Tree Seedling Planter

A Major Qualifying Project

Submitted to the Faculty of

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Abstract

The goal of this project was to design a trailer mechanism that transplants two-year-old evergreen saplings with minimal human input. The mechanism automates the processes of digging holes, planting saplings, and refilling the holes. To dig the hole, a four-bar linkage with a dibble on the end intermittently pierces conical holes into the ground. The saplings are held in a hopper and individually separated by an arm on a linkage that places saplings into the holes. Finally, two angled wheels on the rear of the trailer refill the holes with surrounding dirt. These systems were designed to operate synchronously using the torque generated by the trailer wheels. Future research could use this information to actualize the transplanting mechanism.

2

Table of Contents

3

5

Table of Figures and Charts

Figures:

Tables:

I. Introduction

Each year, almost 15,000 tree farms sell over 25 million evergreen trees during the holiday season (National Christmas Tree Association). The farms vary in size and can either offer pre-cut or cut-your-own trees. However, all these farms rely on new saplings being planted each year to replenish their supply. These trees typically take seven years to grow to their average selling height of six feet (Weir Tree Farms), so farmers must plan well in advance to succeed.

Many of these farms are low-acreage and family-owned. Due to the long growing process, farms typically grow their trees in stages to have a continuous supply of trees that are ready to harvest. To save valuable land space, the first two years of growth are done off-site and the young evergreen saplings are then transplanted onto the local farms. The typical process for growing evergreens is as follows:

1. Seeds are harvested from pine cones.
2. Seeds are planted in fertilized ground in the fall and grow there for two years.
3. Seedlings are transplanted to a larger field to grow for another two years.
4. Saplings are uprooted and planted in their final location. They grow there for 7-10 years, until ready harvest. They are trimmed and fertilized yearly.

This method of harvesting and transplanting has been around for over a century (Michigan Christmas Tree Association). As with most sectors, some tree farmers are looking more to automation as a means to secure their ability to stay active and competitive. Owners of a Massachusetts farm have found there are fewer workers available to them than in the past, spurring their interest in automation (Ellsworth Farm, personal communication, Oct. 2019).

Years of work and innovation in the industry has yielded machinery designed to speed up this process. Many farms utilize specialty trailers pulled behind a tractor to transplant the saplings. The trailers plow trenches where workers then plant the saplings. Afterwards, the trailer recompacts the soil around the saplings. Currently, there is no completely automated planting

mechanism for these saplings. Existing designs have workers sit on the trailer to separate and place the saplings manually. While these trailers are more time-efficient than completely manual planting, they still require several people to operate. Our project goal is to completely mechanize the transplanting process where saplings of about two years old are transplanted into their final growing location. Our projected market for the automated mechanism is for tree farms up to 25 acres, given a 5 foot spacing for each .

II. Background

Although there are some semi-autonomous sapling planters on the market, all still require human operators for the separation and planting operations. A majority of the simpler tasks in the planting process, such as digging and refilling the holes, is done automatically by the machine. Separating and planting individual saplings into the holes is still a human dependent process, however, as many machines will have the trees loaded in random orientations which are sorted tree-by-tree in the planting process. Most planters on the market use a plow to create a continuous trench in the ground (Figure 1). A human operator separates a single tree from the hopper and places it in the trench. Although some planters have an automatic planting mechanism, humans are still required to separate the randomly oriented saplings and insert them uniformly into the planting mechanism. After being placed in the ground, angled wheels pack the soil around the newly planted tree. These machines can typically plant on the order of 1200 saplings in an hour (Yancheng Jiangyang Machinery Company).

Figure 1: Typical mechanical tree seedling transplanter (Mechanical Transplanter Company)

There is still room for improvement with the current devices. The plows they use create holes easily, but disturb more soil than necessary, which is detrimental to the soil (Napper et. al). They can also get caught or disjointed from the ground in soil with rocks, roots, and variable

9

inclines. While generally effective, plows excessively damage the soil and do not work in all conditions. Further, these planters still require humans to separate individual saplings from the hoppers and place them into the feed wheel or directly into the ground. While other completely automatic seedling planters exist, they are not suitable for the intended use environment or functionality of this project.

In the rice farming industry, planting machines can complete all steps of the planting process automatically. Rice shoots are placed into a hopper in the back of the machine and individually planted by the machine. These machines are self-powered with just a driver operating the tractor. These machines can be completely automatic due to the available packing of rice seedlings and minimal variability of ground conditions and rice shoots. Softer soil and more uniform seedlings allow for the digging and planting process to be completed in one motion with high repeatability. Due to the irregular nature of evergreen trees and harder soil, the mechanisms utilized in rice planters cannot be directly retrofitted to plant trees. However, the designs of these existing machines can be adapted to improve tree seedling planting.

Figure 2: Rice Planter (Nairaland)

One benefit of designing farming equipment is that it heavily relies on the use of repetitive motion. Repetitive motion is best accomplished using simple mechanisms that can be powered with a simple rotary motion. Successful farming is very dependent on production volume, so the faster and more efficiently these tasks can be done, the better. Another major consideration when designing farm equipment is durability: these machines are often exposed to dirt, rocks, roots, water, and general abuse. To avoid issues, it is best practice to have as few moving parts as possible. The parts that do move need to be simple and easy to repair. Industrial farming technology has improved over the past decades with robotics and electronics, but some simple mechanisms have proven to be robust and effective.

Four-bar linkages are some of the most common mechanisms used to create simple repetitive motion. These mechanisms are relatively simple to design, manufacture and maintain. They can be designed to create a wide variety of motion curves which can be customized to perform many tasks on a farm. Additionally, these mechanisms can be designed to have a "quick-return" where certain areas of the travel path have the coupler moving faster than others. This can be beneficial in applications where the actuator needs to get out of the way quickly to allow for other operations to occur. A common and repetitive task performed on most produce farms is the displacement of dirt. A plow can be used to accomplish this with no moving parts: by using two combined inclined planes, dirt can be pushed aside to make a consistent rut in the ground for planting. Similarly, two opposing inclined planes can be used to push dirt back into the hole over the newly planted seeds. Finally, most farming processes require some sort of material (seeds, fertilizer, or water) to be distributed at regular intervals. This is done with hoppers that can both store and distribute the materials as the equipment makes its way down the field. These hoppers allow for the machine to carry enough material to work for extended periods of time without being refilled.

To accomplish the task of making a mechanized tree seedling planter, our team created several functional requirements necessary to create an effective machine that will be more efficient than conventional methods. The full list of functional requirements is shown in Appendix A.

11

III. Design Concepts

To create the best final product, the tree transplanting mechanism is split into its four functions: sapling preparation, hole creation, sapling placement, and soil compaction. Potential mechanisms for each function were researched and brainstormed. Following the final selection of each design, the chassis was designed around the needs of the chosen mechanisms.

Sapling Preparation

There are two main operations in the sapling preparation process: storage and separation. The seedlings are stored in a hopper of some sort, from which they are individually transferred to the placement mechanism. The four design options considered for storing the seedlings are a bin, rail system, discrete tubes, and a vertical narrowing hopper. They are described below:

1. Bin
    a. A box attached to the trailer holds the trees dumped in any orientation
2. Rail System (Figures 3 and 4)
    a. A linear rail system holds the seedlings. A plate on the bottom prevents them from falling through. There is a small hole in the plate and a gap in the rails at the end. A V-shaped clamp, driven by a crank and rocker mechanism, moves between the gap in the rails at the end, clamping down on a tree, and carries it through the hole in the bottom plate. The rails extend downward to keep clamping pressure on the tree until it reaches the hole where it is subsequently released. The clamp is made with a torsional spring with the grippers attached to each leg to allow it to open again after exiting the rail system.

Figure 3: Rail System Isometric View
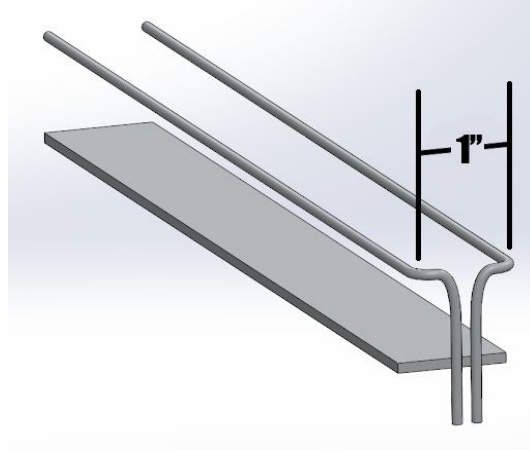

Figure 4: Rail System Side View

3. Discrete Tubes (Figure 5)

    a. An operator loads the trees individually into a rectangular, horizontal belt-like arrangement of tubes before planting begins. The trees fall from the bottom of the black tube, into the placement mechanism. The tube arrangement is propelled by the rotating gear in the corner.
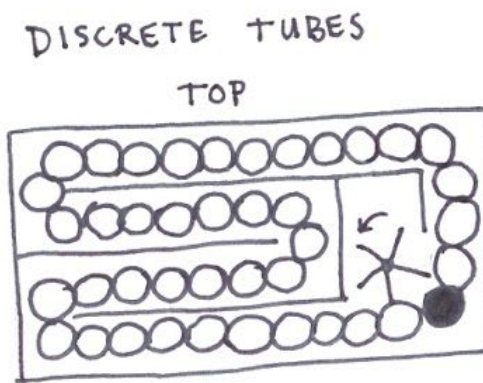
Figure 5: Discrete Tubes

4. Vertical Narrowing Hopper (Figure 6)

   a. The trees are all loaded horizontally into a triangular bin with the roots facing the same direction. The angled side of the bin is a conveyor belt with teeth that drag the trees through a slot in the bottom.
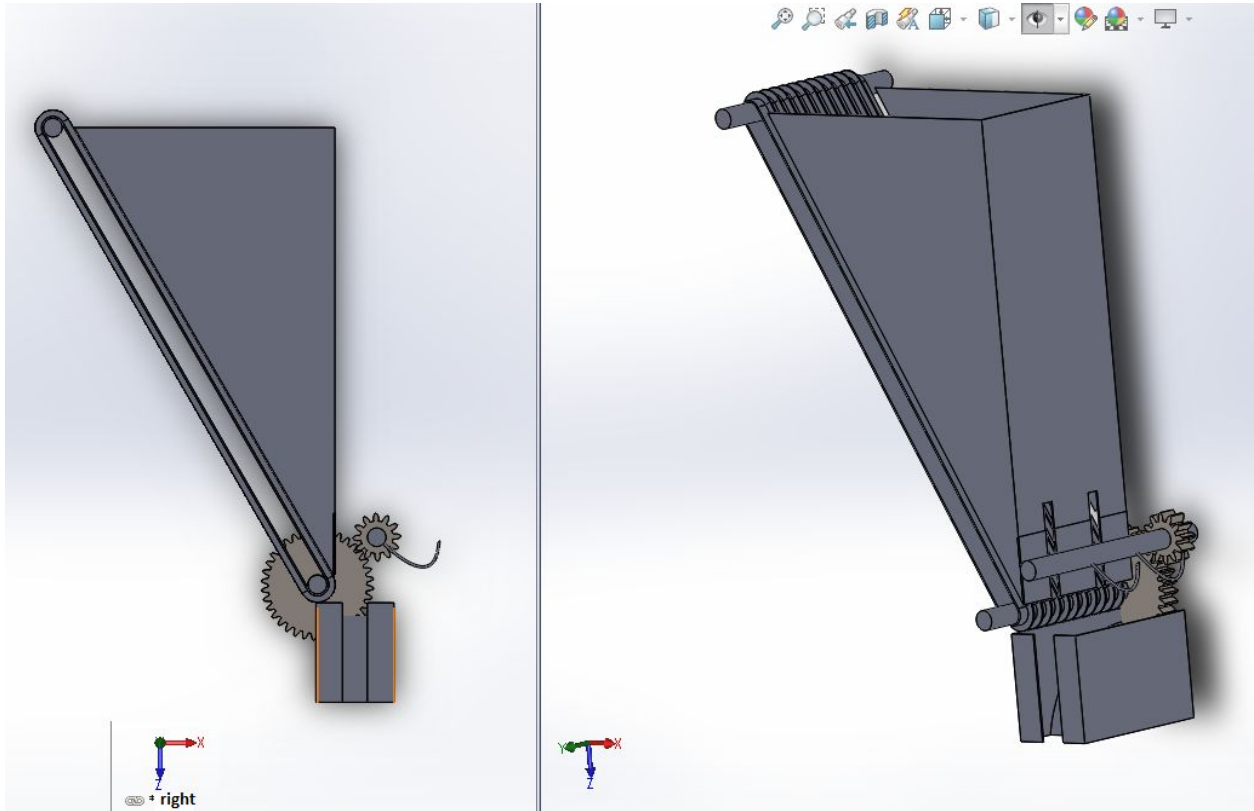
Figure 6: Vertical Narrowing Hopper

The three potential designs for transferring the sapling to the planting mechanism are a spring clamp system, a small displacement hook system, and a rotational hook system.

1. Spring Clamp System (Figure 7)

   a. Two plates spring apart because of a torsional spring unless they are held closed around the tree by a rail system. The plates are attached to a rotating component as they cut into the dirt. They can also be attached to the end of a four-bar linkage. Spring clamps are commonly used to hold tree seedlings in other applications.

