined by measuring its tallest dimension. This dimension is shown in Fig. 27. The testing procedure was as follows for the configuration with the auger dismounted:

1. Place a straight-edge ruler at the uppermost point of the auger, horizontally,
2. Place the end of the tape measure on the ground and extend it perpendicular to the straight-edge ruler until they meet. This will provide the measurement for the maximum height of the grain cart.



Figure 27. Height verification of the grain cart with auger mounted.

4.1.3 Width Verification (S1.3)

The width of the grain cart was determined by measuring across the pieces that extend most outward in the width direction. This dimension is shown in Fig. 28. The testing procedure was as follows:

1. Place a straightedge ruler vertically at the outermost edge of the auger.
2. Place the second straightedge ruler vertically along the outermost edge of the opposite side of the tank body.
3. Hold the end of the tape measure at the extension of one straightedge ruler and extend it horizontally to the edge of the opposite straightedge ruler. This will provide the measurement for the maximum width of the grain cart.



Figure 28. Width verification of the grain cart with auger mounted

The results from all three-dimension tests were considered successful if the measured dimensions are less than or equal to the specified values in Table 1. The results of all three trials for each dimension and their averages are presented in Table 4.

Table 4. Results of dimension measurements.

	Length	Height	Width
Trial 1	80 7/8"	41 1/4"	44 1/2"
Trial 2	81"	41 3/16"	44 5/8"
Trial 3	80 7/8"	41 1/16"	44 1/2"
Average (inches)	80.92"	41.17"	44.54"
Average (feet)	6.74'	3.43'	3.71'
Pass/Fail	Pass	Pass	Pass

4.2 Weight Verifications (S2.1, S2.2)

The empty cart and tongue weights were measured using an SW500 E-Z Weigh Scale System, a CT3037B AccuWeight digital scale, plywood sheets, and a long level. The SW500 E-Z Weigh Scale System consists of a display monitor and four billet pads, which are meant to be placed under each tire of a vehicle. However, one of the billet pads in this system was broken, therefore, the team placed the two left tires on one billet pad and the two right tires each on individual billet pads. This is explained further in the following subsection. The weigh scale system and digital scale

were both tested for accuracy three times prior to the grain cart measurements. This was done using a 20kg weight, it was placed on each scale three times to ensure consistent readings. The outputs from the E-Z Weigh Scale System all read 43lbs, the digital scale output readings from 42.8lbs to 44.4lbs, however, this level of accuracy was deemed acceptable to continue with the verification procedure.

4.2.1 Empty Cart Weight Verification (S2.1)

The empty cart weight was measured by weighing the scaled-down grain cart with no grain inside of the tank. The testing procedure for the empty cart weight was as follows:

1. Have two team members lift the grain cart approximately one foot from the ground and hold it there.
2. Have one team member turn the undercarriage wheels until one side of the wheels are facing toward each other and the other side are facing away from one another.
3. Place one billet pad under the wheels that are facing each other.
4. Place one billet pad under each of the wheels facing away from each other.
5. Use plywood sheets to place the digital scale under the hitch. Use a long level to ensure the digital scale is level with the billet pads.
6. Zero all three function billet pads until the display monitor on the SW500 E-Z Weigh Scale System outputs a reading of zero pounds and zero the digital scale until it outputs a reading of zero pounds.
7. Gently lower the grain cart on all weigh surfaces simultaneously.
8. Record the weight from each billet pad and the digital scale.
9. Zero all three functioning billet pads until the display monitor on the SW500 E-Z Weigh Scale System outputs a reading of zero pounds.
10. Add all four weight readings to get the total empty cart weight

The results for the empty weight test were considered successful if the total measured weight was less than or equal to the specified value in Table 1.

4.2.2 Empty Tongue Weight Verification (S2.2)

The empty tongue weight of the grain cart was measured during the empty cart weight measurement; therefore, the procedure remains the same as from the empty cart weight verification

section. The tongue weight value was taken as the reading from the digital scale placed under the hitch.

The results for the empty tongue weight test were considered successful if the total measured weight from digital scale was less than or equal to the specified value in Table 1.

The results from the final weight tests are presented in Table 5.

Table 5. Weight test results.

	Right tires	Left front tire	Left rear tire	Hitch wheel	Empty cart weight	Tongue weight
Weight	141 lbs	25 lbs	74 lbs	68.8 lbs	308.8 lbs	68.8lbs
Pass/Fail	-	-	-	-	Pass	Pass

4.3 Mobility Verification (S3.1, S3.2)

The ability of the grain cart to be rolled in a straight line and turned will be tested by two group members using human power to move the grain cart. A skid steer awas intended to be used to assess the grain cart's ability to move. However, due to limited available equipment, manual manipulation of the grain cart was deemed a sufficient test mechanism. As such, two team members tested the grain cart mobility in (1) a straight line and (2) a 90 degree turn within four feet.

4.3.1 Moving in a straight line (S3.1)

The mobility of the grain cart was tested by having one group member pull the grain cart via a rope that is tied to the hitch ring on the hitch while another group member leans over and pushes on the rear plate of the grain cart tank. The group members will exert force until the grain cart moves 36 feet in a straight line. The results were considered successful if the group members were able to move the grain cart without it stopping.

4.3.2 Turning Verification (S3.2)

The turning of the grain cart was tested in a similar manner to the mobility test. However, a piece of tape was first placed on the ground four feet in front of the grain cart. This test was conducted by having one group member pull the grain cart via a rope that is tied to the hitch ring on the hitch

while another group member leaned over and pushed on the rear plate of the grain cart tank. The member that was pulling pulled the grain cart toward the side, forcing it to turn, while the pushing member continued to push. The results were considered successful if the group members were able to turn the grain cart 90° before reaching the four-foot tape marker on the ground.

The results from the mobility tests are presented in Table 6.

Table 6. Mobility test results.

	Straight line	Turning
Travel distance	36+ feet	<4 feet
Pass/Fail	Pass	Pass

4.4 Cost Verification (\$4)

The cost of the grain cart was calculated using an Excel spreadsheet. Each row in the spreadsheet represents an individual part or component of the grain cart, while the columns include the unit cost of the part, the required quantity, and the total cost for that part. The total production cost of the grain cart was determined by summing up the total costs of all parts. This calculation included material, fabrication, and labor costs (provided by Elmer's Manufacturing), purchased items cost, and shipping and handling fees. The results were considered successful if the total cost is below \$7,500.

The final cost for the entire production of the grain cart was \$2,138.68 CAD, as summarized in Table 7. This value is below the target specification and therefore passes the verification. The full cost breakdown for each subsystem can be found in the Bill of Materials in Appendix B.

Table 7. Final cost per subsystem.

Subsystem	Cost (CAD)
Mainframe	\$549.83
Undercarriage	\$473.67
Auger	\$423.44
Tank	\$407.16
Tank Extension	\$208.68
Hitch	\$220.97
TOTAL	\$2,238.74

In conclusion, the scaled-down grain cart passed all verification procedures, as summarized in Table 3. This demonstrates that the project can be deemed successful as it hit all required target specifications set out by the client and the team.

5 Sustainability

Increasing sustainability in projects enhances company value while benefiting society and the environment [15]. The Triple Bottom Line (TBL) framework emphasizes long-term sustainability through the “three P’s”, Profit, People, and the Planet. Profit ensures financial viability and profitability, People measure social responsibility, and Planet assesses environmental responsibility.

Green Project Management® (GPM) is a global organization that incorporates the TBL framework into project management and development [15]. It includes methods, tools, and techniques used to consider the whole lifecycle of a project, aiming for a net positive impact on environmental, social, and economic aspects.

The University of Waterloo’s Engineering Faculty adapted the GPM framework to assess projects in TBL areas. This framework was applied to evaluate the 1/6th scale grain cart, focusing on six GPM elements. The results, shown in Table 8, compare the full-size grain cart with the scaled-down model.

The 1/6th scale grain cart project achieved a total change score of +17, showing that the team carefully considered sustainability. Positive changes in the People, Planet, and Prosperity categories confirms the project’s alignment with sustainable practices and its positive contributions to social, environmental, and economic outcome

Table 8. GPM adapted impact analysis table for the 1/6th scale grain cart. [15]

	Description of the situation (Cause)	Potential Sustainability Impact	Impact Score	Proposed Response	New Score	Change
People Impacts						
Local Competence Development	Transporting the full-scale grain cart is challenging due to its size and need for a tractor, limiting demonstration opportunities.	Local farmers lack expertise in operating Elmer's grain carts. Training with the full-size model is time-consuming and requires extensive preparation, making it less appealing for comprehensive staff training.	2	The 1/6th scale grain cart is easier to transport and operate, allowing for efficient and accessible training sessions for local agricultural workers without the need for a tractor.	5	3
Planet Impacts						
Energy Consumption	Operating the full-scale grain cart requires significant energy and is powered by a diesel tractor. Its heavy weight also means high fuel consumption for transport.	The diesel power source is non-renewable, contributing to greenhouse gas emissions and the construction of gas pipelines and oil rigs, which negatively impact communities and the environment.	2	The 1/6th scale grain cart, with a rechargeable system compatible with Manitoba's hydroelectric grid, uses less energy for transport and can be towed by an electric vehicle.	4	2
Greenhouse Gas (GHG) Emissions	Transporting the full-scale grain cart requires towing using trucks or other vehicles. Towing large items increases a vehicle's fuel consumption, leading to significant CO2 emissions. It is also powered by diesel tractors.	These processes increase greenhouse gas emissions, contributing to climate change.	1	The 1/6th scale grain cart, powered by a rechargeable system from Manitoba's hydroelectric grid, reduces fuel consumption and GHG emissions during demonstrations. Its smaller size will contribute to a lower amount of fuel being consumed by the vehicle transporting it.	5	4
Prosperity Impacts						
Flexibility/Optionality	The full-scale grain cart is difficult to modify for new testing as it requires reworking and remodeling of full-size components, making it challenging to conduct tests to modify the design.	Testing and modifying the grain cart demands significant labour and planning. Custom components can lead to waste if they don't function as expected.	2	The 1/6th scale grain cart is easier to modify, as a single person can handle design changes. Components sourced from Elmer's, like the rechargeable battery, simplifies replacements and testing.	4	2
Resiliency	The full-scale grain cart is expensive and difficult to modify due to its size and complexity.	Market fluctuations or natural disasters may require Elmer's to test new software or equipment, which is challenging with the full-scale model.	1	The 1/6th scale grain cart allows for easier software testing and modifications, aiding marketing efforts and increasing farm productivity during crises.	4	3
Local Economic Impact	The full-scale grain cart is hard to market due to the effort needed to transport and operate it. Its complex software and controls require extensive training for farmers.	Showcasing difficulties can lower purchase interest. Advanced tech may deter farmers due to the learning curve, resulting in reliance on outdated equipment, increasing workload, and reducing efficiency.	2	The 1/6th scale grain cart simplifies demonstrations, encouraging purchases of the full-scale model. It helps farmers learn the system, boosting confidence in upgrading equipment, enhancing yields, and reducing workload.	5	3

6 Conclusion

This project aimed to design a fully functional $1/6^{\text{th}}$ scale model of the HaulMaster 2500 grain cart produced by Elmer's Manufacturing to aid with software testing and showcasing its key features. This project aimed to reduce the information gap and boost confidence in the use of new equipment by addressing farmers' hesitation to adopt modern agricultural technology through more accessible and practical demonstration knowledge, as well as increase convenience of software testing for Elmer's Manufacturing. To create this smaller model, Autodesk Inventor software was used to create a complete model of the $1/6^{\text{th}}$ scale grain cart, which was then used to manufacture the required parts for assembly of the scaled-down model.