14

Figure 7: Spring Clamp

2. Small Displacement Hook System (Figure 8)

    a. A four-bar linkage moves a set of hooks back and forth. It hooks trees out of the bin into a space that is easily accessed by the placement mechanism.
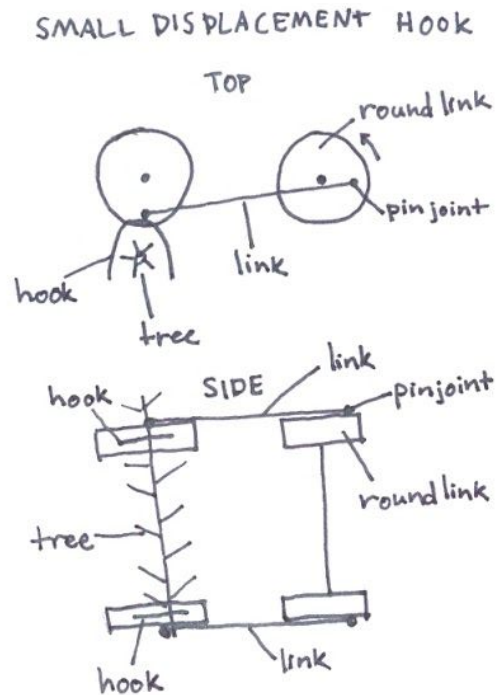
Figure 8: Small Displacement Hook System

3. Rotational Hook System (Figure 9)
    a. Hooks rotate about a rod to pull trees out of the bin and into a space easily accessible by the placement mechanism.
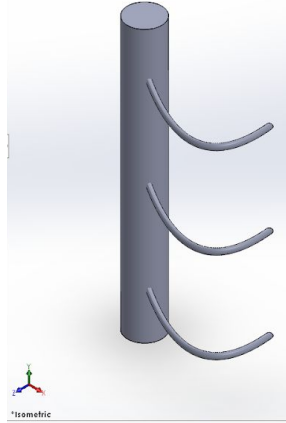
Figure 9: Rotating Hooks

Hole Creation

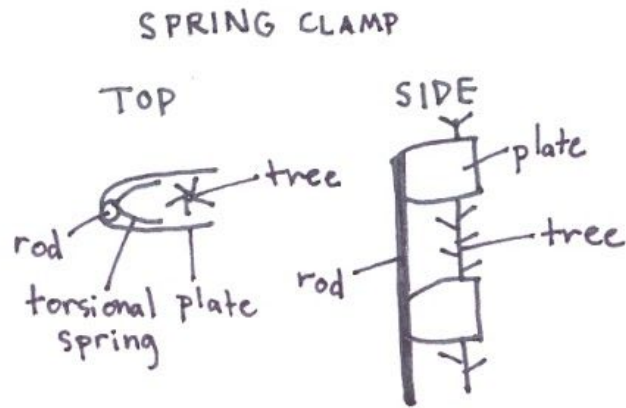Three options for a hole-digging mechanism were considered: a plow, digging iron, and reverse-post hole digger.

1. Plow
    a. A wedge sunk into the ground is pulled through the soil by tractor to create a trough shaped hole for a tree. A plow is already well proven in many farming applications.

2. Digging Iron
    a. A sharp iron cone stabs into the ground to create wedge shaped holes at intervals. A crank-rocker four-bar linkage pushes a wedge into the ground, pivots in the ground to open the hole wider, then exits (Figure 10). Depending on wedge width, this could also be constructed with the triangular face of the wedge normal to the direction of motion, allowing for different soil packing options after the digging operation. The linkage could be designed to run intermittently to dig holes quickly at desired intervals, ensuring the device is not excessively raked through the ground.
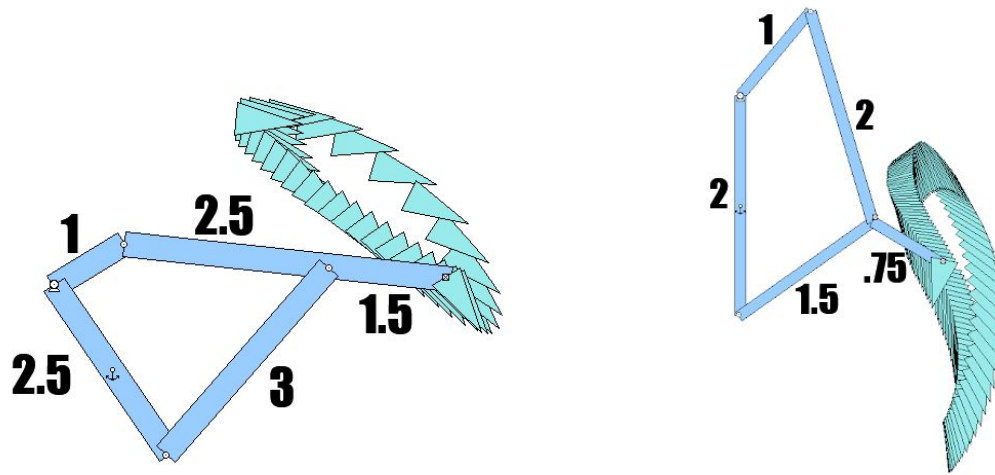
Figure 10: Digging Iron Wedge motion path

3. Reverse Post-Hole Digger (Figure 11)

    a. Two plates at the end of links attached to a slot create a wedge-shaped hole. The sapling falls between plates directly into hole as the plates lift out from the ground.
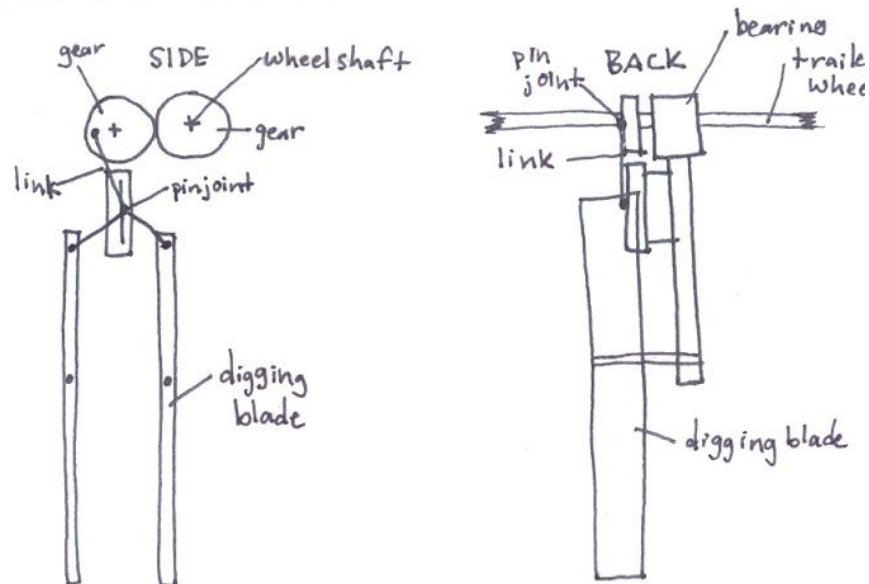
Figure 11: Reverse Post-Hole Digger

Tree Placement

Three options for a mechanism that will place the tree in the ground were considered: a four-bar linkage, a rotating spring clamp, and a chute drop. These designs were required to plant trees with bare roots.

1. Four-Bar Linkage (Figure 12)
    a. This linkage operates intermittently with a spring clamp on the end of the coupler of a crank-rocker four-bar linkage that holds the tree and places it in the ground.
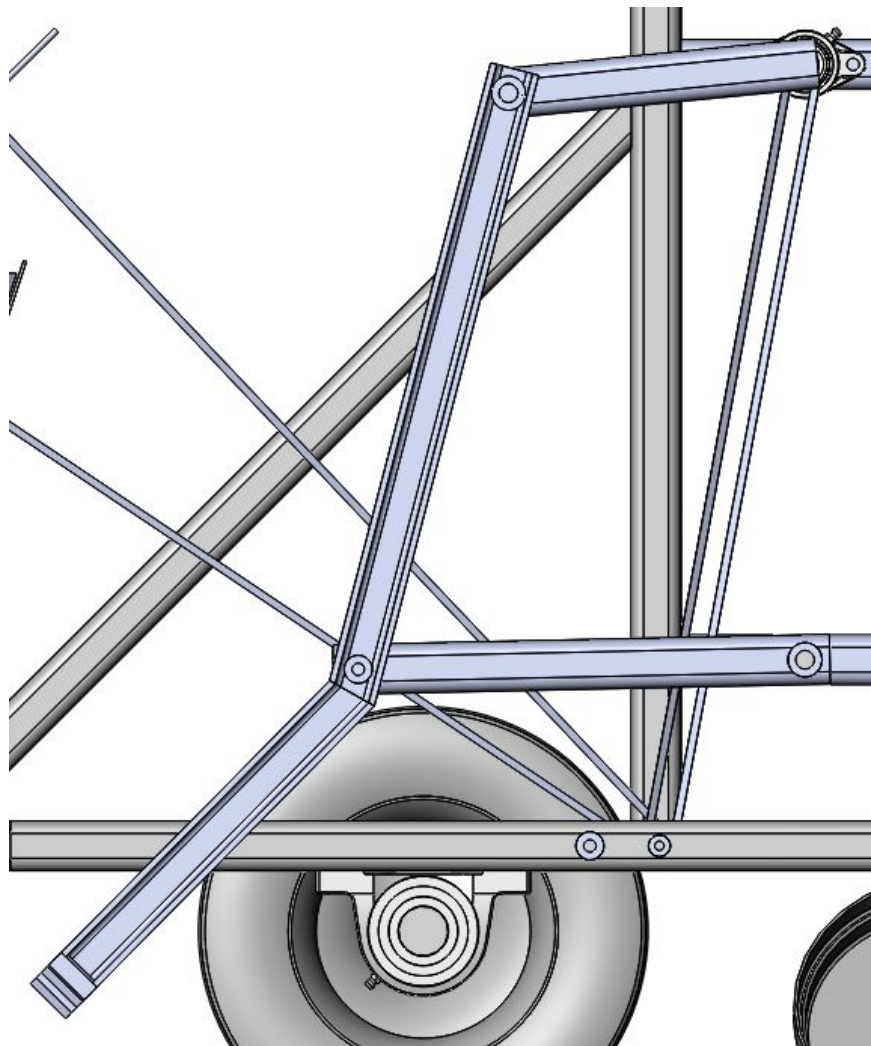
Figure 12: Four-Bar Linkage Tree Placer

2.   Rotating Spring Clamp (Figure 13)

   a.   This is the design commonly used in existing tree planting mechanisms. The
        spring clamps pinch the length of the tree. They are usually loaded by a human
        operator. The clamps rotate continuously to place trees in the ground, typically at
        shorter intervals.

Figure 13: Rotating Spring Clamp (Market Farm)

3.   Chute Drop (Figure 14)

   a.   Trees are held in a chute after being removed from the bin. They are released
        from the chute when the bottom circle rotates out of the way. Chute must be close
        to the ground to ensure trees fall into the hole.
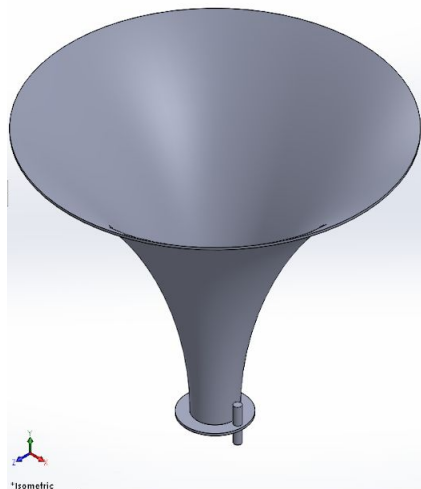
Figure 14: Chute Drop

19

Pack Soil

Three possible methods of packing the soil back into place once the plant has been placed in the ground were considered: angled wheels, an impact mechanism, and a tilting shovel.

1. Angled Wheels (Figure 15)
   a. The commonly practiced method of packing soil after the tree is placed. Two wheels at the back of the trailer are on angled axles to push soil towards the base of the tree. The tree passes between the wheels.

Figure 15: Angled Wheels (Kelco Industries)

2. Impact Mechanism
   a. Acts like a heavy foot to pack the soil down around the tree. It lifts above the tree then stomps down on the soil to compact it. The mechanism of it has a similar design to the digging iron, except with a heavy weight on the bottom.
3. Tilting Shovel
   a. Similar to the digging iron, the shovel slices into the ground beside the tree. It pushes the soil towards the tree, which opens another hole.

IV. Design Selection

A design matrix was created for each of the functions. The designs were rated according to the following system:

Rating	Meaning
0	Antithetical to requirements
1	Doubtful if fulfills requirements
2	Could fulfill requirement with effort
3	Fulfills requirements
4	Exceeds requirements

Table 1: Design Matrix Rating Explanation

Weight values of one through three were assigned to functional requirements and modulate these rating values. A higher weight means it is more important for the design to fulfill the requirement. All the designs are rated on their size, weight, manufacturability, cost, projected failure rate, and durability. Projected failure rate is weighted the most because the planting mechanism cannot be considered helpful if it does not function the majority of the time. Cost and manufacturability are important factors for us since we are creating a prototype and have a finite budget. A tree farmer might reasonably prioritize durability as well.

The design matrices for each task are in Appendix B-F. The highest rated design is described in each section below.

Tree Storage

The best design for tree storage is the vertical narrowing hopper. It is very important that the bin be able to transition the trees to tree placement. The regular bin would need a mechanical arm with the ability to identify and pick up an individual tree. At that point, a human operator would be more feasible. The rail system and discrete tubes do not have the tree capacity to make the planting mechanism better than a person walking and planting trees with a dibble.

Tree Transfer

The spring clamp is the best method of holding the trees to transfer them. The constant clamping pressure applied to the tree throughout the transfer process by the clamp ensures the motion of the tree is more controlled than the relatively loose motion of the trees suspended and guided by the hooks.

Hole Creation

The digging iron is best for creating holes because of the precise hole that it makes. It can be used in most soil types found at tree farms. The reverse post-hole digger is a similar idea, but much more complex and more likely to fail than the digging iron.

Tree Placement

The ideal tree placing mechanism is a four-bar linkage. It can place the tree relatively upright in the hole with the same timing as the digging mechanism and can perform the action cyclically with relative ease. The chute drop has a high probability that the tree's roots will get caught somewhere and the tree will not reach the ground. The rotating spring clamp is more complex to manufacture.

Soil Packing

Angled wheels were determined to be the best choice to pack the soil because of their simplicity and durability. The stomping mechanism has a higher chance of harming the seedling if it is planted crookedly. The tilting shovel would be another linkage mechanism that takes up significant space on the trailer. The main weakness with the angled wheel design is that the hole may not be completely closed at the end. This is acceptable because the hole will close after the seedling has been watered.

Final Design Selection

The final design includes a vertical narrowing hopper, a digging iron, a spring clamp on the end of a four-bar linkage, and angled wheels. The tree begins placed horizontally in the vertical narrowing hopper. The spring clamp at the end of the four-bar linkage grabs the tree from the bottom of the hopper. The digging iron wedges a hole in the ground. The tree is placed in the hole as the trailer moves forward. Finally, the angled wheels push soil back into the hole to cover up the roots. These components must all fit on a trailer pulled by a tractor. This set of components can all function together in series. These components will most securely deliver the tree from the hopper into the soil.

V. Synthesis and Analysis

Following the design of the full mechanism, multiple key components were analyzed to determine their required driving forces, potential stresses induced, and areas where the design could be improved. Much of this analysis was done by hand and is dependent on the final design of the device. However, this analysis allowed for our team to effectively evaluate our first designs.

Digging Force

One of the calculations most fundamental to the operation of the device is the amount of force that can be applied during the digging operation before the device fails. Failure could occur by wheel slippage, instability of the trailer, or mechanical failure of the materials. While the calculations for the frame and mechanism within the device can be easily analyzed, the forces required to pierce the soil require additional testing or complex soil analysis.

The available force for digging before loss of traction occurs was idealized and calculated as follows. Soil compression effects on rolling resistance were not taken into this initial calculation set.
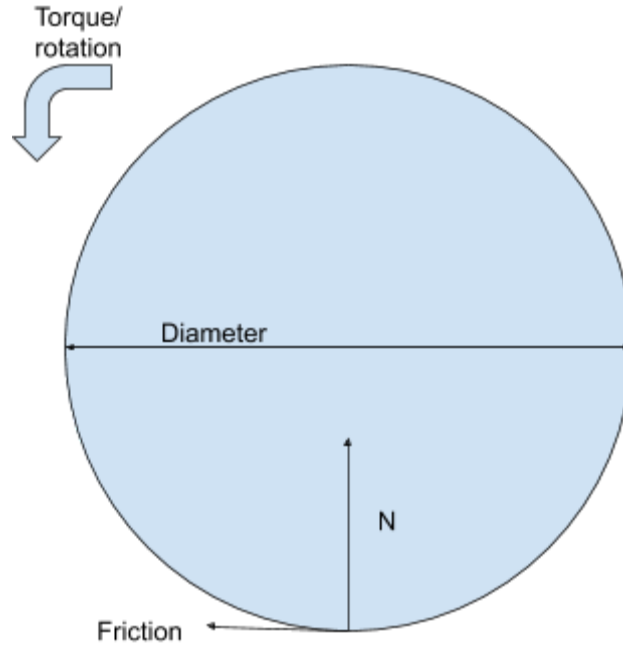
Figure 16: Torque from ground

$$T_w = \frac{\varnothing}{2} * (* N)$$

Where T_w is the torque applied to the wheel by the ground (Figure 16), $\varnothing$ is the diameter of the wheel, μ is the coefficient of friction between the wheel and the soil, and N is the normal force exerted by the ground. This equation states the torque supplied to the wheel for no-slip conditions.

$$T_d = \frac{1}{GR} * T_w = \frac{\varnothing}{2*GR} * (* N) \geq r_d * F_{soil} * sin(\theta)$$

Where T_d is the torque available to the digging mechanism and GR is the gear ratio between the shafts of the wheels and the digging drive as determined by the number of segments on the intermittent gearing. This ratio must be the inverse of that of the intermittent gearing for a full rotation of the wheels to ensure that the digging arm returns to its initial position after the intermittent gearing engages, preventing failure by dragging the arm through the soil for long

25

distances. This must be greater than the torque applied to it by the soil, which can be defined by the radius of the digging device r_d, the normal force the soil applies on the digging arm F_{soil}, and the sine of the angle between the digging arm and the driving arm (Figure 17 below).
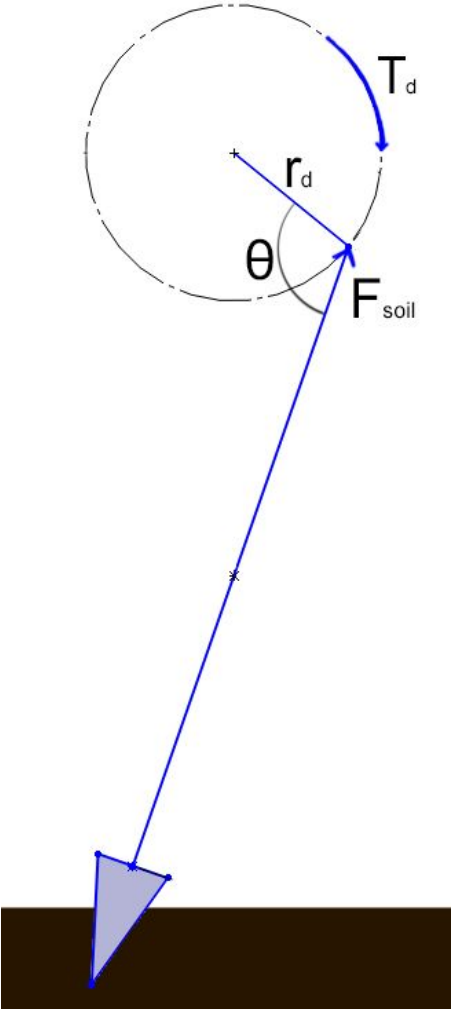

Figure 17: Force of soil applied to digging arm

$$F_{soil} \leq \frac{\emptyset}{2*GR} * (*N)/(r_d * sin(\theta))$$

From these expressions, we can derive the conditions for failure by wheel slippage: failure occurs for values of F_{soil} greater than the ratio of the radius of the wheel to the digging

drive multiplied by the friction on the wheels and divided by the gear ratio and sine of the angle between the digging drive and the digging arm.

A value of F_{soil} was determined experimentally (See: Testing Cone). To drive the cone into the ground 6 inches required approximately 141 pounds of force. Using the values $\mu = 0.5$, N = 200 lb for N (based on machine weight, see frame calculations below), $\varnothing = 14"$ for the selected wheels, $r_d = 12"$, GR = 8, and a θ value of 90 degrees for maximum force application:

$$F_{soil} \leq \frac{14in}{2*8} * (.5 * 200lb)/(12in * sin(90))$$

$$141lb \nleq 7.3lb$$

As can be seen, the force required, F_{soil}, is much higher than the force supplied by the torque. Given that this configuration gives the peak possible power supplied, the force supplied by the friction of the wheels is insufficient to power the device.

Bin Shafts

Another calculation that must be made is whether shafts on the device can withstand their intended loads and their potential lifetime. The loading configurations of many components can be complex, such as the conveyor belt axles on the bin. The belt holds the weight of the trees and must be tensioned to not sag and cause failures. In this case, the most likely failure is trees falling from the bin. This means the shafts, supported at either end, must hold the weight of the trees and the tension of the belt. The tension of the belt is applied at a plane separate from that which the weight of the trees acts in, so a purely 2-dimensional shaft analysis is not sufficient. The case of the bottom shaft of the bin is well-suited to computer modeling in addition to the other shafts but will be used as an example of modeling via equation. Calculations were completed for a worst case scenario of this bin shaft. The full calculations can be found in Appendix G.

Noting that this is for load conditions far in excess of what is expected to be encountered in use, modulation of the belt tension, tree weight, and torsion worst-case assumptions can yield

27

higher part lifetimes. For example, just using a quarter of the available torque (much more of the torque is expected to be used in the digging process), a factor of safety for infinite life of n = 1.407 is obtained. Adjusting all the inputs to less extreme values and using half of the available torque (87.5 in lb available), the weight of 200 seedlings as prescribed by the specifications would be 20 lb, and a tension achievable on a t-slot fastener system may be on the order of 100 lb. These conditions would yield a factor of safety for infinite life of 3.69, which would be acceptable for a prototype application in rough use conditions. It should be noted that those figures only apply to the lower shaft and the upper shaft of the bin must also be analyzed.

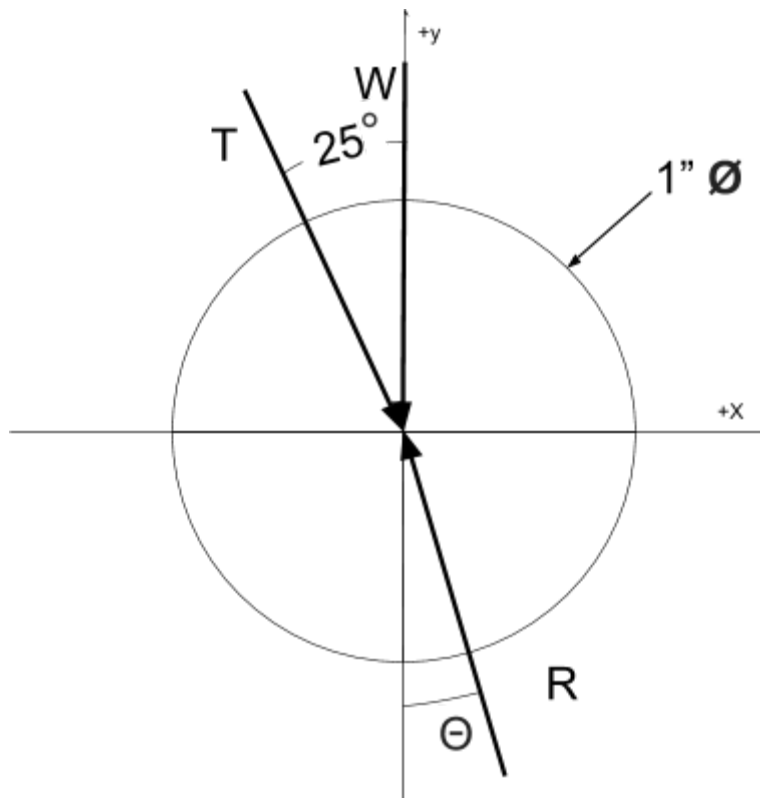*Figure 18: Lower shaft drawing*

Repeating this analysis for the upper shaft, a weight value half that of the lower shaft (⅓ of the total) and a tension in the opposite direction must be applied. This will allow for the reaction force from the frame, the deflection of the shaft, and the fatigue life to be determined. Due to W and T being nearly in the same direction, an R value above the value of W and T will

be produced. For these adjustments and the same initial loading conditions studied with the lower shaft, a frame reaction R of 261.94 lb, a deflection of .094", and a factor of safety for infinite life of n = .382, and cycles to failure N = 1630.2 were found. Using the more reasonable figures from the lower shaft calculations of W = 20 lb, T = 100 lb, and torque = 50% of total 87.5 in lb torque, an infinite life factor of safety of n = .974 and 846,381 cycles to failure were obtained. While this may not be passable for a production run of this machine, it should serve for a prototype.

Chassis

Due to a late change in supplier options for our prototype materials, an analysis of what loads the frame could hold when made from different materials and profiles became important. Given the available budget, the performance of 2in^2 square steel tubing and 30mm^2 aluminum t-slot were compared. This analysis does not capture the full benefits of one over the other, as the t-slot profile would be much easier to assemble. The full analysis can be found in Appendix H.

While the analysis showed the aluminum stock would sustain the loads, these calculations are idealized and should be analyzed further. There are three ways this can be addressed: the weight can be reduced, the weight distribution can be changed, or the frame material can be made larger or stronger. To meet the specifications within the report the weight distribution requirements cannot be changed. However, using estimates of the actual weight of the built device yields a much safer case: the device would only need to hold 20 pounds of trees and the entirety of frame material would weigh about 58 pounds (Arbor Day Foundation). There is also the fact that many of the assumptions went against the strength of the frame: there are additional bracing components along the back and upper portions of the frame. These lower bracing components, in addition to increasing the effective moment of the frame, will have their weight distributed along the length of the frame. There is still at least one assumption which may compromise the material in use, though: there will be some dynamic and fatigue components of stress due to the moving digging and planting arms which have been neglected in this analysis.

29

Due to the weight of the major weight contributors among the interior components (roughly 27 lb for a birch 4'x4'x1/2" plywood sheet, which would be more than what is ultimately present in components due to cuts, 3.78lb for 30" of a ¾" ∅ shaft, minor contributions of other components) and the likely addition of weights to influence the weight distribution, an empty weight of triple the t-slot frame components (58lb * 3) was used to overestimate the weight. Taken with the number of trees in the specifications (200, or 20 lb), the reaction forces R1 and R2 were found to be 22.47 lb and R3 and R4 26.08 lb. For the same distribution of weight and application locations, this yielded a maximum deflection of .0186", a yield factor of safety of 3.76, and an ultimate tension factor of safety of 4.84. Given the additional bracing in the device, we conclude based on these figures that the 30mm^2 profile t-slot would be a passable frame component for the use conditions and as a prototype, but it would not be suitable for a build complying with the initial specifications.

Two cases of alternate frame components were also tested: a 2 in^2 profile square steel bar and a 1.5 in^2 profile aluminum t-slot. For these cases, a maximum deflection of .05" and .2" respectively were found for the same load conditions. These conditions yielded a static loading yield factor of safety of 9.71 and 5.93 and a static load ultimate tension factor of safety of 7.63 and 11.65, respectively. Both would be more suitable for the frame than the 30mm^2 profile for a device which was built to specifications and would of course provide a more robust structure in the reduced load conditions described for the 30mm^2 profile t-slot above. Budget and manufacturing constraints, however, must also be factored in, especially at a point in the project where the original specifications were outdated due to design changes, namely moving from a 9'x5' trailer to a 6'x2'. A square tube would require welding and permanent hole creation, slowing down the build process and making it more susceptible to error; the 1.5 in^2 profile t-slot would be roughly $250 more expensive than the 30mm^2 profile t-slot.

VI. Detailed Design Description

The entire machine is divided into 7 different sub-assemblies: the chassis, wheel & gear assembly, packing wheels, tree separator, funnel & rail system, tree placer, and hole digger. This section will review the functions and components of each of the subassemblies and provide an overall description of the entire mechanism. Fabrication drawings of individual parts and subassemblies are included in the appendix.
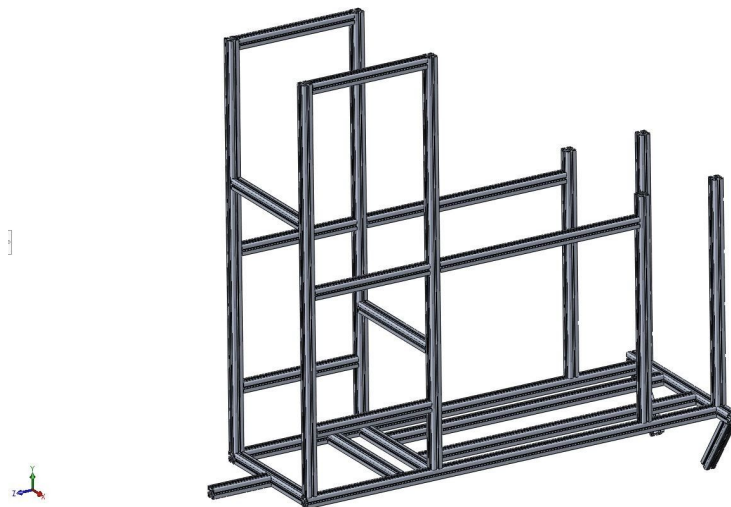
Chassis

Figure 19: Chassis

The chassis had two main constraints: weight and size. Our functional requirements required that the entire device be less than 500 pounds when empty and less than 7 feet tall and 8 feet wide. In our preliminary designs, we decided that square steel tubing would be the best material for the frame as it is easy to manufacture parts with and is cheap compared to other standard structural materials. However, we determined that this would not be ideal for our prototype and revised the designs to use aluminum t-slot. Aluminum T-slot is commonly used

31

for prototyping as it is easy to fabricate and change parts on the fly. This led to multiple design changes within our chassis design. Aluminum T-slot is more expensive than Steel square tubing of similar size, so minimizing material would allow us to maximize our use of our given budget. Additionally, T-slot is not easily attached on angles that are not square, as it cannot be welded practically in such configurations. In our initial design, we used angled tubes as support for our free standing structures. In our revised design using T-slot, we minimized the use of angled cuts and kept all other joints square.