The design process involved overcoming challenges related to downscaling, such as maintaining functionality and manufacturability while simplifying subsystems, especially the undercarriage and auger designs. Some components were adjusted to fit the smaller scale and load cells were integrated for precise weight measurement.

Outlined verification procedures were used to ensure that the $1/6^{\text{th}}$ scale grain cart met target specifications. Dimensions were measured using a tape measure and rulers, and the weight was measured with a weigh scale system, a digital scale, and plywood sheets. Total costs were calculated using a Microsoft Excel spreadsheet with the individual cost for each component from the BOM. The results of these verification procedures, outlined in Table 3, show that the scaled-down design passed the target specifications, which will allow the client to easily transport the scaled-down model to showcasing events with a pick-up truck. This will in turn enable more potential customers in remote locations to take a closer look at the design and learn about the benefits of using a grain cart, enabling them to make an informed decision when considering acquiring this equipment.

From a sustainability perspective, the $1/6^{\text{th}}$ scale model offers significant benefits, such as reduced emissions and optimized material energy and use, which contributes to waste reduction during showcases.

6.1 Limitations

While the project has successfully produced a scaled-down grain cart that meets all target specifications, some design and verification limitations were still faced. Understanding these limitations will aid Elmer's Manufacturing when producing further scaled-down models or refining this first prototype. The major limitations faced throughout the duration of the project are detailed in the following sections.

6.1.1 Limitations of design solution

The biggest limitations of the current design solution are regarding the moving components. The initial scope of the project included a fully functioning auger and gate system in the mainframe. The original design planned for the auger to pivot, fold, and include functioning flighting to demonstrate grain movement through the cart. Additionally, a gate system in the mainframe was intended to control grain flow into the auger. While both the auger and gates are included in the physical model, their movement was removed from the project scope due to time constraints. As a result, the model has limitations in demonstrating the auger and gate functions found in the full-scale grain cart.

The project also faced limitations with the electrical components. Due to the reduced scope, the power supply and sensor systems were not implemented. Since the auger and gate movements were removed, the power supply was no longer necessary, as it was originally intended to operate these components. Based on discussions with the client, the team decided to postpone integrating the sensor systems until the moving parts were ready for their power supply, allowing all electrical work to be completed at once. While the force sensors and motors are included in the physical build, they are not connected to any system. As a result, the model cannot demonstrate auger and gate movements or provide weight readings from the sensors, both of which are key functions of the full-scale grain cart.

Several minor limitations encountered during the building stage of the project. These issues resulted in more time spent building than initially estimated and some minor changes to the aesthetics of the grain cart, such as the removal of paint and the addition of bolt holes. The full list of these issues is listed in a change log in Appendix A.

6.1.2 Limitations of verification procedures and results

The verification stage of the project faced several limitations that affected the ability to accurately measure some of the target specifications. Weight tests, as mentioned in the verification section, were conducted using three billet pads and a digital scale leveled with plywood sheets. These tests were limited by the lack of fully functional equipment. Ideally, all four billet pads would have worked to evenly distribute the grain cart's weight, with each pad feeding into the same display monitor for more accurate results. The use of plywood and a digital scale may have slightly affected the weight readings, reducing accuracy. Additionally, for measuring the tongue weight, a dedicated tongue weight scale would have been ideal, but the team did not have access to one. The weight tests were further limited by the inability to take multiple readings, as setting up the grain cart on the scales was challenging and required assistance from non-team members.

The accuracy of the dimension measurements was primarily limited by the measuring technique. Although three readings were taken for each measurement to improve precision, there remains a possibility that team members did not measure from the exact outermost points of the grain cart or did not align the tape measure perfectly straight.

6.2 Recommendations

To address the current design limitations related to moving components, a mechanism should be added to the auger to replicate the movement functions of the full-scale grain cart. This includes enabling the auger to pivot, fold, and incorporate functional flighting to demonstrate grain movement and unloading. Additionally, actuators should be implemented for the gate mechanism to ensure its functionality, allowing for the demonstration of controlled grain flow, as in the full-scale model. Once the moving mechanisms are implemented, the electrical system, including a power supply and control system, should be integrated to operate these components. Additionally, the load sensors should be connected to the electrical system after the moving parts are functional, enabling the model to accurately measure the grain cart's weight.

To optimize the build process of the grain cart, certain adjustments can be made. Components that require bolting but have limited clearance for hands or tools can be welded instead, provided this does not interfere with the placement of other parts. Additionally, connecting points, joints, bolt holes, and shafts should remain unpainted, as the added paint layer may require sanding or grinding,

increasing assembly time. To optimize the build further, follow the suggested actions in the change log in Appendix A.

The testing equipment for the verification procedure should be upgraded to improve accuracy. For weight verification, a scale system with four fully functional billet pads is recommended to ensure each tire is placed on a separate pad, allowing for even weight distribution and more precise measurements. A tongue weight scale should also be acquired to accurately measure the grain cart's empty tongue weight. Additionally, verification procedures should be improved by conducting measurements on a level surface to minimize potential errors. The weight measurement process should also be streamlined with a more efficient setup, enabling multiple readings for greater accuracy.

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Appendix A – Change Log

This appendix contains information about problems that have been encountered by the team during the assembly process up to Mar. 26, 2025. The issues, mitigation measures, and suggested action to fix the problems in the future are shown in Table 9.

Table 9. Assembly issues and mitigations.

System	Issue	Implemented Mitigation	Suggested Action
Auger - Spout	Half gear on spout flange is 90° off	None; auger spout rotation is outside of project scope	Remake the part after rotating gear 90° or mount motor on the backside of the auger
Undercarriage	Wheel shaft too thick for wheel bushings with paint	Sanded/filed down wheel shafts	Add no paint zone on wheel shafts
Mainframe & Auger Spout	Holes for auger shaft bushing were too small	Filed holes to make larger	Increase hole size to a more clearance fit
Mainframe – Auger Chute	Holes in trapdoor panels do not line up with mounting brackets on auger chute	Bent brackets with pliers. One side was bolted, and the other side was secured with a bobby pin	Make mounting brackets and trapdoor hinge larger to reduce manufacturing tolerance affect
Mainframe – Auger Chute	Trapdoor holes too close to bend which caused the holes to warp	Grinded down edges until they were flush with bottom face of auger chute	Make trapdoor holes thinner and increase the width of bottom flange on the auger chute
Undercarriage	Clevises are too wide and there is too much clearance on wheel shaft housing	Added an extra washer	Decrease clevis width
Hitch	Weld beads prevent top plate from sitting flush and caused unaligned	Grinded down weld beads	Shorten top plate to allow for weld bead
Mainframe & Undercarriage	Hex plates, meant to hold nut in place when connecting mainframe to load cell had too big of a hole for the nut, did not stop it from spinning	Used wrench to hold nut instead	Decrease size of hole in hex plate

Table 9. Assembly issues and mitigations.

System	Issue	Implemented Mitigation	Suggested Action
Auger – Mainframe Attachment	Bolt access for bottom bolt is very small. Made it very difficult or not possible to use all bolt holes.	Did not use some of the holes, used tape and wrench to hold nut on inside of mainframe.	Reposition bolt holes or make cutouts in mainframe assembly to allow bolt access.
Tank	Bolt holes did not line up perfectly from the side tank wall and corner braces; could not get bolts through.	Used a drill to make holes from the outside of the tank to ensure a bolt could get through.	Increase bolt hole clearance.
Mainframe – Hitch Sliders	Bolt holes on mainframe for hitch sliders are inaccessible and very difficult to tighten.	Took 4 hours and 4 people to tighten the bolts properly.	Use carriage bolts to limit need for access to both bolt sizes. Use rivets instead.
Auger – Gear Box	Difficult to assess to get bolts and nuts into the auger cylinder to attach gear box.	One person held the nuts on the inside using pliers and a wrench while another person tightened the bolts from the outside of the auger cylinder.	Redesigning the lower auger cylinder so that the area behind the gear box can be easily accessed.
Auger – Drag Auger & Unload Auger	End stub too thick for bushing	Grinded down auger stub shaft ends.	Pre-grind auger stub shaft.
Auger – Drag Auger & Auger Housing	Difficult to find the set screw hole on the drag auger shaft stub once the unload auger and auger cylinder were attached to the mainframe.	Put the drag auger in place and put the set screw where it needed to be once the unload auger was in place. Lined up the drag auger shaft with the gear box with the unload auger in place and added bolts. Used a flashlight to find the set screw and rotated the drag auger until it lined up.	Adjust hitch design or auger flange so that the drag auger can be added to the unload auger assembly prior to insertion into mainframe.
Tank – Support Bracket	Front tank wall slit too thin.	Grinded open support bracket slit.	Widen slit in support bracket.
Hitch – Hitch Plates	Holes do not align with mainframe.	Drilled new holes.	Manufacturing error. No change needed.
Auger – Unload Auger Spout & Tubing	Weld beads on the upper auger flange prevent spout pivot flanges from sitting flush. Bolts are too short to secure them.	Grinded down weld beads.	Use longer bolts.

Appendix B – Bill of Materials (BOM)

This appendix contains a labelled drawing and a list of parts, part quantities, and part costs for each of the subsystems, along with total cost summation of each subsystem at the end. The tank extension has been treated as its own subsystem for the purpose of the BOM to ensure drawings are comprehensible. The costs include labour done by Elmer's manufacturing in welding and painting the parts. The parts are labelled by individual weldments and hardware received by the team, and the components of each weldment are listed below it in the subsequent BOM tables.

The blue entries in each BOM table are summed to get the total cost of each subsystem. The white entries, which are numbered as subsections of an above blue entry, are individual parts of a weldment, and their costs are included in their respective blue entries. Only blue entries are labelled in the subsystem views, and they can be located using the 'Label No.' column of the BOM tables.

The following abbreviations are used in the BOM tables:

Wdmt – Weldment (Used in part names)

XS ILT – Extra Small Inline Tandem (Used in part names)

NL – Not Labeled (Used for blue entries that are not labelled in the drawings due to lack of visibility or practicality)

The labelled drawings and BOM for the mainframe, undercarriage, auger, tank, tank extension, and hitch are shown in Fig. 29 and Table 10, Fig. 30 and Table 11, Fig. 31 and Table 12, Fig. 32 and Table 13, Table 14 and Fig. 33, and Table 15 and Fig. 34, respectively.

Table 10. Mainframe BOM.

Label No.	Part No.	Part Name	Manufacturer	QTY	Unit Cost	Line Cost
1	TEMP34433	Mainframe Wdmt - XS ILT	Elmer's Manufacturing	1	\$133.21	\$133.21
1.01	TEMP34420	Front Left Frame Rail - Mainframe Wdmt - XS ILT	Elmer's Manufacturing	1	\$11.42	\$11.42
1.10	TEMP34391	Trapdoor Mount - Mainframe Wdmt - XS ILT	Elmer's Manufacturing	32	\$0.00	\$0.10
1.11	TEMP34421	Trough - Mainframe Wdmt - XS ILT	Elmer's Manufacturing	1	\$26.99	\$26.99
1.12	TEMP34399	Gate Support - Mainframe Wdmt - XS ILT	Elmer's Manufacturing	2	\$0.04	\$0.08
1.13	TEMP34408	Load Cell Spacer - Mainframe Wdmt - XS ILT	Elmer's Manufacturing	4	\$0.03	\$0.14
1.14	TEMP34445	Hex Plate - Mainframe Wdmt - XS ILT	Elmer's Manufacturing	4	\$0.03	\$0.14
1.02	TEMP34393	Outer Support Rib - Mainframe Wdmt - XS ILT	Elmer's Manufacturing	4	\$0.21	\$0.83
1.03	TEMP34418	Seam Plate - Mainframe Wdmt - XS ILT	Elmer's Manufacturing	1	\$0.11	\$0.11
1.04	TEMP34419	Rear Left Frame Rail - Mainframe Wdmt - XS ILT	Elmer's Manufacturing	1	\$10.05	\$10.05
1.05	TEMP34417	Front Plate - Mainframe Wdmt - XS ILT	Elmer's Manufacturing	1	\$4.62	\$4.62
1.06	TEMP34414	Hitch Mount Plate - Mainframe Wdmt - XS ILT	Elmer's Manufacturing	1	\$4.57	\$4.57
1.07	TEMP34416	Rear Plate - Mainframe Wdmt - XS ILT	Elmer's Manufacturing	1	\$4.76	\$4.76
1.08	TEMP34410	Rear Right Frame Rail - Mainframe Wdmt - XS ILT	Elmer's Manufacturing	1	\$10.05	\$10.05
1.09	TEMP34411	Front Right Frame Rail - Mainframe Wdmt - XS ILT	Elmer's Manufacturing	1	\$11.42	\$11.42
1.15	N/A	Labour Cost	Elmer's Manufacturing	1	\$47.95	\$47.95
2	10737700	Flat Washer, USS, 1/4, YZ	McMaster-Carr Supply Co.	72	\$0.01	\$0.58
3	TEMP34436	Lock Nut, Nylon Insert, M8x1, Gr. 8	McMaster-Carr Supply Co.	12	\$0.36	\$4.32
4	TEMP34437	Cap Screw, Hex Head, M8x1 x 35mm, Gr. 8.8	McMaster-Carr Supply Co.	4	\$0.53	\$2.12
5	TEMP34434	Load Cell - 50KG	Flintec Inc.	4	\$91.29	\$365.16
6	TEMP34435	Cap Screw, Hex Head, M8x1.0 x 80mm, Gr. 8.8	McMaster-Carr Supply Co.	8	\$1.72	\$13.74

Table 10. Mainframe BOM.

Label No.	Part No.	Part Name	Manufacturer	QTY	Unit Cost	Line Cost
7	TEMP34412	Load Cell Spacer - XS ILT	Elmer's Manufacturing	4	\$0.14	\$0.57
8	TEMP34439	Large Trapdoor Wdmt - XS ILT	Elmer's Manufacturing	1	\$0.93	\$0.93
8.1	TEMP34389	Door - Large Trapdoor Wdmt - XS ILT	Elmer's Manufacturing	1	\$0.38	\$0.38
8.2	TEMP34390	Hinge - Trapdoor Wdmt - XS ILT	Elmer's Manufacturing	2	\$0.02	\$0.03
8.3	N/A	Labour Cost	Elmer's Manufacturing	1	\$0.51	\$0.51
9	TEMP34440	Small Trapdoor Wdmt - XS ILT	Elmer's Manufacturing	2	\$0.26	\$0.53
9.1	TEMP34388	Door - Small Trapdoor Wdmt - XS ILT	Elmer's Manufacturing	1	\$0.08	\$0.08
9.2	TEMP34390	Hinge - Trapdoor Wdmt - XS ILT	Elmer's Manufacturing	2	\$0.02	\$0.03
9.3	N/A	Labour Cost	Elmer's Manufacturing	1	\$0.15	\$0.15
10	TEMP34441	Medium Trapdoor Wdmt - XS ILT	Elmer's Manufacturing	1	\$0.71	\$0.71
10.1	TEMP34404	Door - Medium Trapdoor Wdmt - XS ILT	Elmer's Manufacturing	1	\$0.28	\$0.28
10.2	TEMP34390	Hinge - Trapdoor Wdmt - XS ILT	Elmer's Manufacturing	2	\$0.02	\$0.03
10.3	N/A	Labour Cost	Elmer's Manufacturing	1	\$0.40	\$0.40
11	TEMP34446	Bronze Flange Bushing, 1-1/8" ID x 1-3/8" OD x 3/4" L	McMaster-Carr Supply Co.	1	\$10.78	\$10.78
12	13532400	Lock Nut, Nylon Insert, 10-24, Zinc	McMaster-Carr Supply Co.	12	\$0.04	\$0.45
13	TEMP34448	Carriage Bolt, #10-24 x 1", Gr. 2	McMaster-Carr Supply Co.	12	\$0.11	\$1.37
14	TEMP34405	Rear Left Gate Hood Support - XS ILT	Elmer's Manufacturing	1	\$3.28	\$3.28
15	TEMP34406	Rear Right Gate Hood Support - XS ILT	Elmer's Manufacturing	1	\$3.49	\$3.49
16	TEMP34413	Gate Hood - XS ILT	Elmer's Manufacturing	1	\$11.12	\$11.12
17	TEMP36213	Carriage Bolt, #10-24 x 1/2", Gr. 2	McMaster-Carr Supply Co.	10	\$0.06	\$0.56
18	13532400	Lock Nut, Nylon Insert, 10-24, Zinc	McMaster-Carr Supply Co.	10	\$0.04	\$0.38
19	TEMP34442	Washer, M8	McMaster-Carr Supply Co.	8	\$0.03	\$0.24

Table 10. Mainframe BOM.

Label No.	Part No.	Part Name	Manufacturer	QTY	Unit Cost	Line Cost
NL	TEMP34449	Button Head Screw, #5-40 x 1/2"	McMaster-Carr Supply Co.	16	\$0.05	\$0.84
NL	TEMP34450	Lock Nut, Nylon Insert, #5-40	McMaster-Carr Supply Co.	16	\$0.04	\$0.67
NL	BIOE1	Max Bond Super Glue, Cyanoacrylate	Krazy Glue - UM Bookstore	1	\$8.38	\$8.38
TOTAL					\$549.83	

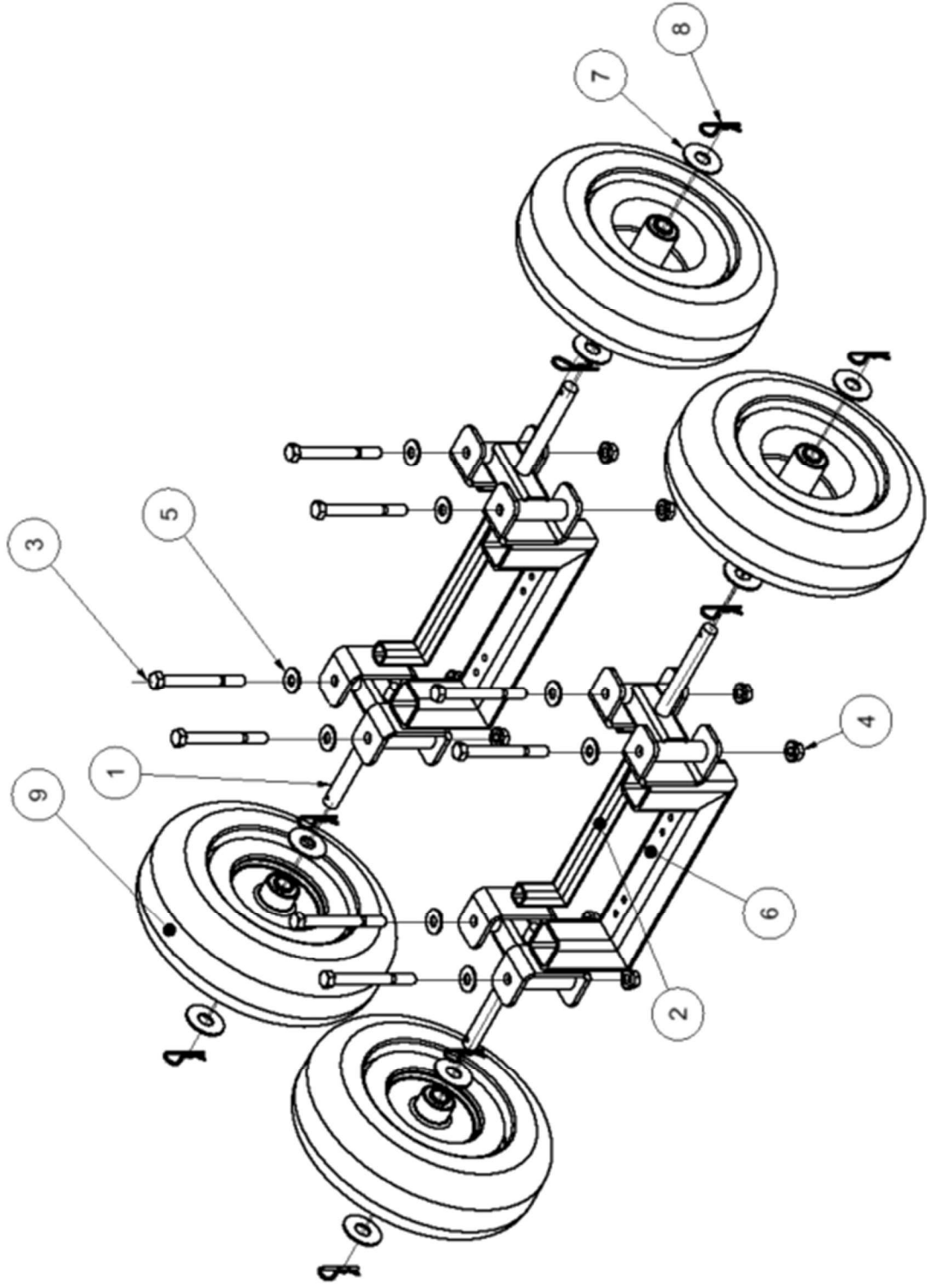


Figure 30. Drawing of hitch components

Table 11. Undercarriage BOM.