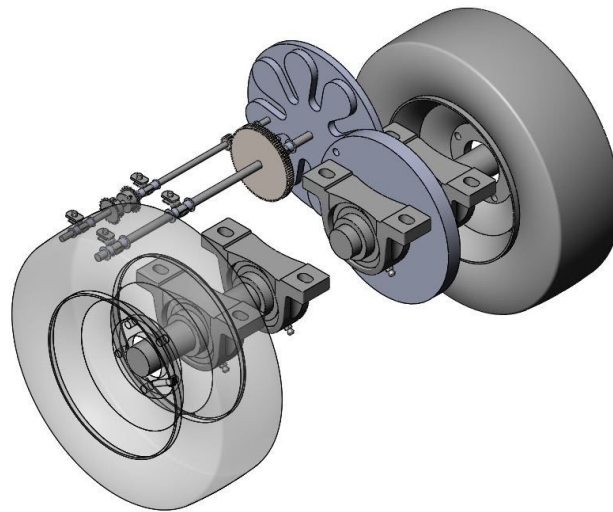## Wheel & Gear Assembly

Figure 20: Wheel & Gear Assembly

The wheel and gear assembly's primary functions are to allow the machine to roll across the field and power all the other mechanisms on the device. The power is transmitted from the wheels moving across the field into an intermittent gear drive. The intermittent gear drive uses a modified geneva drive mechanism that causes each full rotation of the wheels to move the driven gear (frond gear) one eighth of a turn. To have each mechanism complete one cycle from one rotation of the wheel, a second gear set is used to return the ratio to 1 to 1. That torque is

32

transmitted to the small spur gear and into the sprockets that drive the other mechanisms. As a result of the multiple moments on each axle, they are all hardened steel which can resist the torques applied. Similarly, the peg gear is made of carbon steel. For prototyping, the frond gear was planned to be made from some sort of polycarbonate or plywood with a backplate to add strength. This would make the manufacturing process much more achievable on the available machines and with the available budget than if we were to use steel. The final product would likely have a steel frond gear. The bearings and wheels are both standard parts that can be easily ordered. Both were chosen to ensure that they could withstand the loads that would be applied during operation of the device.
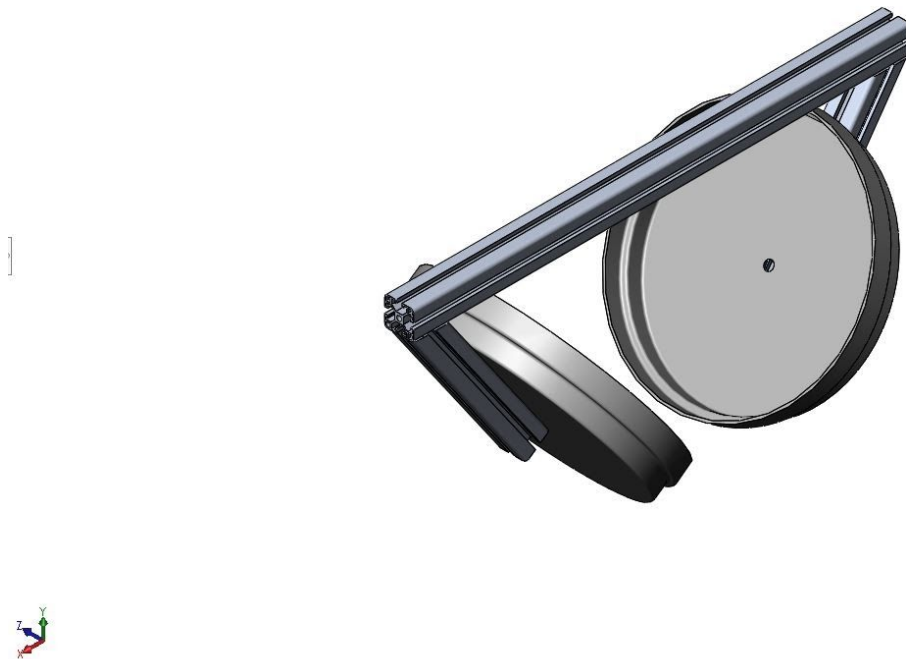
Packing Wheels

Figure 21: Packing Wheels

The packing wheels are the simplest subassembly on the mechanism. The assembly is used to refill the holes once the trees are placed and compact the soil and stabilize the tree. The wheels are both made from steel to resist and damage as they roll over the ground. The design was inspired by existing designs of compaction wheels. This design has been used in other farm equipment for many years and has proven to work. The added benefit of the compacting wheels over our other design options is the ease with which they can be repaired or replaced. Using low carbon steel for these components will allow for slight deformation and cycling without cracking.
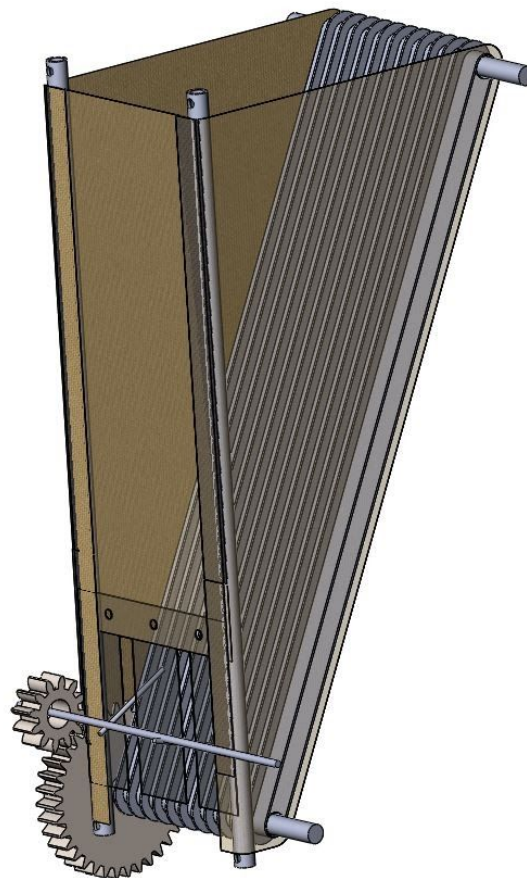
Tree Separator

Figure 22: Tree Separator

The tree separator has two purposes: storing the trees while the machine is in use and separating individual trees from the full hopper. It consists of three components, the hopper, the conveyor belt, and the hooks. In our current design, the hopper is made from cloth. This reduces weight and is significantly cheaper than rigid materials. The cloth is held up and tensioned with two vertical rods attached to the chassis. The conveyor belt makes up the floor of the hopper. This conveyor belt continuously pushes trees to the bottom of the hopper. Due to the irregular nature of saplings, this is necessary to prevent the saplings from getting clogged. Finally, the hooks at the bottom of the separator pull individual trees through to the funnel. The hooks are made from steel and rotate as the conveyor belt rotates. It is important to only have one sapling exit the hopper during each cycle to prevent unintended planting conditions.
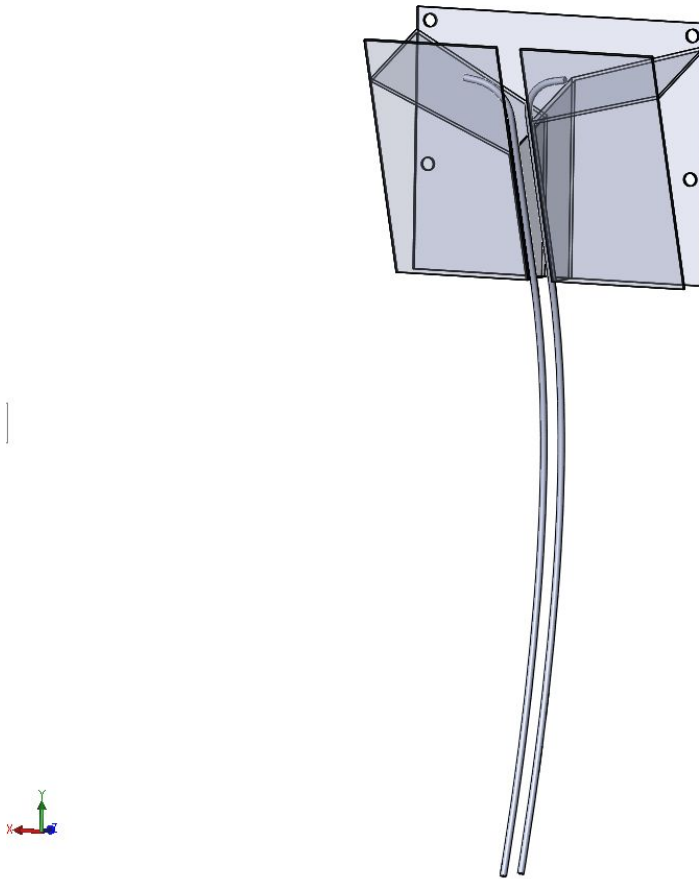
Funnel & Rail System

Figure 23: Funnel & Rail System

The funnel and rail system reorient the saplings to their final vertical position and constrain the clamp of the tree planting mechanism as it moves down towards the hole. The funnel would likely be made from steel in the final construction but was made from wood during testing. Due to its slightly complex design, steel would be ideal because it could be bent and welded into shape. The rails are made from steel rods bent into shape. They are attached to the funnel and extend towards the bottom of the chassis. In the final assembly, it is likely that these rails will need to be reinforced periodically along their length to ensure the clamp stays firmly shut on the sapling as it moves towards the hole.

Tree Placer

Figure 24: Tree Placer

Similar to the chassis, the original intent was to make the tree placer out of square steel tubing. In our prototype design, this subassembly uses T-slot to allow for easy manufacturing and quick revisions. This assembly also is one of the few areas in the overall design where an angled connection is necessary. Due to the nature of the linkage, the angle allows for the clamp to align with the funnel and rails to accurately grab and place the saplings. The clamp is made with a torsional spring and two plates attached to each prong of the spring. The torsional spring would be held somewhat loosely in place by plates above and below it fastened to the T-slot. The plates will be compressed between the rails beneath the funnel and rail system to hold the sapling as it is placed into the hole.
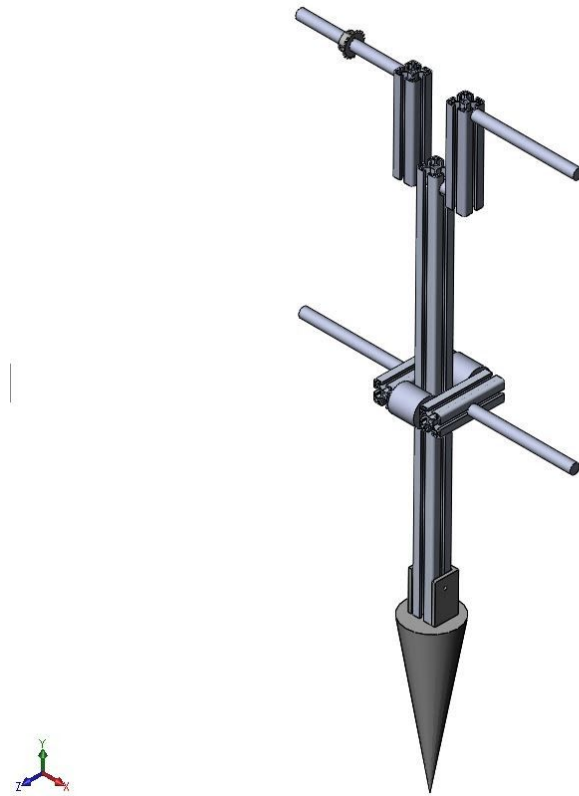
Hole Digger

Figure 25: Hole Digging Mechanism

The hole digging mechanism is the second four-bar linkage on the device and uses an inverted sliding linkage to pierce into the ground to create a hole. The linkage itself is again made from T-slot but would be made out of square steel tubing in the final assembly. The sliding portion of the linkage has two wide bearings that allow the digging arm to slide up and down during operation. In the final assembly, we believe it would be beneficial to add some sort of softer material to the digging arm or rollers to reduce wear and noise between these two components.

The cone is made from hardened carbon steel with steel C channel welded to the top. The C channel allows for holes to be drilled through the digging arm for attachment. Because the cone is constantly pushing into the ground where it can hit roots and rocks, it was important to design it to be removable. This will allow for regular maintenance or replacement. The hardened steel will be able to resist wear to a point, but repeated use will require some sort of maintenance.

Entire Assembly

Figure 26: Entire Assembly

The final assembly combines all the subassemblies into one mechanism. The device is made to be as compact as possible. The subassemblies were designed so that the space was used as efficiently as possible. This can be seen in our triangular hopper design, where the digging mechanism is contained entirely within the hopper's vertical footprint. Using these methods allowed for the final design to be just 3 feet tall, 7 feet long, and 6 feet tall. This would allow for two of the devices to easily fit side-by-side in a single garage bay.

VII. Manufacturing

The most significant obstacle to the manufacturing of a prototype was the COVID-19 pandemic. Due to safety measures, the manufacturing of the full device was rendered impossible. Manufacturing was limited to a prototype of the digging cone and bin for the planting system for testing purposes. Plans for the methods to be used component-by-component were baked into the design of the machine and will be discussed despite the actual manufacturing not taking place.

Most of the manufacturing decisions were determined as a result of the resources available to us. The process capabilities we had—milling machines, welding, and basic shop tools—allowed for enough design freedom to create components from bars, sheets, and cylinders, as well as some simple machining processes. Complex machined parts would be outside of our scope and abilities, which resulted in the design of a prototype where parts are fixed to each other with fasteners. This allows for quicker assembly times than with welding, in addition to easy repair and adjustment after testing.