Label No.	Part No.	Part Name	Manufacturer	QTY	Unit Cost	Line Cost
1	TEMP34430	Upright Wdmt - XS ILT	Elmer's Manufacturing	4	\$35.99	\$143.97
1.1	TEMP34427	Upright Cross Bar - Upright Wdmt - XS ILT	Elmer's Manufacturing	1	\$12.69	\$12.69
1.2	TEMP34415	Spindle - Upright Wdmt - XS ILT	Elmer's Manufacturing	1	\$8.90	\$8.90
1.3	TEMP34424	King Pin Receiver - Upright Wdmt - XS ILT	Elmer's Manufacturing	2	\$6.34	\$12.67
1.4	N/A	Labour Cost	Elmer's Manufacturing	1	\$1.73	\$1.73
2	TEMP34432	Tie Rod Wdmt - XS ILT	Elmer's Manufacturing	2	\$50.63	\$101.25
2.1	TEMP34423	Main Beam - Tie Rod - XS ILT	Elmer's Manufacturing	1	\$14.10	\$14.10
2.2	TEMP34422	End Piece - Tie Rod - XS ILT	Elmer's Manufacturing	2	\$12.03	\$24.06
2.3	TEMP34428	King Pin Clevis - Tie Rod - XS ILT	Elmer's Manufacturing	2	\$4.69	\$9.38
2.4	N/A	Labour Cost	Elmer's Manufacturing	1	\$3.09	\$3.09
3	10724100	Cap Screw, Hex Head, Gr 5, 1/2 UNC x 5, YZ	McMaster-Carr Supply Co.	8	\$0.61	\$4.85
4	13625500	Flange Nut, Top Lock, Gr G, 1/2 UNC, YZ	McMaster-Carr Supply Co.	8	\$0.25	\$2.00
5	10723200	Flat Washer, USS, 1/2, YZ	McMaster-Carr Supply Co.	8	\$0.04	\$0.31
6	TEMP34431	Axle Wdmt - XS ILT	Elmer's Manufacturing	2	\$63.42	\$126.85
6.1	TEMP34428	King Pin Clevis - Axle Wdmt - XS ILT	Elmer's Manufacturing	2	\$4.69	\$9.38
6.2	TEMP34425	End Piece - Axle Wdmt - XS ILT	Elmer's Manufacturing	2	\$14.40	\$28.79
6.3	TEMP34426	Main Beam - Axle Wdmt - XS ILT	Elmer's Manufacturing	1	\$19.04	\$19.04
6.4	N/A	Labour Cost	Elmer's Manufacturing	1	\$6.21	\$6.21
7	10721300	Flat Washer, USS, 3/4, YZ	McMaster-Carr Supply Co.	8	\$0.14	\$1.12
8	TEMP36238	Cotter Pin, 1/8", For 5/8" - 7/8" Pin Diameter	McMaster-Carr Supply Co.	8	\$0.00	\$0.01
NL	BIOE3	Paulin 3/4-inch Plain Steel Washers -Zinc Plated	Paulin - Home Depot	8	\$1.12	\$8.96
NL	BIOE4	Paulin 1/2-inch Flat Washer - 18.8 Stainless Steel	Paulin - Home Depot	8	\$0.55	\$4.39
9	BIOE2	PowerFist 13 x 4.00-6 Turf Tire Assembly	PowerFist - Princess Auto	4	\$19.99	\$79.96
					TOTAL	\$473.67

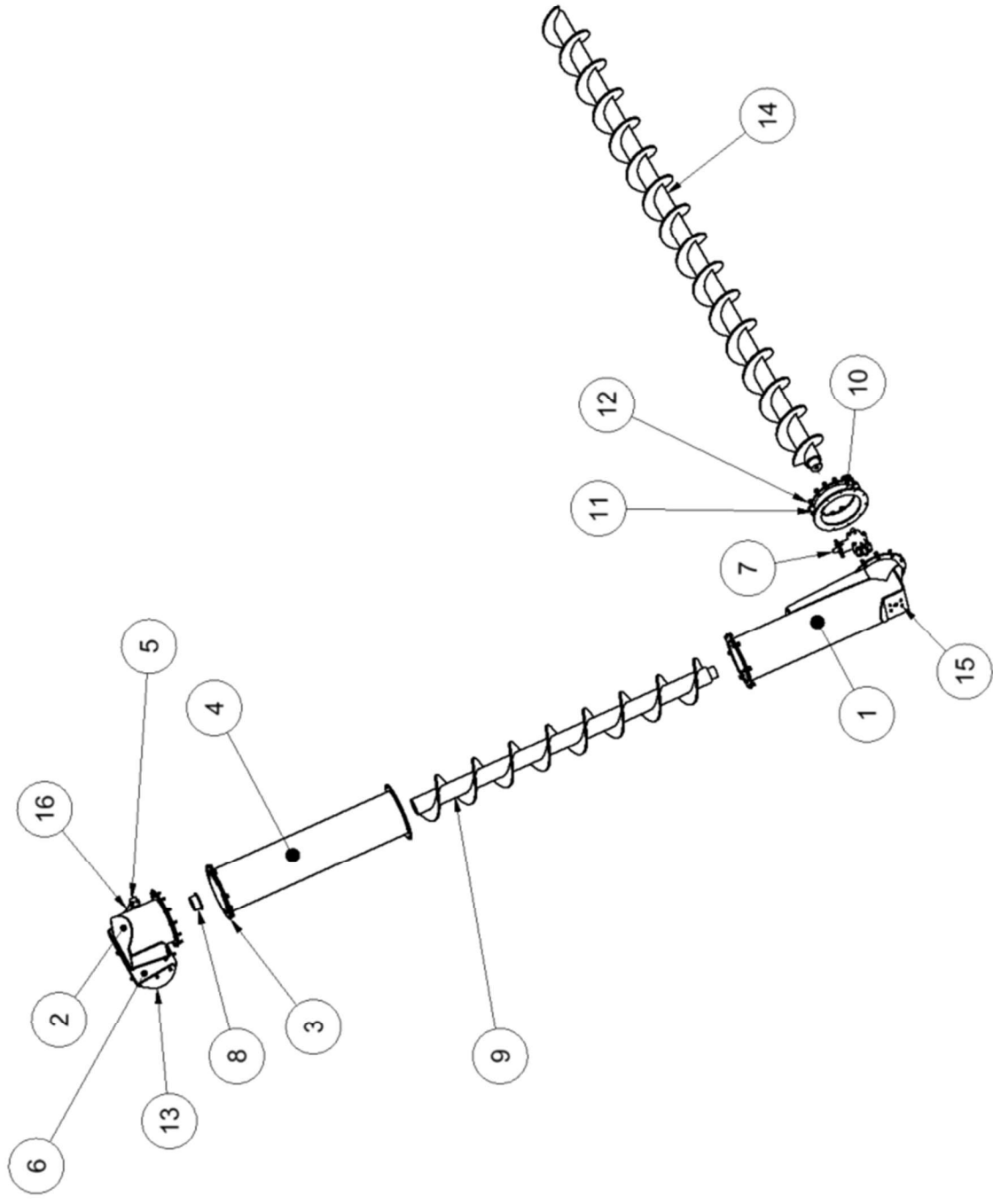


Figure 31. Drawing of auger components

Table 12. Auger BOM.

Label No.	Part No.	Part Name	Manufacturer	QTY	Unit Cost	Line Cost
1	TEMP36043	Lower Vertical Auger Wdmt - SX ILT	Elmer's Manufacturing	1	\$40.61	\$40.61
1.01	TEMP35997	Pivot Ring Mount, Lower Auger Wdmt - XS ILT	Elmer's Manufacturing	1	\$1.24	\$1.24
1.02	TEMP36181	Tube, Lower Vertical Auger Wdmt - XS ILT	Elmer's Manufacturing	1	\$13.27	\$13.27
1.03	TEMP36182	Horizontal Tube, Bottom Vertical Auger Wdmt - XS ILT	Elmer's Manufacturing	1	\$12.72	\$12.72
1.04	TEMP36183	Base Plate A, Bottom Vertical Auger Wdmt - XS ILT	Elmer's Manufacturing	1	\$0.14	\$0.14
1.05	TEMP36184	Base Plate, Bottom Vertical Auger Wdmt - XS ILT	Elmer's Manufacturing	1	\$3.85	\$3.85
1.06	TEMP36185	Base Plate B, Bottom Vertical Auger Wdmt - XS ILT	Elmer's Manufacturing	1	\$0.09	\$0.09
1.07	TEMP36190	Flange, Vertical Auger Wdmt - XS ILT	Elmer's Manufacturing	1	\$0.42	\$0.42
1.08	TEMP36216	Pivot Box Wall A, Lower Vertical Auger Wdmt - XS ILT	Elmer's Manufacturing	1	\$0.37	\$0.37
1.09	TEMP36218	Pivot Box Top, Lower Vertical Auger Wdmt - XS ILT	Elmer's Manufacturing	1	\$0.06	\$0.06
1.10	TEMP36217	Pivot Box Wall B, Lower Vertical Auger Wdmt - XS ILT	Elmer's Manufacturing	1	\$0.39	\$0.39
1.11	N/A	Labour Cost	Elmer's Manufacturing	1	\$8.05	\$8.05
2	TEMP36044	Spout Wdmt - XS ILT	Elmer's Manufacturing	1	\$25.57	\$25.57
2.1	TEMP36002	Tube, Spout Wdmt - XS ILT	Elmer's Manufacturing	1	\$11.83	\$11.83
2.2	TEMP36005	Spout Bottom Brkt, Spout Wdmt - XS ILT	Elmer's Manufacturing	1	\$5.01	\$5.01
2.3	TEMP36004	Spout Top, Spout Wdmt - XS ILT	Elmer's Manufacturing	1	\$4.94	\$4.94
2.4	TEMP35999	Spout Gear Ring, Spout Wdmt - XS ILT	Elmer's Manufacturing	1	\$0.50	\$0.50
2.5	N/A	Labour Cost	Elmer's Manufacturing	1	\$3.29	\$3.29
3	TEMP36001	Spout Pivot Flange - XS ILT	Elmer's Manufacturing	2	\$0.27	\$0.55
4	TEMP36192	Upper Vertical Auger Wdmt - XS ILT	Elmer's Manufacturing	1	\$21.00	\$21.00
4.1	TEMP35998	Bushing Holder, Upper Vertical Auger Wdmt - XS ILT	Elmer's Manufacturing	1	\$0.28	\$0.28

Table 12. Auger BOM.

Label No.	Part No.	Part Name	Manufacturer	QTY	Unit Cost	Line Cost
4.2	TEMP36191	Tube, Upper Vertical Auger Wdmt - XS ILT	Elmer's Manufacturing	1	\$13.85	\$13.85
4.3	TEMP36190	Flange, Vertical Auger Wdmt - XS ILT	Elmer's Manufacturing	1	\$0.42	\$0.42
4.4	N/A	Labour Cost	Elmer's Manufacturing	1	\$6.45	\$6.45
5	TEMP36194	Spout Actuator Brkt - XS ILT	Elmer's Manufacturing	1	\$3.35	\$3.35
6	TEMP36197	Spout Rubber Wdmt - XS ILT	Elmer's Manufacturing	1	\$13.82	\$13.82
6.1	TEMP36195	Rubber Mount B, Spout Rubber Wdmt - SX ILT	Elmer's Manufacturing	1	\$4.44	\$4.44
6.2	TEMP36196	Actuator Mount, Spout Rubber Wdmt - XS ILT	Elmer's Manufacturing	1	\$3.33	\$3.33
6.3	TEMP36198	Rubber Mount A, Spout Rubber Wdmt - XS ILT	Elmer's Manufacturing	1	\$4.44	\$4.44
6.4	N/A	Labour Cost	Elmer's Manufacturing	1	\$1.60	\$1.60
7	TEMP36199	Right-Angle Gear Box, 3-1/2" Overall Width	McMaster-Carr Supply Co.	1	\$212.15	\$212.15
8	TEMP34446	Bronze Flange Bushing, 1-1/8" ID x 1-3/8" OD x 3/4" L	McMaster-Carr Supply Co.	1	\$10.78	\$10.78
9	TEMP36208	Vertical Auger Wdmt - XS ILT	Elmer's Manufacturing	1	\$37.02	\$37.02
9.1	TEMP36207	LH Flighting, Vertical Auger Wdmt - XS ILT	g&h Distributing	1	\$5.38	\$5.38
9.2	TEMP36206	Core Tube, Vertical Auger Wdmt - XS ILT	Elmer's Manufacturing	1	\$15.41	\$15.41
9.3	TEMP34429	Stub Shaft, Auger Wdmt - XS ILT	Elmer's Manufacturing	2	\$5.92	\$11.85
9.4	N/A	Labour Cost	Elmer's Manufacturing	1	\$4.38	\$4.38
10	TEMP36042	Pivot Ring Wdmt - XS ILT	Elmer's Manufacturing	1	\$13.52	\$13.52
10.1	TEMP35987	Tube, Pivot Ring Wdmt - SX ILT	Elmer's Manufacturing	1	\$11.65	\$11.65
10.2	TEMP35985	Frame Mount, Pivot Ring Wdmt - XS ILT	Elmer's Manufacturing	1	\$0.29	\$0.29
10.3	TEMP35986	Auger Mount, Pivot Ring Wdmt - XS ILT	Elmer's Manufacturing	1	\$0.48	\$0.48
10.4	N/A	Labour Cost	Elmer's Manufacturing	1	\$1.10	\$1.10
11	TEMP36229	Cap Screw, Hex Head, #8-32 x 5/8", CZ	McMaster-Carr Supply Co.	50	\$0.12	\$6.06
12	TEMP36228	Hex Nut, #8-32, CZ	McMaster-Carr Supply Co.	50	\$0.02	\$1.01

Table 12. Auger BOM.

Label No.	Part No.	Part Name	Manufacturer	QTY	Unit Cost	Line Cost
13	TEMP3623 6	Spout Rubber - XS ILT	McMaster-Carr Supply Co.	1	\$5.52	\$5.52
14	TEMP3620 5	Drag Auger Wdmt - XS ILT	Elmer's Manufacturing	1	\$29.84	\$29.84
14.1	TEMP3440 2	Core Tube, Drag Auger Wdmt - XS ILT	Elmer's Manufacturing	1	\$4.92	\$4.92
14.2	TEMP3620 4	RH Flighting, Drag Auger Wdmt - XS ILT	g&h Distributing	1	\$10.51	\$10.51
14.3	TEMP3442 9	Stub Shaft, Auger Wdmt - XS ILT	Elmer's Manufacturing	2	\$5.92	\$11.85
14.4	N/A	Labour Cost	Elmer's Manufacturing	1	\$2.57	\$2.57
15	TEMP3623 0	Socket Head Screw, #6-32 x 1/2", CZ	McMaster-Carr Supply Co.	6	\$0.33	\$2.00
16	TEMP3623 2	Spout Linkage - XS ILT	Elmer's Manufacturing	1	\$0.05	\$0.05
NL	10753100	Set Screw, Hex Socket, 1/4 UNF x 3/8, Plain	McMaster-Carr Supply Co.	2	\$0.18	\$0.35
NL	TEMP3623 1	Lock Nut, Nylon Insert, 6-32, CZ	McMaster-Carr Supply Co.	6	\$0.04	\$0.24
					TOTAL	\$423.44

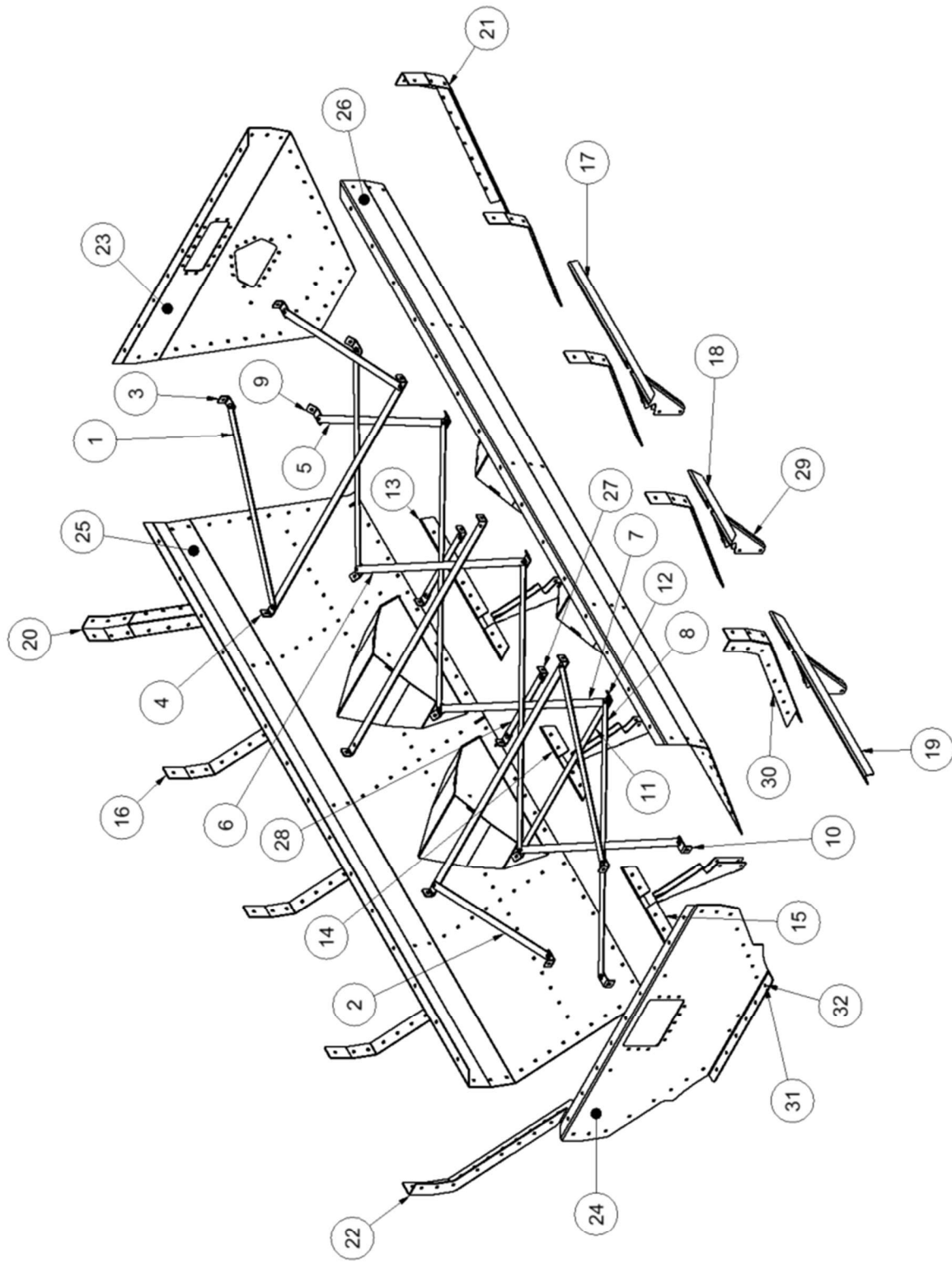


Figure 32. Drawing of tank components

Table 13. Tank BOM.

Label No.	Part No.	Part Name	Manufacturer	QTY	Unit Cost	Line Cost
1	TEMP34354	Cross Member J - Tank - XS ILT	Elmer's Manufacturing	2	\$0.36	\$0.72
2	TEMP34355	Cross Member A - Tank - XS ILT	Elmer's Manufacturing	2	\$0.35	\$0.70
3	TEMP34356	Cross Member Mount A - Tank - XS ILT	Elmer's Manufacturing	4	\$3.28	\$13.13
4	TEMP34357	Cross Member C - Tank - XS ILT	Elmer's Manufacturing	3	\$4.19	\$12.57
5	TEMP34358	Cross Member H - Tank - XS ILT	Elmer's Manufacturing	2	\$0.26	\$0.53
6	TEMP34359	Cross Member G - Tank - XS ILT	Elmer's Manufacturing	2	\$0.35	\$0.69
7	TEMP34360	Cross Member E - Tank - XS ILT	Elmer's Manufacturing	2	\$0.48	\$0.96
8	TEMP34361	Cross Member B - Tank - XS ILT	Elmer's Manufacturing	2	\$0.33	\$0.66
9	TEMP34362	Cross Member Mount E - Tank - XS ILT	Elmer's Manufacturing	2	\$3.28	\$6.56
10	TEMP34365	Cross Member Mount B - Tank - XS ILT	Elmer's Manufacturing	2	\$3.28	\$6.56
11	TEMP34366	Cross Member D - Tank - XS ILT	Elmer's Manufacturing	1	\$0.25	\$0.25
12	TEMP34367	Cross Member Mount D - Tank - XS ILT	Elmer's Manufacturing	6	\$3.28	\$19.65
13	TEMP34368	Mid Seam F - Tank - XS ILT	Elmer's Manufacturing	1	\$4.84	\$4.84
14	TEMP34369	Mid Seam E - Tank - XS ILT	Elmer's Manufacturing	1	\$4.12	\$4.12
15	TEMP34370	Mid Seam D - Tank - XS ILT	Elmer's Manufacturing	1	\$5.11	\$5.11
16	TEMP34371	Vertical Seam - Tank - XS ILT	Elmer's Manufacturing	6	\$4.45	\$26.69
17	TEMP34372	Mid Seam C - Tank - XS ILT	Elmer's Manufacturing	1	\$4.84	\$4.84
18	TEMP34373	Mid Seam B - Tank - XS ILT	Elmer's Manufacturing	1	\$4.12	\$4.12
19	TEMP34374	Mid Seam A - Tank - XS ILT	Elmer's Manufacturing	1	\$5.11	\$5.11
20	TEMP35981	Rear Right Corner Wdmt - Tank - XS ILT	Elmer's Manufacturing	1	\$5.20	\$5.20
20.1	TEMP34375	Rear Right Corner - Rear Right Corner Wdmt - XS ILT	Elmer's Manufacturing	1	\$4.94	\$4.94
20.2	N/A	Labour Cost	Elmer's Manufacturing	1	\$0.26	\$0.26
21	TEMP35980	Rear Left Corner Wdmt - Tank - XS ILT	Elmer's Manufacturing	1	\$6.08	\$6.08
21.1	TEMP34376	Rear Left Corner - Rear Left Corner Wdmt - XS ILT	Elmer's Manufacturing	1	\$4.94	\$4.94
21.2	N/A	Labour Cost	Elmer's Manufacturing	1	\$1.14	\$1.14
22	TEMP35552	Front Right Corner Wdmt - Tank - XS ILT	Elmer's Manufacturing	1	\$5.85	\$5.85

Table 13. Tank BOM.