Components such as frame components, gears, and bearings were to be purchased off-the-shelf for the prototype, which would likely also be done in a commercial setting. Components that were going to be purchased can be seen in Appendix I.

Chassis and Tires

The frame was to be constructed from 30mm square profile t-slot aluminum. Sections were to be cut to length by bandsaw and fastened with t-slot nuts and bolts to allow for ease of assembly and adjustment. One component which would cause some trouble in this configuration would be the planting arm: custom plates would have to be constructed to allow the two pieces to be joined at an angle of 150 degrees. Plates would bolt into the t-slot channels above and below the spring clamp to keep it from sliding out of the device. In a commercial or mass-production context, these sections would be steel bars or channels rather than t-slot. Additionally, sheet metal guards would be added to shield axles and gear systems on the device from debris and

minimize potential for user injury. The steel channel would be welded together, though key components could be attached with bolts. Bolted parts would make it convenient to the end user to replace parts, should they fail.

The axles were to similarly be cut to length and attached to the frame with bearings. The bearings would be held in place by t-slot nuts, allowing for adjustment along the axis of the t-slot. These axles would have flat surfaces machined to allow gears and sprockets to be attached with set screws. Channels in the axles would be machined to allow for retention rings to keep the axle and gears in place.

The wheels would attach to their respective axles via bolting to plates welded to the end of the axles. If the wheels purchased contained bearings, they would be removed, as the wheels must co-rotate with their axles.

Digging Arm

The digging cone would be made of a solid steel cylinder. The top would have a short length of steel C-channel welded to the top that would allow for the cone to be bolted to the digging arm. In a commercial run, if the digging cone design were implemented, it would still likely be milled from cylindrical stock and attached with fasteners for ease of repair.

The digging arm was to attach between the rotating arms via bearings and be located by retention rings. The rotating arms would attach to the axles across the device by drilling a hole through their center, threading, screwing in a bolt, and screwing the bolt into t-slot nuts in the digging arm. Due to the nature of the device's use case, some sort of bolt adhesive would be helpful to prevent loosening over time. In a commercial run, that joint would be welded, but the others would likely be largely the same. The driving arm of the digging mechanism would be driven by one sprocket fastened by a set screw. The axle bearings for this component could be moved to tension the chain to some extent, as it has some freedom in its placement along the length of the device. The digging mechanism and planting mechanism would need to be timed to allow for proper hole spacing and successful planting.

Hopper

The sides of the hopper were going to be prototyped with plywood for convenience. These would be cut to the proper dimensions by jigsaw. Other components would be fastened by screws or nuts and bolts as appropriate. Sleeve bearings would be used to suspend the bin by the bin shafts, as the bin shafts are attached to the device frame. The bin would additionally be braced by tubing running vertically across the front and bolted to t-slot at the top of the device and at the top of the bin. In a commercial run of the device, the hopper sides could be constructed from a strong canvas or tarp material. In the case of a canvas, it would need to be tightly tensioned around the bars on the front to retain the trees properly.

The belt in the hopper would be prototyped by sewing several rubber sheets together. Whether or not such a belt could be tensioned properly and how it would fare with cycling needs further research but could be tested and may be of limited concern in prototype applications. Owing to the adjustability of the t-slot system, a tensioning device could comprise simply of another shaft suspended below the bin area. In a commercial run, purchase or direct manufacture of a belt would be necessary. Such a belt could be studded with long wires to allow direct pushing of trees and greater reliability. Driving long staple-like configurations through the belt would accomplish this.

The rod for pushing the trees out was to be prototyped by drilling holes radially into an axle at angular and axial offsets such that they would enter the openings in the hopper at different timings and would pre-orient the saplings. This would also be attached to the frame by bearings and be driven by a sprocket.

The chute was initially prototyped with ½" plywood and duct tape to allow adjustability during testing. The planar geometry was broken down into individual pieces, which were cut to size by circular saw.In commercial runs, this component would likely be sheet metal, but the interior pieces would both be one bent piece as opposed to two individual pieces. These pieces could be attached by welding a series of tee joints in commercial settings.

Railings were not attached on the existing prototype due to lack of material but were planned to be attached to the bin by adhesive. These could be attached by welding in commercial applications. Bracing could be achieved by welding rings the trees could fit through on the back side of the rails with openings to allow the clamp through or by attaching struts or cables periodically down the rails and to points on the frame. Testing would likely have to be performed to determine the best configuration, as the geometry, motion, and forces would make modeling the deflection from first principles difficult. In commercial settings, the rails may be able to be braced some by attachment to sheet metal across the bottom if that were implemented.

Planting Arm

The planting device would be constructed from the same material as the frame. In commercial applications, a square bar may be preferable to lessen bending or torsion of the arm. Gears and axles which co-rotate at attachment points would be attached by axles which extend through the components. These components would be drilled through at these locations with a great enough diameter to accommodate bearings. Whether the architecture of the t-slot would allow through-holes of the prescribed size would need to be investigated. As mentioned above, the angled connection on the planting arm would necessitate several plates be made custom to allow nuts and bolts to be attached to both pieces to join them. In commercial applications, the arm could be bent from a single piece. The ground link of the four-bar mechanism would be the point at which the axles for the rotating arm and the rocker arm connect to the device. Due to the T-slot architecture, the length of this link can be adjusted if a purpose is found for doing so (adjusting the curve or contact with the rails, etc.).

Transmission of Power

The intermittent gearing was to be constructed from plywood for the purposes of prototyping but could be made from a metal sheet or polymer in commercial applications. The frond gear could be made on a jigsaw for prototyping or a mill to ensure the geometry can be replicated accurately. The peg gear could be milled from a sheet or cut from a large cylindrical

43

stock if one of such a size is available. The peg on the peg gear was to be attached by nuts and a bolt through the center, with a bearing to allow rotation of the peg to minimize friction against the frond gear. It could be welded in commercial applications, with the caveat that the frond gear would need to be filleted along its edges to ensure the weld bead does not push into the frond gear. These components will be subjected to high impacts, so selection of a tough material is crucial.

The components would be driven by two chains. The digging arm and rod for pushing the trees out of the hopper would be driven by one chain which could be tensioned by placements of both components; the planting arm would be driven by the other chain and could be tensioned by moving the vertical placement of the planter assembly along its t-slot. Since these two systems would need to move in opposite directions, a set of gears may be used to reverse the direction on one drive or two or more sprockets may be added to one system offset such that the outside of the chain may be wrapped around the sprocket driving the planting arm. In a commercial setting, this could be done easily with belts by simply twisting one belt by 180 degrees. If belts were to be used, careful selection of belt size given the availability of pulleys that can perform a 1:8 ratio or using a series of belts would be necessary.

VIII. Testing

The following tests ensured that our design fulfilled the functional requirements outlined in the Background and Design Selection sections of this paper.

We were only able to perform one test that informed our design. The rest of the tests outlined here are hypothetical because we were not able to acquire materials for and manufacture the transplanter. The force required to drive the digging arm was determined in the Cone Test below.

Cone Test

Purpose

Determine the amount of force the digging arm needs to provide.

Model machined cone with wood of the same size.

Procedure

- A 7" long octagonal cone was cut from a 3"x3"x9" piece of wood (Figure 27).

Figure 27: Octagonal cone

Cone Test Setup

- Weigh the cone and a thick wooden platform (see Figure 28).
- Place the cone in the ground such that it stands by itself with no additional weight.
- Mark ground level on cone with pencil. Remove the cone from dirt and measure depth sunk.
- Place the platform on top of the cone and support it with stakes according to Figure 28.
- Load the platform corresponding to weights listed in Appendix J and record depth that the platform sinks. It was necessary to adjust the stakes in between measurements to ensure the platform remained level. This skewed the measured depth sunk.

Figure 28: Cone Platform Setup

Results

The 5.8 in deep hole created by 135 lb force can be seen in Figure 29.

Figure 29: Conical Hole
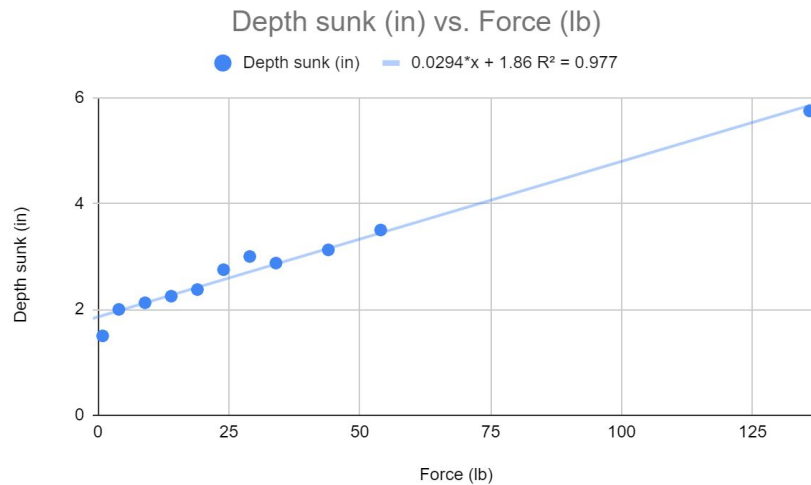
Figure 30: Depth Sunk vs. Force

Force required to create a 6 inch deep hole (Figure 30):

$$6 = 0.0294 * (Force) + 1.86$$

$$Force = 141 \text{ lbs}$$

It takes approximately 141 lbs to create a 6 in deep hole in dirt that has been fallow for 1 year, using a 3 in wide octagonal cone.

Conclusions

This test was performed using an octagonal wooden cone of the same dimensions instead of a machined steel cone. Despite this, the 141 lbs expected necessary force is still a valid estimate. The machined cone would weigh 5.5 lbs instead of the wooden cone at 0.9 lbs. Initially, the machined cone would sink deeper than 2 in because it is heavier. Additionally, we expect the machined cone to have a smoother surface finish than the wooden cone. This means it will take less than 141 lbs of force to create a 6 inch hole in the ground. We use the 141 lbs force as the force the digging arm needs to provide to create a 6 in deep hole that fits the roots of the tree saplings. It is important to note that the force applied to the cone by the digging arm design means the maximum force is applied as the cone enters the ground and diminishes until the digging arm and rotating arm are parallel, as the cone reaches the bottom of its arc.

Hypothetical Tests

Below, we outline the hypothetical tests that would have been performed, the functional requirement that the test verifies, and how it would have been carried out.

A test measuring tree sapling density could have informed the size requirements of the tree hopper. The other tests verify that each design choice fulfills the functional requirements outlined in the Design Selection. The individual functions are tested first, then the entire mechanism is tested.

Tree Density Test

Purpose

Determine average size of two-year old, twelve inch blue spruce saplings from the Arbor Day Foundation.
Determine packing density of the saplings.
Calculate hopper size necessary to hold required 200 saplings.

Procedure

- Purchase 50 Blue Spruce Saplings from the Arbor Day Foundation website
- Measure and record the total height, root depth, and width of each tree. Take the average.
- Loosely bundle 20 trees. Measure the collective volume.
- Calculate volume necessary to hold 200 trees. Calculate hopper dimensions based on triangular design.

In addition to determining the hopper size, this test informs the size needed for the conveyor belt length, conveyor belt texture, chute width, spring clamp size, and how far apart the angled wheels need to be.

The calculated tree density is an estimate because trees lower in the hopper are subject to compression from the weight of the trees above. This skews the hopper size found by this test to be larger than necessary, ensuring design requirements are fulfilled.

Hopper Reliability Test

Purpose

Determine where and how often tree saplings get stuck in the hopper system to measure failure rate.

Procedure

- Load all 20 trees into the hopper.

- Rotate the large gear which turns the conveyor belt and hook system.

- Observe how many trees are pulled out of the hopper individually, in bunches, or get stuck.

- Observe where roots and branches get caught.

- Observe and measure the angle at which the trees fall out of the bin.

The angle at which the trees fall out of the bin is important to know for the chute design; the chute's dimensions may need modification. It is also important to observe how the mechanism continues to function when the trees become stuck or out of place. It is acceptable If the trees just get stuck and the transplanter stops planting. However, if the mechanism snaps the saplings when they are out of place, the tree grower loses investment. If less than 18 trees (90%) fall properly oriented into the chute, the hopper does not meet its functional requirements.

Planter Reliability Test

Purpose

Determine failure rate of planting arm. The tree must be upright in the hole.

Procedure

- Drop all 20 trees by hand at intervals into the chute at angle determined by the Hopper Reliability Test.

- Rotate the gear that moves the planting arm four-bar mechanism by hand.

- Count how many trees of the 20 are placed upright into a pre-dug conical hole.

- Observe where the trees get stuck and if the saplings break or are damaged in the process.

It is important to note the effectiveness of the spring clamp and how reliably it grabs and maintains pressure on the trees. This is assumed to be the main reason the planting arm would fail to plant the tree upright. If less than 18 trees (90%) make it successfully upright into the ground, this mechanism fails to meet functional requirements.

Limited aspects of this test were performed. A prototype of the chute without rails was manufactured and tested with pine saplings. Due to lack of measurement equipment and weights, these tests were qualitative and used purely to inform what design parameters for the system may be, but not their values. High stiffness observed in the saplings relative to the 1" slot width yielded insight that slot width and in turn clamp size should be variable at least for the purposes of further testing, if not in the built product to allow for saplings of different sizes.

Digging Iron Reliability Test

Purpose

Determine the failure rate of the digging iron. The hole must be 6 inches deep and in a consistent location in line with the center of the trailer.

Procedure

- Pull the trailer along the ground over farming soil to rotate the wheels and operate the digging iron until it digs 20 holes.
- Measure the depth of each hole.
- Measure how far off the hole is from the center of the tire ruts.
- Observe what happens when the cone head hits rocks or other hazards.

If the hole dug is less than 5.5 inches in depth or more than 2 inches off center, the hole is considered inadequate. If less than 18 holes (90%) are adequate, the digging iron is considered unreliable.

Soil Pack Reliability Test

This test would be performed after the hopper, planter, and digging iron proved functional.

Purpose

Determine failure rate of angled wheels. The trees must not be damaged as they pass through the wheels and the sapling's roots must be at least 60% covered.

Procedure

- Pull the trailer along the ground over farming soil to operate the transplanter until it plants 20 trees.
- Count the number of trees that safely passed between the angled wheels.
- Count the number of trees that have at least 60% of their roots buried under soil.