Label No.	Part No.	Part Name	Manufacturer	QTY	Unit Cost	Line Cost
22.1	TEMP34377	Brkt - Right Front Corner Wdmt - XS ILT	Elmer's Manufacturing	1	\$4.69	\$4.69
22.2	N/A	Labour Cost	Elmer's Manufacturing	1	\$1.15	\$1.15
23	TEMP34381	Rear Wall Panel - Tank - XS ILT	Elmer's Manufacturing	1	\$16.89	\$16.89
24	TEMP34382	Front Wall - Tank - XS ILT	Elmer's Manufacturing	1	\$15.18	\$15.18
25	TEMP34384	Right Wall Wdmt - Tank - XS ILT	Elmer's Manufacturing	1	\$77.77	\$77.77
25.1	TEMP34379	Wheel Well - Wall Wdmt - XS ILT	Elmer's Manufacturing	2	\$6.09	\$12.18
25.2	TEMP34380	Right Wall Panel - Right Wall Wdmt - XS ILT	Elmer's Manufacturing	1	\$30.48	\$30.48
25.3	N/A	Labour Cost	Elmer's Manufacturing	1	\$35.12	\$35.12
26	TEMP34385	Left Wall Wdmt - Tank - XS ILT	Elmer's Manufacturing	1	\$77.77	\$77.77
26.1	TEMP34383	Left Wall Panel - Left Wall Wdmt - XS ILT	Elmer's Manufacturing	1	\$30.48	\$30.48
26.2	TEMP34379	Wheel Well - Wall Wdmt - XS ILT	Elmer's Manufacturing	2	\$6.09	\$12.18
26.3	N/A	Labour Cost	Elmer's Manufacturing	1	\$35.12	\$35.12
27	TEMP34364	Cross Member Mount C - Tank - XS ILT	Elmer's Manufacturing	4	\$3.28	\$13.12
28	TEMP34363	Cross Member F - Tank - XS ILT	Elmer's Manufacturing	2	\$0.10	\$0.20
29	TEMP34386	Faux Support Wdmt - Tank - XS ILT	Elmer's Manufacturing	6	\$4.53	\$27.19
29.1	TEMP34352	Faux Support A - Faux Support Wdmt - XS ILT	Elmer's Manufacturing	1	\$0.24	\$0.24
29.2	TEMP34353	Faux Support B - Faux Support Wdmt - XS ILT	Elmer's Manufacturing	1	\$3.59	\$3.59
29.3	N/A	Labour Cost	Elmer's Manufacturing	1	\$0.70	\$0.70
30	TEMP35551	Front Left Corner Wdmt - XSIL T	Elmer's Manufacturing	1	\$5.85	\$5.85
30.1	TEMP34378	Brkt - Front Left Corner Wdmt - XS ILT	Elmer's Manufacturing	1	\$4.69	\$4.69
30.2	N/A	Labour Cost	Elmer's Manufacturing	1	\$1.15	\$1.15
31	13532400	Lock Nut, Nylon Insert, 10-24, Zinc	McMaster-Carr Supply Co.	305	\$0.04	\$11.44
32	TEMP36212	Carriage Bolt, #10-24 x 3/4", Gr. 2	McMaster-Carr Supply Co.	305	\$0.09	\$26.75
					TOTAL	\$407.16

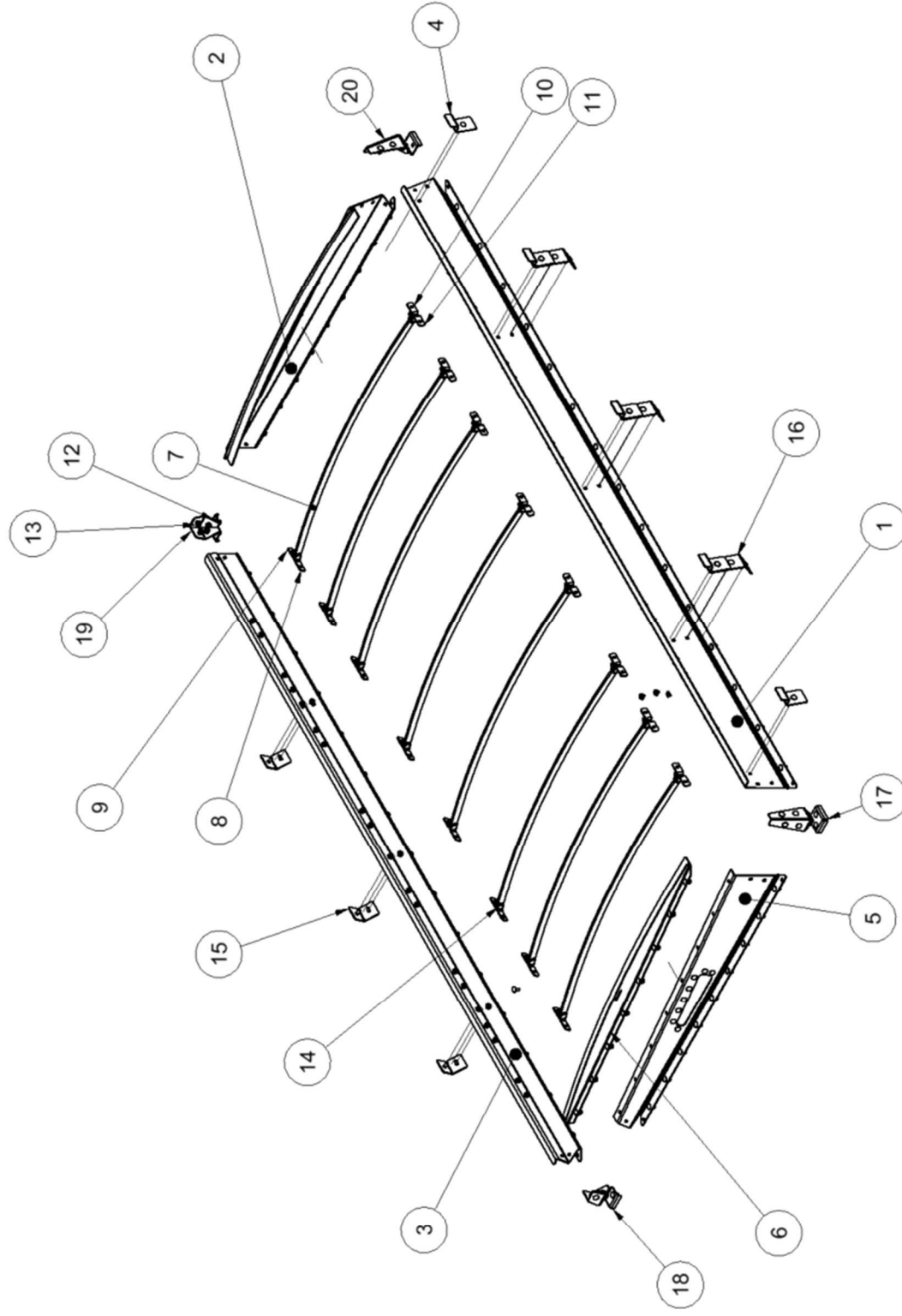


Figure 33. Drawing of tank extension components

Table 14. Tank Extensions BOM.

Label No.	Part No.	Part Name	Manufacturer	QTY	Unit Cost	Line Cost
1	TEMP36133	Extension Panel, Left - XS ILT	Elmer's Manufacturing	1	\$20.92	\$20.92
2	TEMP36135	Extension Panel, Rear - XS ILT	Elmer's Manufacturing	1	\$9.57	\$9.57
3	TEMP36136	Extension Panel, Right - XS ILT	Elmer's Manufacturing	1	\$15.10	\$15.10
4	TEMP36166	Tarp Stop - XS ILT	Elmer's Manufacturing	5	\$3.68	\$18.40
5	TEMP36134	Extension Panel, Front - XS ILT	Elmer's Manufacturing	1	\$9.34	\$9.34
6	TEMP36167	Tarp Hood Wdmt - XS ILT	Elmer's Manufacturing	2	\$9.67	\$19.35
6.1	TEMP36168	Plate A - Tarp Hood Wdmt - XS ILT	Elmer's Manufacturing	1	\$4.17	\$4.17
6.2	TEMP36169	Plate B - Tarp Hood Wdmt - XS ILT	Elmer's Manufacturing	1	\$3.76	\$3.76
6.3	N/A	Labour Cost	Elmer's Manufacturing	1	\$1.75	\$1.75
7	TEMP36142	Tarp Hoop - XS ILT	Elmer's Manufacturing	8	\$1.14	\$9.09
8	TEMP36144	Tarp Hoop Bracket, Right, Front - XS ILT	Elmer's Manufacturing	8	\$3.27	\$26.15
9	TEMP36145	Tarp Hoop Bracket, Right, Rear - XS ILT	Elmer's Manufacturing	8	\$3.27	\$26.15
10	TEMP36146	Tarp Hoop Bracket, Left, Rear - XS ILT	Elmer's Manufacturing	8	\$3.27	\$26.15
11	TEMP36143	Tarp Hoop Bracket, Left, Front - XS ILT	Elmer's Manufacturing	8	\$3.27	\$26.15
12	TEMP36213	Carriage Bolt, #10-24 x 1/2", Gr. 2	McMaster-Carr Supply Co.	144	\$0.06	\$8.02
13	13532400	Lock Nut, Nylon Insert, 10-24, Zinc	McMaster-Carr Supply Co.	163	\$0.04	\$6.11
14	TEMP36212	Carriage Bolt, #10-24 x 3/4", Gr. 2	McMaster-Carr Supply Co.	19	\$0.09	\$1.67
15	TEMP36165	Extension Seam Plate, Right - XS ILT	Elmer's Manufacturing	3	\$3.39	\$10.16
16	TEMP36163	Extension Seam Plate, Left - XS ILT	Elmer's Manufacturing	3	\$3.50	\$10.49
17	TEMP36200	Extension Corner Seam Wdmt, Left, Front - XS ILT	Elmer's Manufacturing	1	\$10.52	\$10.52
17.1	TEMP36147	Plate A - Corner Seam Wdmt - XS ILT	Elmer's Manufacturing	1	\$3.56	\$3.56
17.2	TEMP36148	Plate C - Corner Seam Wdmt - XS ILT	Elmer's Manufacturing	1	\$3.33	\$3.33
17.3	TEMP36157	Plate E - Corner Seam Wdmt - XS ILT	Elmer's Manufacturing	1	\$3.34	\$3.34
17.4	N/A	Labour Cost	Elmer's Manufacturing	1	\$0.29	\$0.29

Table 14. Tank Extensions BOM.