If at least 90% of the trees that were planted upright were undamaged and properly buried, the angled wheels can be considered reliable. Otherwise, adjustments such as the angle and separation of the wheels can be made.

Transplanter Reliability Test

A full test of the transplanter would determine the overall rate of transplant success. The procedure for the Soil Pack Reliability Test can be used to check this. It is important to note how well the timing of each function works with the other operations.

At a rate of 90% success for each function, statistically, 13 (65%) of the 20 original trees would make it into the ground planted upright, with their roots covered and ready to grow. If the Transplanter Reliability Test plants more than 13 trees successfully, the Transplanter can overall be judged to fulfill the functional requirements.

In addition, the time it takes to plant all 20 trees should be measured to determine the planting rate. It would be difficult to measure the durability of the Transplanter with respect to cycling or environmental effects because of time constraints.

IX. Conclusions and Recommendations

The following section describes the main issues with our final design and process, and how they could be improved.

Weaknesses in Design

Chief among the design weaknesses is the inability for the driving components to drive all if any of the components. The digging arm required 141 pounds of force to be driven into the ground 6 inches. Calculations of the maximum force which could be applied to the cone yielded an estimated 7.3 pounds, assuming the digging arm was perpendicular to the rotating driving arm and that all the torque generated by the wheels was available to drive the digging. This discrepancy is made worse by the driving force diminishing with the rotating arm and digging arm going parallel, which must occur at the maximum depth to be driven. The digging device may be assisted in digging by some of the weight of the trailer above at this point, but it should be noted that this is close to the hitch, meaning much of the weight is supported unless the device lifts off the ground and that only 15% of the total machine weight will be available by lifting off the hitch and not lifting the entire machine. Additionally, all the other moving components of the device must be driven by the same torque, diminishing the amount which may be made solely available to the digging process. In short, the device must be able to provide significantly more torque to the driven components and/or the driven components must be driven with significantly less torque.

The orientation chute may not be currently suitable for operation. Trees of correct specifications may be unable to be driven through the opening without breaking, let alone with minimal force.

Suggested Improvements

Device driving torque could be improved by increasing machine weight supported by the wheels or by increasing wheel diameter. If device weight is increased to increase drive torque, care should be taken to distribute weight such that 15% is supported by the hitch per specifications and that the additional weights do not cause bending sufficient to hamper component motions or induce failure of the frame. Increasing wheel diameter and modulating the

surface would be highly suggested approaches to improving torque. Using ridged, spiked, or toothed wheels or covering the wheels with chains may be potential methods to improve torque output for different soil conditions with lower-friction, higher root-density grass.

Torque required by driven components could be reduced by redesign of the components. The first design change which comes to mind across all components to improve torque requirements is to remove the 1:8 gear ratio between the intermittent gear driven by the wheels and all the devices. The intermittent gear was initially introduced to allow the device functions to be performed in a more discrete fashion while in motions and so that the digging cone wouldn't be dragged through the ground as it dug, but it is clear that without greatly increased torque supplied and decreased torque required that reducing the torque available by a factor of 8 is not conducive to the device functioning at all. Fortunately, all the driven components lend themselves to intermittent operation to some extent and may likely be adapted to continuous drive configurations.

The planting arm may be redesigned to reduce torque required by driving it continuously. The timing on the process of orienting and placing the tree could be modulated by modulating the lengths of the bars in the linkage, though this would also modulate the coupler path geometry. Care should be taken with updated timing that the planting arm does not linger in the vicinity of the placed sapling, as the motion of the machine could push the planting arm into the sapling and upset its orientation or remove needles or limbs as it runs across the sapling.

The hopper and tree-retrieving axle may not require a redesign to function continuously and reduce required torque. Experiments would have to be run on the ability of the front of the hopper to retain trees with a continuously driven belt. The axle is already designed to retrieve one tree per cycle, so no fundamental change other than perhaps the angle between the protruding rods may be required.

To improve chute performance, modulation of the chute slot width and the width of the tree clamp are recommended. Having a chute slot with variable width would be highly recommendable, as that would allow for testing and tuning of the effects of chute slot width on

the forces required to push trees of different sizes through. To compensate for this change in chute slot width, the clamp width should be adjustable. This can be accomplished by padding the interior and exterior of the clamp as required to ensure the clamp closes on the tree at the given chute slot width. Additional bracing of the rails at the end and to some extent along their entire length would also be recommended to ensure minimal flexure of the rails and consistent pressure on the trees from the clamp.

The digging arm would be the greatest challenge to redesign for continuous driving. As mentioned above, the longer the cycle it is driven in, the longer it will be moved laterally while it is in the ground, meaning either the soil or the device must yield laterally, potentially inducing high bending stresses and cycling. It is also important to reiterate that the device produces a diminishing amount of force as it is driven into the ground. A more fundamental redesign of this component would be recommended. Investigating the use of motors, spring-loaded devices, or a plough may be fruitful.

Important Considerations for Similar Projects

Additional research beyond what exists in the market but why it exists as it does could be useful for future projects. During initial phases of research, no devices driven by the friction of their wheels for any applications were found, let alone for multi-step agricultural processes. Greater research into why these devices tend to be motorized and what the motors are primarily used for could have yielded earlier insights into where the most torque would be required. In retrospect, it seems the geometrical happenstance in the digging mechanism by which the driving force applied to it for a given torque is greatly reduced as it is driven into the ground may also be linked with the lack of precedent in existing designs.

Incorporating quantitative analysis of components as early as possible would also be advisable. For example, the design of the digging arm had long been selected and finalized before determining it was not conducive to digging holes force-wise. Incorporation of mathematical analysis early, even in a "back-of-a-napkin" sense, can yield further insights which may prove useful in design selection and in guiding preliminary designs, minimizing future need of redesign.

54

X. Appendices

Appendix A: Functional Requirements

- Create holes
    - Assume transplants are 2 years old, 6 in to 1 ft tall total, 6 in of bare roots (Arbor Day Foundation)
        - 1 acre = 1700 plants for 5 ft x 5 ft grid
    - Hole must be at least 5.5 in deep and dug within 2 in of center
- Place individual seedlings in the hole
    - Capacity
        - Able to plant 200 trees before reloading
- Fill hole
    - Press down the soil to remove 60% of air gaps in the soil and stabilize the tree
- Towable and tow-powered
    - Mechanism can be deactivated for towing without planting
        - No parts aside from the wheels should move during transit when not planting
    - Minimal human interaction
        - Humans should not be needed to operate the machine during movement
            - Humans load the seedlings into the hopper
    - Size and weight constraints
        - The machine should weigh less than 500 pounds while empty
        - The machine should have the capability of being street legal
        - The machine should fit through a typical garage door (Garaga)
            - No larger than 8 feet in width
            - No taller than 7 feet
- Each individual function must have a 90% success rate, for an overall minimum success rate of 65%

- Work on given terrain types:
  - Rocks and roots
    - Should be able to create a 6 inch deep hole in all typical soil types
    - Mechanical give for impacts above and beyond those provided by soil and roots.
  - Operates in soil above freezing
  - Incline
    - Operates between 0 degrees and 25 degrees (small hills have no negative impact)
  - Debris resistance
    - Belts and gears completely housed to avoid buildup of dirt, mud, and plant matter in drive components.
    - Housing can be opened easily for maintenance
  - Corrosion resistance
    - Components should resist functional changes due to corrosion for 10 years with yearly use in humid, rainy environments adjacent to an ocean.
    - Corrosion resistance should not rely on coatings and should be inherent in the material used, especially on shovel or other components likely to undergo wear
  - Drain
    - Avoid buildup of water inside housing
- Pricing range
  - Current product price range: $1600-$8000
  - Materials cost: $750

Appendix B: Tree Storage Design Matrix

Tree Storage		Designs							
		Bin		Vertical Narrowing Hopper		Discrete Tubes		Rail System	
Wei ght	Functional Requirement	Description	Rati ng	Description	Rati ng	Description	Rati ng	Description	Rati ng
2	Capacity	Volume Limited	4	Volume Limited	4	Limited by Space	0	Row-Limited	1
1	Contains trees (no bouncing out, etc.)	Assuming Lid	3	Trees Can Only Bounce Vertically	2	Tall Tubes	3	Unclear	2
2	Keeps trees safe	Potential Harm When Unloading, Esp. Due to Random Orientation	2	Some Potential Damage During Transition	3	Tubes Protect Trees	4	Potential Harm When Unloading	3
1	Ease of initial loading	Toss in Bin	4	Unbundle Trees and Placed Gently in Bin as Groups	3	Individually Separated by Hand	0	Separated and Placed Vertically	1
3	Ease of transition to tree loading	Orientation Random	0	Works with Rotating Hook Assembly	2	How to Grab Trees After Out of Tube is Undetermined	2	Trees Are Vertical, but Hard to Ensure Only One Tree is Grabbed	2
1	Size	Minimum Size Per Tree	4	Triangular, May Not Package Neatly	3	Tube Takes Up A Lot of Space Per Tree	0	Individual Planes for Capacity	2
1	Weight	Minimum Weight Per Tree	4	Complex System, but High Capacity	3	Plastic Tubes Are Fairly Light	2	Several Rails Needed	2
2	Manufacturability	Doable with Fasteners or Welding	4	Several Complex Components	2	Large Arrangement	3	Welding and Bending	3
2	Cost	Few Components	4	Metal Sheets or Rods	3	Tubes Likely Pvc	3	Metal Sheets and Rods	3
3	Projected failure rate	No Way to Get Trees Out of Bin	0	Trees Likely Get Stuck Transitioning to	3	Roots Likely to Stick Anywhere	2	Possibility of Dropping Trees	2

				Loader		Along Magazine			
1	Durability	Few Places for Water/Dust to Collect and Build Rust	4	Places for Water/Dust to Collect and Build Rust	2	Some Moving Parts	3	Rail is Susceptible to Failure if Not Properly Supported	3
	Total Points		47		52		40		42

Appendix C: Tree Transfer Design Matrix

Tree Transfer		Designs					
		Spring Clamp		Small Displacement Hook System		Rotational Hook System	
Weight	Functional Requirement	Description	Rating	Description	Rating	Description	Rating
1	Load Individual Trees	May Take More Than One Tree	3	Make Take More Than One Tree	2	May Take More Than One Tree	2
1	Orients Trees from Hopper	Limited Ability to Account for Orientation	2	Some Variation in Tree Orientation from Hopper is Ok	3	Some Variation in Tree Orientation from Hopper is Ok	3
2	Grab and Release Securely	Can Hold of and Release the Tree	3	Tree Can Slip from Hooks	1	Tree Can Slip from Hooks	1
1	Size	Four-Bar Mechanism	2	Needs Space for Different Rotating Axles	1	Depends on Displacement Needed	2
1	Weight	Small Part	3	Several Small Parts	2	Few Small Parts	4
2	Manufacturability	Torsional Spring, Metal Sheets	3	Many Components to Put Together	2	Welding	3
2	Cost	Spring, Plates Are Common	3	Several Different Components Needed	2	Few Parts Needed	4
3	Projected Failure Rate	Functionality Depends Heavily on Components in Other Systems	3	Overly Complex for Function	0	Hard to Maintain Tree Alignment Accuracy	1
2	Durability	Torsional Spring is Fatigue Limit	3	Wear on Several Components	2	Minimal Wear Opportunity	4
	Total Points		43		22		38

Appendix D: Hole Digging Design Matrix

Hole Digging		Design					
		Plow		Digging Iron		Reverse Post-Hole Digger	
Weight	Functional Requirement	Description	Rating	Description	Rating	Description	Rating
1	Potential Max Force to Soil	Very Efficient	4	Large Force Applied to Small Area	4	Two Components Need to Enter Soil	3
1	Torque Required	1-1, No Mechanical Advantage	2	Small Crossection to Penetrate Soil	2	Two Components Need to Enter Soil and Actuate	1
1	Technique (Ability to Shear for Given Force)	Effective in Most Conditions	4	Comes in at an Angle for Easier Shear	3	Enters Vertically	2
1	Obstacle Maneuverability	Can Not Avoid Obstacles	3	Smaller Area to Worry About Obstacles	2	No Way to Avoid Obstacles	1
2	Avoids Tree Planting Components	No Moving Parts, Relatively Small	4	Movement Takes Up A Large Space	2	Two Vertical Moving Arms	3
1	Soil Disruption	All Soil in Planting Line Affected	0	Soil Around Hole Affected	3	Only Soil from Hole Affected	4
3	Ease of Planting in Created Hole	Difficult to Keep Tree Straight in Trough	1	Small Hole Makes Planting Easy	4	Small Hole Makes Planting Easy	4
1	Size	Relatively Large to Make Deep Enough Hole	3	Only One Component	4	Two Components Need to Enter Soil	3
1	Weight	One Part Means Low Weight	3	One Part So Low Weight	3	Multiple Components Could Get Heavy	2
2	Manufacturability	Welded	4	Requires Linkages	3	Needs Linkages and Two Arms	2
2	Cost	Very Cheap to Make	4	Relatively Cheap to Manufacture	3	Unique Design Hard to Manufacture	2
3	Projected Failure Rate	Could Fail on Uneven Hills	3	Could Potentially Get Caught on Obstacles	3	Many Ways for Operation to Fail	2
1	Durability	Robust Depending on Soil	3	Wear from Many Moving Parts	3	Wear on Many Linkages and Connection Points	1
	Total Points		58		61		49

Appendix E: Tree Placement Design Matrix

Tree Placement		Design name					
		Rotating Spring Clamp		**Hrones and Nelson**		**Chute Drop**	
Weight	**Functional Requirement**	**Description**	**Rating**	**Description**	**Rating**	**Description**	**Rating**
1	Torque Required	Cutting into the Ground Takes A Lot of Power	1	Greatest Resistance from Interaction withRail System	3	Just Need to Open the Chute	4
2	Works withHole Digger	Only Works withPlow	1	Works with Any Hole Digger	3	Hole Must Be Large and Round	1
2	Orients Tree in Hole	Tree Sometimes Ends Tilted	3	Releases Tree Upright	3	No Guarantee of Orientation	0
3	Ease of Transition from Tree Loading Mechanism	Pinches Tree Easily	4	Integrated withRail System	4	Just Drop Seedlings into Chute	4
1	Failsafe for Rocks	Plow Moves Rocks Out of the Way	3	Complex Failsafe Avoids Damage to Mechanism.	1	Tree Does Not Get into the Ground	0
1	Size	Large Disk Shape	2	Linkage, Potentially Thin but Bulky in Plane	2	Round and Tall	3
1	Weight	Light, Rotating Mass	2	Light Linkages	3	Lightweight Chute	4
2	Manufacturability	Welding and Spring Grabber is Complex	2	Linkages, Sheets, Torsional Spring	3	No Unique Parts	4
2	Cost	Complex Parts	2	Linkages, Sheets, Torsional Spring	3	Few Parts	4
3	Projected Failure Rate	Low Complexity of Motion	3	Possible for Tree to Miss Hole	2	Likely to Fail - Based on Gravity, Roots Will Catch	0
2	Durability	Drags in the Ground Continuously	1	No Interface with Ground, Only Supports Own and Tree's Weight	3	Minimal Moving Parts	4
	Total Points		47		57		49