Label No.	Part No.	Part Name	Manufacturer	QTY	Unit Cost	Line Cost
18	TEMP36201	Extension Corner Seam Wdmt, Right, Front - XS ILT	Elmer's Manufacturing	1	\$10.36	\$10.36
18.1	TEMP36159	Plate G - Corner Seam Wdmt - XS ILT	Elmer's Manufacturing	1	\$3.30	\$3.30
18.2	TEMP36160	Plate H - Corner Seam Wdmt - XS ILT	Elmer's Manufacturing	1	\$3.30	\$3.30
18.3	TEMP36150	Plate B - Corner Seam Wdmt - XS ILT	Elmer's Manufacturing	1	\$3.56	\$3.56
18.4	N/A	Labour Cost	Elmer's Manufacturing	1	\$0.20	\$0.20
19	TEMP36202	Extension Corner Seam Wdmt, Right, Rear - XS ILT	Elmer's Manufacturing	1	\$10.36	\$10.36
19.1	TEMP36161	Plate I - Corner Seam Wdmt - XS ILT	Elmer's Manufacturing	1	\$3.30	\$3.30
19.2	TEMP36162	Plate J - Corner Seam Wdmt - XS ILT	Elmer's Manufacturing	1	\$3.30	\$3.30
19.3	TEMP36147	Plate A - Corner Seam Wdmt - XS ILT	Elmer's Manufacturing	1	\$3.56	\$3.56
19.4	N/A	Labour Cost	Elmer's Manufacturing	1	\$0.20	\$0.20
20	TEMP36203	Extension Corner Seam Wdmt, Left, Rear - XS ILT	Elmer's Manufacturing	1	\$10.52	\$10.52
20.1	TEMP36149	Plate D - Corner Seam Wdmt - XS ILT	Elmer's Manufacturing	1	\$3.33	\$3.33
20.2	TEMP36158	Plate F - Corner Seam Wdmt - XS ILT	Elmer's Manufacturing	1	\$3.34	\$3.34
20.3	TEMP36150	Plate B - Corner Seam Wdmt - XS ILT	Elmer's Manufacturing	1	\$3.56	\$3.56
20.4	N/A	Labour Cost	Elmer's Manufacturing	1	\$0.29	\$0.29
TOTAL					\$208.68	

Table 15. Hitch BOM.

Label No.	Part No.	Part Name	Manufacturer	QTY	Unit Cost	Line Cost
1	TEMP34455	Top Plate - Hitch - XS ILT	Elmer's Manufacturing	1	\$1.02	\$1.02
2	TEMP34456	Slider Plate - Hitch - XS ILT	Elmer's Manufacturing	2	\$3.40	\$6.81
3	TEMP34457	Outer Mount Plate - Hitch - XS ILT	Elmer's Manufacturing	2	\$0.39	\$0.78
4	TEMP34458	Inner Plate - Hitch - XS ILT	Elmer's Manufacturing	2	\$4.01	\$8.03
5	TEMP34468	Hitch Wdmt - XS ILT	Elmer's Manufacturing	1	\$77.87	\$77.87
5.1	TEMP34460	Rear Right Tube - Hitch Wdmt - XS ILT	Elmer's Manufacturing	1	\$13.08	\$13.08
5.2	TEMP34462	Front Right Tube - Hitch Wdmt - XS ILT	Elmer's Manufacturing	1	\$13.93	\$13.93
5.3	TEMP34453	Puck Tray - Hitch Wdmt - XS ILT	Elmer's Manufacturing	1	\$4.11	\$4.11
5.4	TEMP34454	Spacer Bar - Hitch Wdmt - XS ILT	Elmer's Manufacturing	1	\$1.80	\$1.80
5.5	TEMP34463	Rear Left Tube - Hitch Wdmt - XS ILT	Elmer's Manufacturing	1	\$13.08	\$13.08
5.6	TEMP34461	Front Left Tube - Hitch Wdmt - XS ILT	Elmer's Manufacturing	1	\$13.93	\$13.93
5.7	TEMP34452	Hitch Receiver - Hitch Wdmt - XS ILT	Elmer's Manufacturing	1	\$11.82	\$11.82
5.8	TEMP34467	Front Plate - Hitch Wdmt - XS ILT	Elmer's Manufacturing	1	\$0.25	\$0.25
5.9	TEMP34459	Chain Mount - Hitch Wdmt - XS ILT	Elmer's Manufacturing	2	\$0.01	\$0.01
5.10	N/A	Labour Cost	Elmer's Manufacturing	1	\$5.86	\$5.86
6	TEMP34469	Drawbar Wdmt - XS ILT	Elmer's Manufacturing	1	\$0.57	\$0.57
6.1	TEMP34464	Hole Plate - Drawbar Wdmt - XS ILT	Elmer's Manufacturing	1	\$0.30	\$0.30
6.2	TEMP34466	Bottom Spacer - Drawbar Wdmt - XS ILT	Elmer's Manufacturing	2	\$0.02	\$0.04
6.3	N/A	Labour Cost	Elmer's Manufacturing	1	\$0.23	\$0.23
7	10752800	Cap Screw, Hex Head, Gr 5, 1/4 UNC x 1-3/4, YZ	McMaster-Carr Supply Co.	1	\$0.04	\$0.04
8	10736200	Flange Nut, Top Lock, Gr F, 1/4 UNC, YZ	McMaster-Carr Supply Co.	1	\$0.04	\$0.04
9	10704200	Cap Screw, Hex Head, Gr 5, 3/8 UNC x 2, YZ	McMaster-Carr Supply Co.	2	\$0.15	\$0.30
10	13625400	Flange Nut, Top Lock, Gr F, 3/8 UNC, YZ	McMaster-Carr Supply Co.	2	\$0.07	\$0.15
11	13682000	Flat Washer, SAE, 3/8, YZ	McMaster-Carr Supply Co.	8	\$0.01	\$0.09

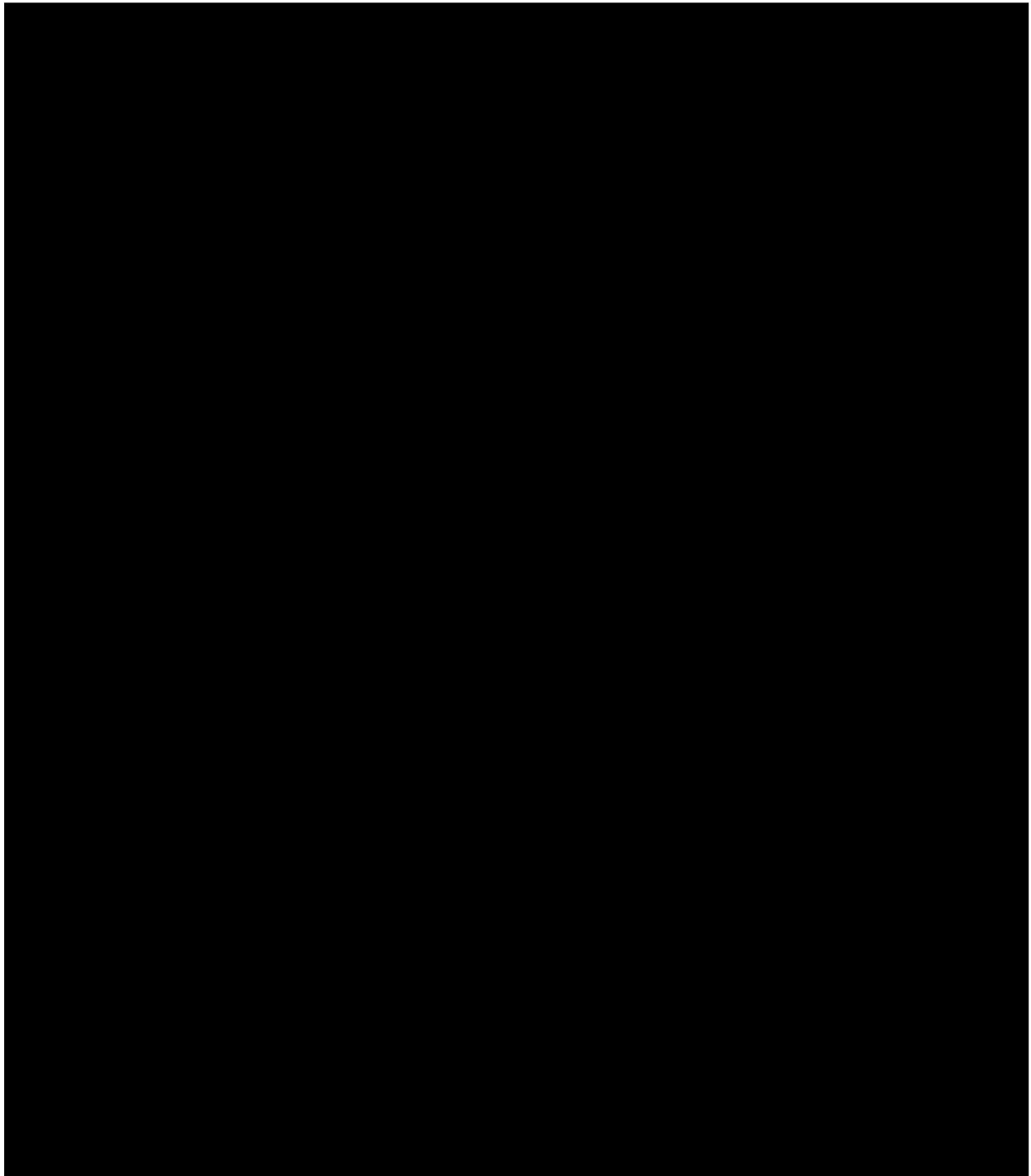
Table 15. Hitch BOM.

Label No.	Part No.	Part Name	Manufacturer	QTY	Unit Cost	Line Cost
12	TEMP34434	Load Cell - 50KG	Flintec Inc.	1	\$91.29	\$91.29
13	TEMP34412	Load Cell Spacer - XS ILT	Elmer's Manufacturing	1	\$0.14	\$0.14
14	TEMP34436	Lock Nut, Nylon Insert, M8x1, Gr. 8	McMaster-Carr Supply Co.	2	\$0.36	\$0.71
15	TEMP34437	Cap Screw, Hex Head, M8x1 x 35mm, Gr. 8.8	McMaster-Carr Supply Co.	2	\$0.53	\$1.07
16	TEMP34450	Lock Nut, Nylon Insert, #5-40	McMaster-Carr Supply Co.	18	\$0.04	\$0.76
17	TEMP34470	Screw, Pan Head, #5-40 x 2", CZ	McMaster-Carr Supply Co.	4	\$0.31	\$1.24
18	TEMP34472	Swivel Caster Wheel, 50mm OD, 5537T314	McMaster-Carr Supply Co.	1	\$13.56	\$13.56
19	TEMP34474	Hex Thread Adapter, M6x1.0 - M8x1.0	McMaster-Carr Supply Co.	1	\$13.24	\$13.24
20	TEMP34475	Cap Screw, Hex Head, M8x1.0 x 20mm, Gr. 10.9, YZ	McMaster-Carr Supply Co.	1	\$0.26	\$0.26
21	TEMP34476	Cap Screw, Hex Head, #10-24 x 5/8", CZ	McMaster-Carr Supply Co.	10	\$0.12	\$1.22
22	TEMP34477	Screw, Pan Head, #5-40 x 1-1/4"	McMaster-Carr Supply Co.	8	\$0.12	\$0.97
23	TEMP34449	Button Head Screw, #5-40 x 1/2"	McMaster-Carr Supply Co.	6	\$0.05	\$0.31
24	13532400	Lock Nut, Nylon Insert, 10-24, Zinc	McMaster-Carr Supply Co.	10	\$0.04	\$0.38
NL	TEMP34473	Washer, M6, CZ	McMaster-Carr Supply Co.	7	\$0.02	\$0.13
TOTAL					\$220.97	

Appendix C –Sensor Information

This section contains specifications regarding the load cell used in the undercarriage and hitch. Both subsystems will utilize the Flintec ZLS planar beam 50 kg (110 lb) load cell. The technical specifications of this load cell are shown in Table 16.