Appendix F: Soil Packing Design Matrix

Pack Soil		Design name					
		Angled Wheels		Stomping Mechanism		Tilting Shovel	
Weight	Functional Requirement	Description	Rating	Description	Rating	Description	Rating
2	Closes Hole Completely	Not Completely Closed	2	No Empty Space at Base of Trunk	4	No Space Near Bottom of Trunk	4
2	Does Not Harm Tree	Could Squash Tree	2	Could Crush Tree if Bad Timing	2	Does Not Operate Close to Tree	4
1	Torque Required	Minimal/No Relation to Drive Shaft	4	Driven	2	Driven	2
1	Technique (Output for Given Force)	Direct Application of Force	2	Possible Mechanical Advantage	3	Possible Mechanical Advantage	3
2	Leaves Tree Upright	Yes	4	if It Does not Hit the Tree	3	Probably Not	1
2	Interference Possibility with Rest of Design	No Interference	4	Back of Trailer - Should Not Interfere	3	Back of Trailer - Should Not Interfere	3
1	Size	Very Compact System	4	Takes Up Space Around Wheel Shaft	2	Links Take Up Space	2
1	Weight	Only Weight of Wheels	4	Depends on Force Desired	2	Lightweight Linkage	3
2	Manufacturability	Parts Already Exist	4	Complex to Make	2	Somewhat Complex to Make, Welding	2
2	Cost	Standard Parts	4	Made from Standard Parts	3	Standard Parts	3
3	Complexity/Projected Failure Rate	Very Low Complexity - Self-Powered	3	Timing is Very Important	1	Timing is Important	2
2	Strength (Durability)	Minimal Maintenance	4	Potential for Dirt Buildup and Wear	2	Potential for Dirt Buildup	3
	Total Points		71		50		56

Appendix G: Bin Shaft Analysis

Known: Dimensions of bin

Find: Deflection of shaft, fatigue factor of safety

Assumptions:

    1. 200 pounds of trees are loaded in (much more than expected in use conditions)

    2. Belt is tightened to 200 pounds of tension (more than we expect to be able to physically apply and fasten securely).all of

    3. All of the system torque calculated is resisted by the seedlings in the bin acting against the tree hook mechanism

    Boundary conditions: $y(0) = 0$, $x(0) = 0$, $y(18) = 0$, $x(18) = 0$

    Loading diagrams:

Bin Dimensions:
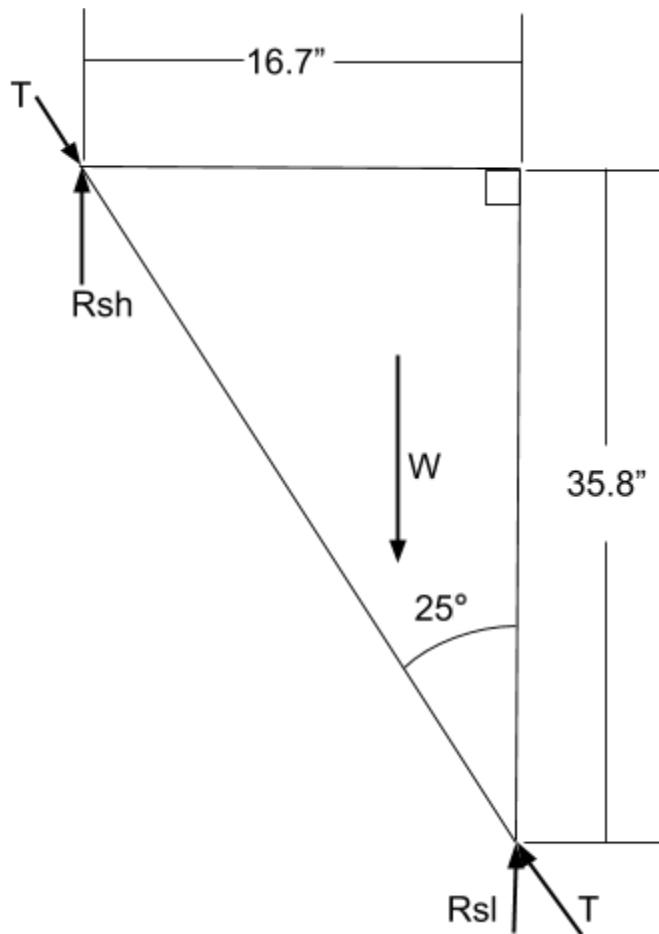
W: weight of trees, idealized as a force from the center of gravity of the filled bin

T: tension in belt

R_{sh} = reaction of upper shaft

R_{sl} = reaction of lower shaft

$W = 200lb$

$T = 200lb$

$$\Sigma F_y = -W + R_{sl} + R_{sh} + T\cos(25) - T\cos(25) = 0$$

$$W = R_{sl} + R_{sh}$$

$$\Sigma M_z = R_{sl} * 0 - R_{sh} * 16.7 + W * 16.7/3 = 0$$

$$R_{sh} = W/3 = 66.67$$

$$R_{sl} = W - R_{sh} = 200 - 66.67 = 133.33$$

Lower shaft drawings:
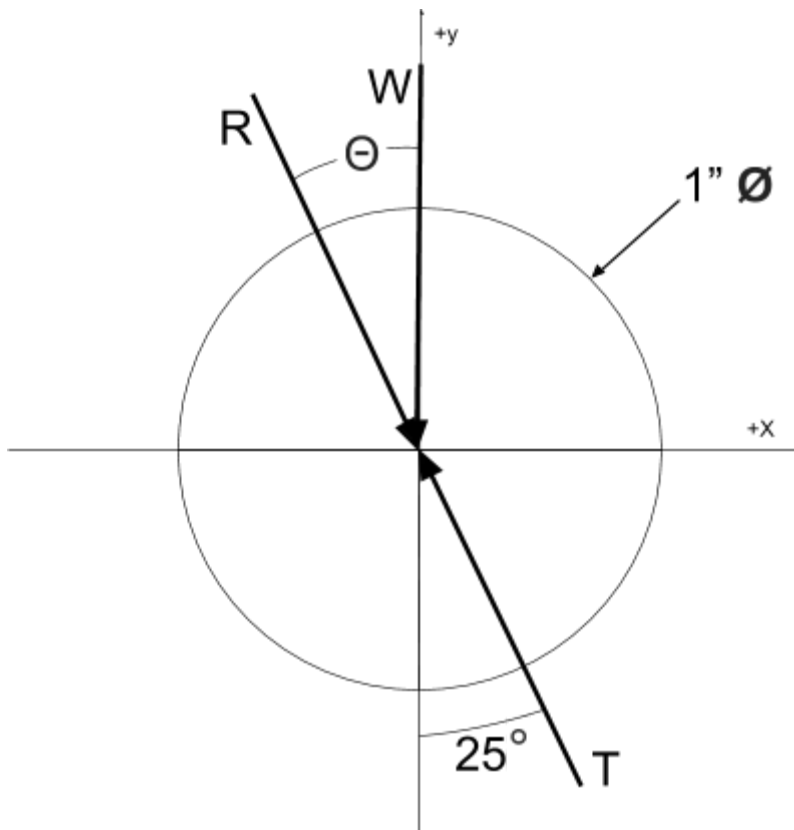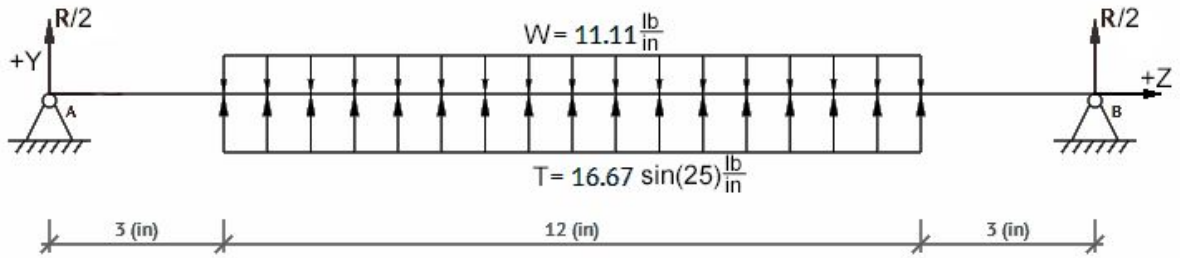
Image via beamguru.com (https://beamguru.com/online/beam-calculator/)
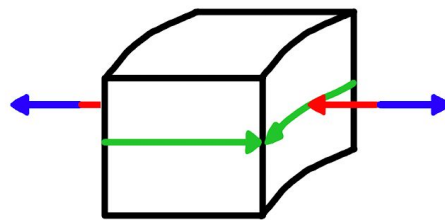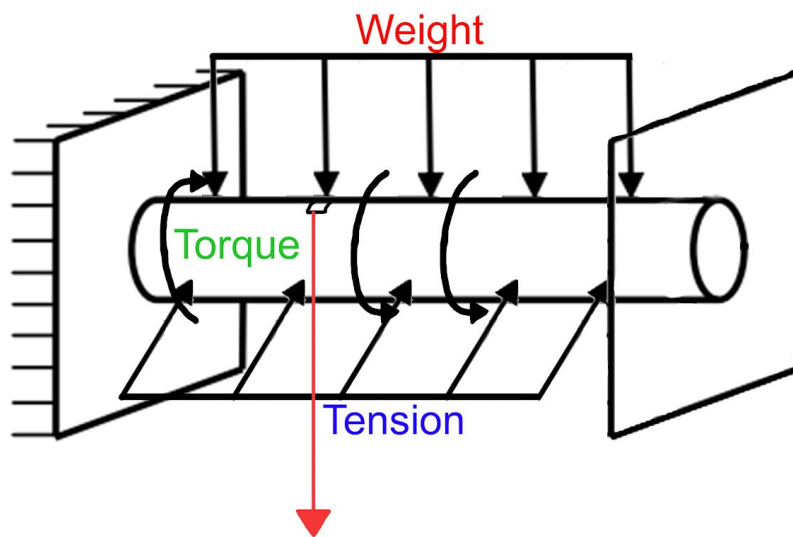
Representative stress element for top of shaft

W: weight of trees on lower shaft = 133.33 lb, spread over 12" width of bin

T: belt tension = 200lb, spread over 12" width of belt

R: reaction of frame on shaft

Θ: angle of reaction of frame on shaft

E: modulus of elasticity, taken as $3.9*10^7$ psi for the steel used

I: area moment of inertia of shaft along x/y directions

J: polar moment of inertia of shaft along z direction

⌀: shaft diameter = 1"

r: radius, ⌀/2

d: displacement of shaft

σ: tensile stress induced in beam via bending

σ_a: alternating stress

σ_m: mean stress

σ_{rev}: equivalent fully reversing stress

T: torque applied (see torque calculations)

τ_a: alternating shear from torque

τ_m: mean shear from torque

n: infinite life factor of safety

N: cycles to failure

S_{ut}: steel ultimate tensile strength = 60900 psi

S_e: endurance limit

S_e': unmodified endurance limit, = $S_{ut} / 2$

k_a: surface factor, cold-finished steel, values for this and below taken from Shigely's Mechanical Design 10th edition

k_b: Size factor

k_c: load factor

k_d: temperature factor (not applied for use conditions)

k_e: reliability factor

k_f: notch factor (not applied for uniform shaft)

f: fatigue strength fraction of S_{ut} at 10^3 cycles

$$I = pi \frac{1}{4}(\frac{2}{2})^4 = pi * \frac{1}{4} * \frac{1}{16} = .04909 \ in^4$$

$$\Sigma F_x = R \ sin\Theta + T \ sin(25) = 0$$

$$R = \frac{T \ sin(25)}{sin\Theta} = \frac{84.5}{sin\Theta}$$

$$\Sigma F_y = -W + T \ cos(25) - R \ cos\Theta = 0$$

$$W = T \ cos(25) - R \ cos\Theta = 181.3 + R \ cos\Theta = 133.33$$

$$-47.93 = -R \ cos\Theta = -(\frac{84.5}{sin\Theta}) \ cos\Theta$$

$$\frac{sin\Theta}{cos\Theta} = tan\Theta = \frac{84.5}{47.93} = 1.76$$

$$\Theta = 60.4$$

$$R = \frac{84.5}{sin(60.4)} = 97.17 \ lb$$

$R/2 = 48.58 \ lb$

$$q_y(z) = -48.58 \ cos(60.4) <z>^{-1} - \tfrac{133.33}{12} <z-3>^0 + \tfrac{133.33}{12} <z-15>^0 + \tfrac{200}{12} \ cos(25) <z-3>^0$$

$$- \tfrac{200}{12} \ cos(25) <z-15>^0 - 48.58 \ cos(60.4) <z-18>^{-1}$$

$$q_x(z) = 48.58 \ sin(60.4) <z>^{-1} - \tfrac{200}{12} \ sin(25) <z-3>^0 + \tfrac{200}{12} \ sin(25) <z-15 + 48.58 \ sin(60.4) <z-18>^{-1}$$

$$V_y(z) = -23.96 <z>^0 - 11.11 <z-3>^1 + 11.11 <z-15>^1 + 15.11 <z-3>^1 - 15.11 <z-15>^1 - 23.96 <z-18>^0$$

$$V_x(z) = -42.26 <z>^0 + 7.04 <z-3>^1 - 7.06 <z-15>^1 - 42.26 <z-18>^0$$

$$M_y(z) = -23.96 <z>^1 - 5.56 <z-3>^2 + 5.56 <z-15>^2 + 7.55 <z-3>^2 - 7.55 <z-15>^2 - 23.96 <z-18>^1$$

$$M_x(z) = -42.26 <z>^1 + 3.52 <z-3>^2 - 3.52 <z-15>^2 - 42.26 <z-18>^1$$

$$EIy'(z) = -11.98 <z>^2 - 1.85 <z-3>^3 + 1.85 <z-15>^3 + 2.52 <z-3>^3 - 2.52 <z-15>^3 - 11.98 <z-18>^2 + C_{1y}$$

$$EIx'(z) = -21.13 <z>^2 + 1.17 <z-3>^3 - 1.17 <z-15>^3 - 21.13 <z-18>^2 + C_{1x}$$

$$EIy(z) = -3.99 <z>^3 - .463 <z-3>^4 + .463 <z-15>^4 + .629 <z-3>^4 - .629 <z-15>^4 - 3.99 <z-18>^3$$

$$+ C_{1y} * y + C_{2y}$$

$$EIx(z) = -7.04 <z>^3 + .293 <z-3>^4 - .293 <z-15>^4 - 7.04 <z-18>^3 + C_{1x} * x + C_{2x}$$

$$EIy(0) = -3.99 (0)^3 - .463 (0)^4 + .463 (0)^4 + .629 (0)^4 - .629 (0)^4 - 3.99 (0)^3 + C_{1y} * 0 + C_{2y} = 0 = C_{2y}$$