Table 16: Technical specifications of the Flintec ZLS planar beam load cell [14].

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The dimensions of the Flintec ZLS planar beam load cell are shown in Fig. 35.

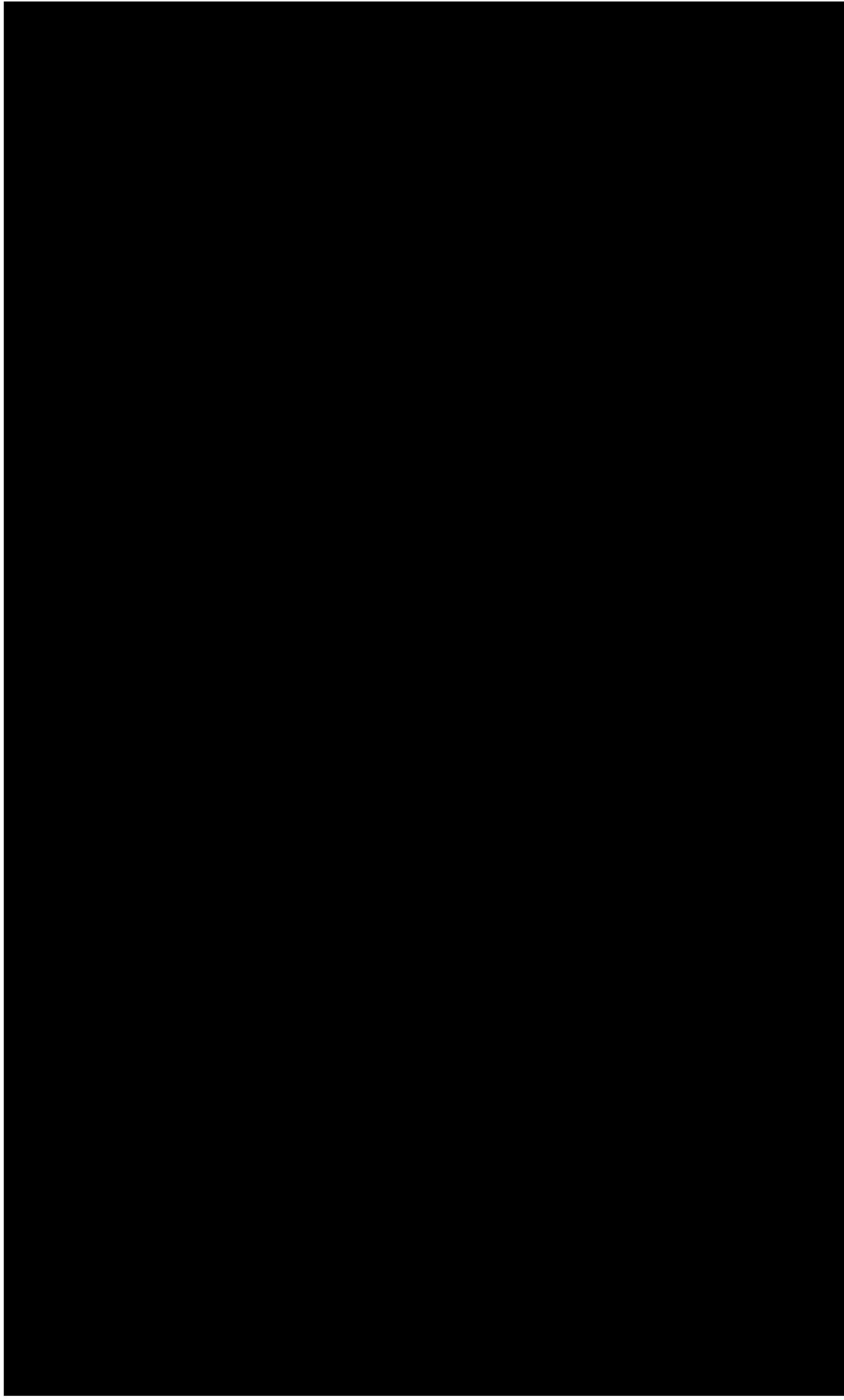


Figure 35. Dimensions of the Flintec ZLS planar beam load cell [16].

The wiring diagram of the Flintec ZLS planar beam load cell is shown in Fig. 36.

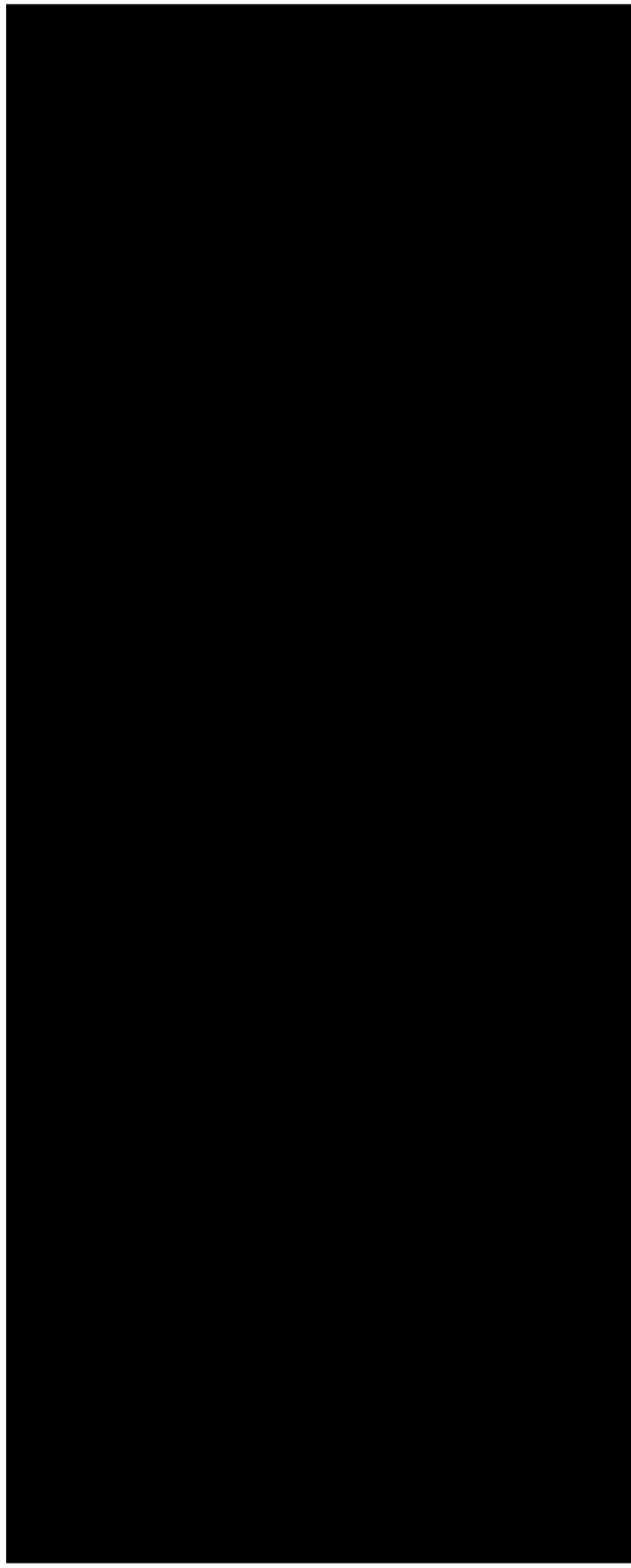


Figure 36. Wiring diagram of Flintec ZLS planar beam load cell [16].

Appendix D –Load Calculations

This appendix contains information regarding how the estimated load on the undercarriage support bar, as well as the load capacity of the load cells utilized in the undercarriage, were calculated.

Load requirement of undercarriage support bar

The undercarriage support bar was designed near the beginning of the term, with little design data to base load estimates from. Due to this, the undercarriage support beam was designed to support a maximum possible load estimate made before any parts were created, calculated as follows:

Maximum weight of 1/6th scale grain cart (S2.1):

1200 lb

Capacity of full-scale Haulmaster 2500:

2500 bushels

Estimated capacity of 1/6th scale Haulmaster 2500, as it is being scaled down in all three dimensions:

$2500 \text{ bushels} / 6^3 = 11.6 \text{ bushels}$

Average weight of bushel of wheat:

60 lb/bushel [17]

Estimated maximum weight of grain in 1/6th scale Haulmaster 2500:

$11.6 \text{ bushels} * 60 \text{ lb/bushel} = \mathbf{696 \text{ lb}}$

Total preliminary estimated max weight: $1200 \text{ lb} + 696 \text{ lb} = 1896 \text{ lb}$

Since the max empty tongue weight of 200 lbs (S2.2), was six times smaller than the max empty grain cart weight of 1200lbs, it was assumed that 1/6 of the total weight would be carried by the hitch. This leads to the following:

$\text{Load carried by tires} = 1896 \text{ lb} * (5/6) = 1580 \text{ lb}$

$\text{Load carried per tire} = 1580 / 4 = 395 \text{ lb}$

Since this was a rough estimate, and the grain cart may be subjected to impact when rolling on uneven ground or when being lifted in and out of truck/trailer, a factor of safety (FOS) of 1.9 was applied. This leads to the following load requirement per tire:

$$\text{Load requirement per tire} = \text{Load carried per tire} * \text{FOS} = 395 \text{ lb} * 1.9 = 750 \text{ lb}$$

The undercarriage was designed to support a design load of **750 lb per tire**. It should be reiterated that this value was chosen very early on in the design process based on a preliminary estimate. This was acceptable because an overdesign of this support bar would not be detrimental to the design.

Load capacity of undercarriage load cell

The load cells for the undercarriage were selected much later in the design process, after many parts had been modeled. Autodesk inventor was used to estimate the weight of all designed parts, and estimates were made for all other components based on past experience. When values were hard to estimate, overestimates were made. The estimated design loads used to choose the undercarriage load cells can be seen in Table 17.

Table 17. Estimated weight of grain cart components in initial design

Item	Estimated Weight (lb)
Mainframe	37
Undercarriage	21.5
Auger	30
Tank	155
Hitch	10.8
Sensors/Actuators	10
Motors	10
Wheels	20
Hardware	50
Auger Flighting	50
TOTAL	394.3

This total load was multiplied by 5/6, due to the estimated hitch support and then divided by 4 to get the load per load cell:

$$\text{Estimated weight per load cell} = 394.3 \text{ lb} * (5/6) / 4 = 82.1 \text{ lb per load cell}$$

Again, a safety factor of 1.9 was used to account for impact loading, leading to the design load per load cell.

Design load per load cell = $82.1 * 1.9 = \mathbf{156\ lb}$

After discussion with the client, it was decided that this design load was too high as the only available load cell to handle this weight had a capacity of 100 kg (220 lb). Since the estimate was an overestimate, and the factor of safety was very high for this application, the actual load experienced by the load cells is likely normally $< 82.1\ lb$. This would have been in the low range of the 220 lb load cell capacity, and it is important to select a load cell that has a load capacity close to the maximum load it will experience, so that the voltage output of the load cell can be the most sensitive and accurate to the loads.. Since an issue caused by under-design of the load cells would not lead to safety issues, it was determined that a 50 kg load cell would suffice, giving the readings more sensitivity. The load selected was the **50 kg (110 lb) Flintec ZLS planar beam load cell**.