69

$$EIx(0) = -7.04\,(0)^3 + .293(0)^4 - .293\,(0)^4 - 7.04\,(0)^3 + C_{1x} * 0 + C_{2x} = 0 = C_{2x}$$

$$EIy(18) = -3.99\,(18)^3 - .463\,(18-3)^4 + .463\,(18-15)^4 + .629\,(18-3)^4 - .629\,(18-15)^4 + C_{1y} * 18$$

$$+ 0 = 0 = -46683 + C_{1y} * 18$$

$$C_{1y} = 2593.5$$

$$EIx(18) = -7.04\,(18)^3 + .293(18-3)^4 - 7.04\,(18-3)^3 + C_{1x} * 18 + 0 = 41079 + C_{1x} * 18$$

$$C_{1x} = -2282.2$$

Symmetrical, continuous distributed load: maximum deflection at midpoint, z = 9

$$EIy(9) = -3.99\,(9)^3 - .463\,(9-3)^4 + .629\,(9-3)^4 + 2593.5 * 9 = 19834$$

$$y(9) = \frac{19834}{2.9*10^7 *.015625} = .0438\ in$$

$$EIx(9) = -7.04\,(9)^3 + .293(9-3)^4 - 7.04\,(9-3)^3 + C_{1x} * 9 = -15403$$

$$x(9) = \frac{-15403}{2.9*10^7 *.015625} = -.0340\ in$$

$$d(9) = \sqrt{(y(9))^2 + (x(9))^2} = .0554\ in$$

$$M_x(9) = 42.26 * (9) - 3.52 * (9-3)^2 = 253.54\ lb\ in$$

$$M_y(9) = -23.96 * (9) + 5.56 * (9-3)^2 - 7.55 * (9-3)^2 = -287.56\ lb\ in$$

$$M(9) = \sqrt{(253.54\ lb\ in)^2 + (-287.56\ lb\ in)^2} = 383.37\ lb\ in$$

$$\sigma(z) = \frac{M*r}{I}$$

$$\sigma(z) = 3905\ \frac{lb}{in^2}$$

70

Assuming

$$\tau = \frac{T*r}{J}$$

$$J = pi * \frac{1}{2} * (\frac{1}{2})^4 = .09817 \; in^4$$

$$\tau = \frac{1000 \; in \; lb * .5 \; in}{.09817 \; in^4} = 5092.96 \frac{lb}{in^2}$$

Bending, rotation: fully reversed loading

$$\sigma_a = \frac{\sigma_{maximum} - \sigma_{minimum}}{2} = \frac{3905 - (-3905)}{2} = 3905 \frac{lb}{in^2}$$

$$\sigma_m = \frac{\sigma_{maximum} + \sigma_{minimum}}{2} = \frac{3905 + (-3905)}{2} = 0$$

Intermittent gearing: repeated torque loading

$$\tau_a = \frac{\tau_{maximum} - \tau_{minimum}}{2} = \frac{5092.96 - 0}{2} = 2546.48 \frac{lb}{in^2}$$

$$\tau_m = \frac{\tau_{maximum} + \tau_{minimum}}{2} = \frac{5092.96 + 0}{2} = 2546.48 \frac{lb}{in^2}$$

$$\frac{1}{n} = \frac{\sigma_a'}{S_e} + \frac{\sigma_m'}{S_{ut}}$$

$$\sigma_a' = \sqrt{\sigma_a^2 + 3\tau_a^2} = \sqrt{3905^2 + 3 * 2546^2} = 5890.9 \frac{lb}{in^2}$$

$$\sigma_m' = \sqrt{\sigma_m^2 + 3\tau_m^2} = \sqrt{0^2 + 3 * 2546^2} = 4410.6 \frac{lb}{in^2}$$

$$S_e = k_a k_b k_c k_d k_e k_f S_e'$$

$$k_a = 2.7 \, (S_{ut}(kpsi))^{-.265} = 2.7 \, (60.9)^{-.265} = .909$$

$$k_b = (\varnothing/.3)^{-.107} = (1/.3)^{-.107} = .879$$

$$k_c = 1 \; (bending)$$

$$k_d = 1$$

$$k_e = .753 \; (99.9\% \; reliability)$$

$$k_f = 1$$

$$S_{e'} = \frac{S_{ut}}{2} = 30450 \ \frac{lb}{in^2}$$

$$S_e = .909 * .879 * 1 * 1 * .753 * 1 * 30450 = 18318 \frac{lb}{in^2}$$

$$\frac{1}{n} = \frac{5890.9}{18318} + \frac{4410.6}{60900} = .394$$

$$n = 2.54$$

As calculated, the shaft can survive infinite cycling. Updating these calculations to account for the standard ¾" rod purchased implemented across the device, the shaft cannot survive infinite cycling.

$$I = pi * \frac{1}{4} * (\frac{3/4}{2}in)^4 = .0155 \ in^4$$

$$J = pi * \frac{1}{2} * (\frac{3/4}{2})^4 = .0311 \ in^4$$

$$\sigma(z) = \frac{M*r}{I} = 12341.8$$

$$\tau = \frac{T*r}{J} = 12072.2 \frac{lb}{in^2}$$

$$\sigma_a = \frac{\sigma_{maximum} - \sigma_{minimum}}{2} = \frac{12341.8 - (-12341.8)}{2} = 12341.8 \frac{lb}{in^2}$$

$$\sigma_m = \frac{\sigma_{maximum} + \sigma_{minimum}}{2} = \frac{12341.8 + (-12341.8)}{2} = 0$$

$$\tau_a = \frac{\tau_{maximum} - \tau_{minimum}}{2} = \frac{12072.2 - 0}{2} = 6036.1 \frac{lb}{in^2}$$

$$\tau_m = \frac{\tau_{maximum} + \tau_{minimum}}{2} = \frac{12072.2 + 0}{2} = 6036.1 \frac{lb}{in^2}$$

$$\sigma_{a'} = \sqrt{\sigma_a^2 + 3\tau_a^2} = 16174.8 \frac{lb}{in^2}$$

$$\sigma_{m'} = \sqrt{\sigma_m^2 + 3\tau_m^2} = 10454.8 \frac{lb}{in^2}$$

$$k_b = (\emptyset/.3)^{-.107} = (\frac{3}{4}/.3)^{-.107} = .907$$

$$S_e = .909 * .907 * 1 * 1 * .753 * 1 * 30450 = 18890 \frac{lb}{in^2}$$

$$\frac{1}{n} = \frac{\sigma_a'}{S_e} + \frac{\sigma_m'}{S_{ut}} = \frac{16174.8}{18890} + \frac{10454.8}{60900} = 1.028$$

$$n = .973$$

$$N = \left(\frac{\sigma_{rev}}{a}\right)^{1/b}$$

$$\sigma_{rev} = \frac{\sigma_a'}{1 - \sigma_n'/S_{ut}} = \frac{16174.8}{1 - 10454.8/60900} = 19527 \frac{lb}{in^2}$$

$$a = \frac{(f*S_{ut})^2}{S_e} = \frac{(.9*60900)^2}{18890} = 159029$$

$$b = \frac{1}{3}\log_{10}\left(\frac{S_e}{f*S_{ut}}\right) = \frac{1}{3}\log_{10}\left(\frac{18890}{f*60900}\right) = -.154$$

$$N = (19527/159029)^{1/(-.154)} = 806613 \text{ cycles to failure}$$

Appendix H: Steel Tube vs. Aluminum T-slot Analysis

Known: Dimensions of frame

Find: Deflection of frame, static loading factor of safety

Assumptions:

1. Maximum allowable empty load of 500 pounds of load on the frame and 40 pounds of trees (an overestimate taken for convenience), neglecting the weight of the frame sides.

2. All the weight is held by the vertical components for the planting device and digging device, with the weight distributed evenly within these systems.

3. One side of the frame is calculated for, so weight values used are half of the total. This analysis includes the hitch, which is centered and will experience the full load. The length for which this is relevant (0-12.94") will be analyzed individually after the full beam analysis.

Boundary conditions: $y(0) = 0$, $y(57.37) = 0$

4. Assuming the hitch carries 15% of the total load, as per the project specifications

Loading diagrams:
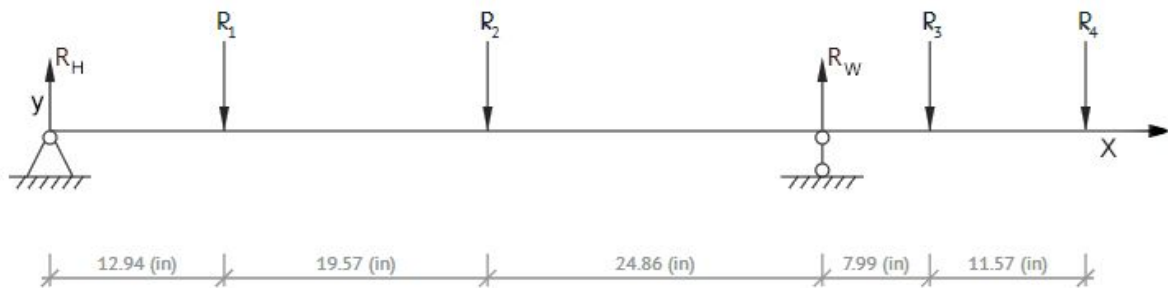
Idealized frame side (image via beamguru.com)
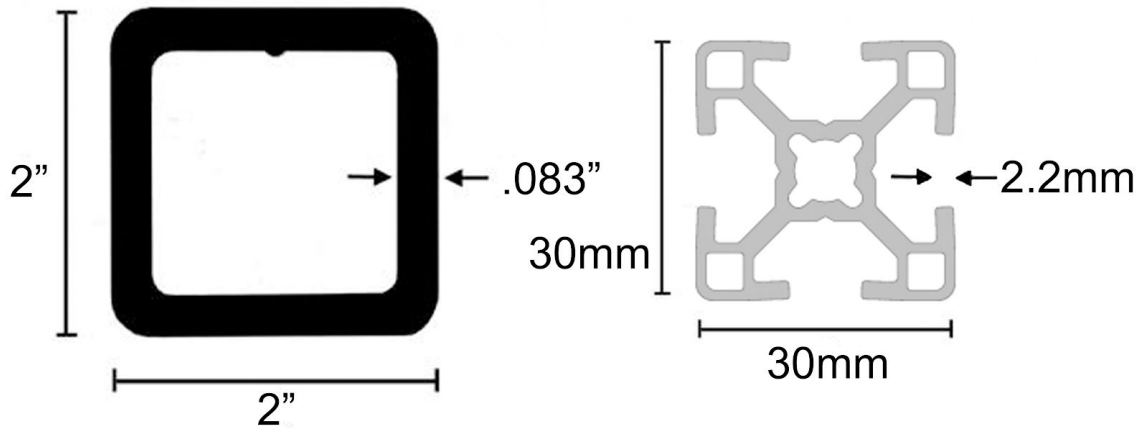
Profile images via Metals Depot (left) and 80/20 (right)

Terms:

P1 and P2: Weight of the bin and digging devices on the frame. P1+P2 taken as half of the total weight of the devices, distributed evenly between the two

P3 and P3: Weight of the planting device on the frame. P3+P4 taken as half of the total weight of the device, distributed evenly between the two

Rh: Reaction of the hitch. Ideally 9-15% of the total trailer weight

Rw: Reaction of the wheels.

E: modulus of elasticity, taken as $2.7*10^7$ psi for the steel used and $1.0*10^7$ for the aluminum used

I: area moment of inertia of the frame component along y/z direction. Taken as $.3825in^4$ for the 2 in^2 profile square bar (via SolidWorks), $.0654in^4$ for the 30mm^2 profile t-slot (via 20/80), and $.2542in^4$ for the 1.5 in^2 profile t-slot.

d: deflection of frame

σ: tensile stress induced in beam via bending

n: static loading factor of safety

The case of the t-slot profile selected will be shown

Defined above: $Rh = .15 * \frac{540}{2} = 40.5$

$R1 = R2$

$R3 = R4$

$\Sigma F_x = 0$

$\Sigma F_y = Rh - R1 - R2 + Rw - R3 - R4 = 0$

$Rh + Rw = R1 + R2 + R3 + R4 = 270 = 40.5 + Rw$

$Rw = 270 - 40.5 = 229.5$

$\Sigma M_z(0) = -R1 * 12.94in - R2 * 32.51in + Rw * 57.37in - R3 * 65.35in - R4 * 76.93in = 0$

$229.5lb * 57.37in = R1 * 12.94in + R1 * 32.51in + R3 * 65.36in + R3 * 76.93in = 13166.4 \; in \; lb$

$R1 * 45.45 + R3 * 142.29 = 13166.4 \; in \; lb$

$2R1 + 2R3 = 270 \; in \; lb$

$45.45 \; R1 - 2R1 * \frac{45.45}{2} + 142.29 \; R3 - 2R3 * \frac{45.45}{2} = 13166.4 \; in \; lb - 270 * \frac{45.45}{2} \; in \; lb$

$96.84in * R3 = 7030.65 \; in \; lb$

$R3 = 72.6 = R4$

$R1 = \frac{(270 - 2*72.6)}{2} = 62.4 = R2$

$$q(x) \;=\; 40.5 <x>^{-1} - 62.4 <x-12.94>^{-1} - 62.4 <x-32.51>^{-1} + 229.5 <x-57.37>^{-1}$$

$$- 72.6 <x-65.36>^{-1} - 72.6 <x-76.93>^{-1}$$
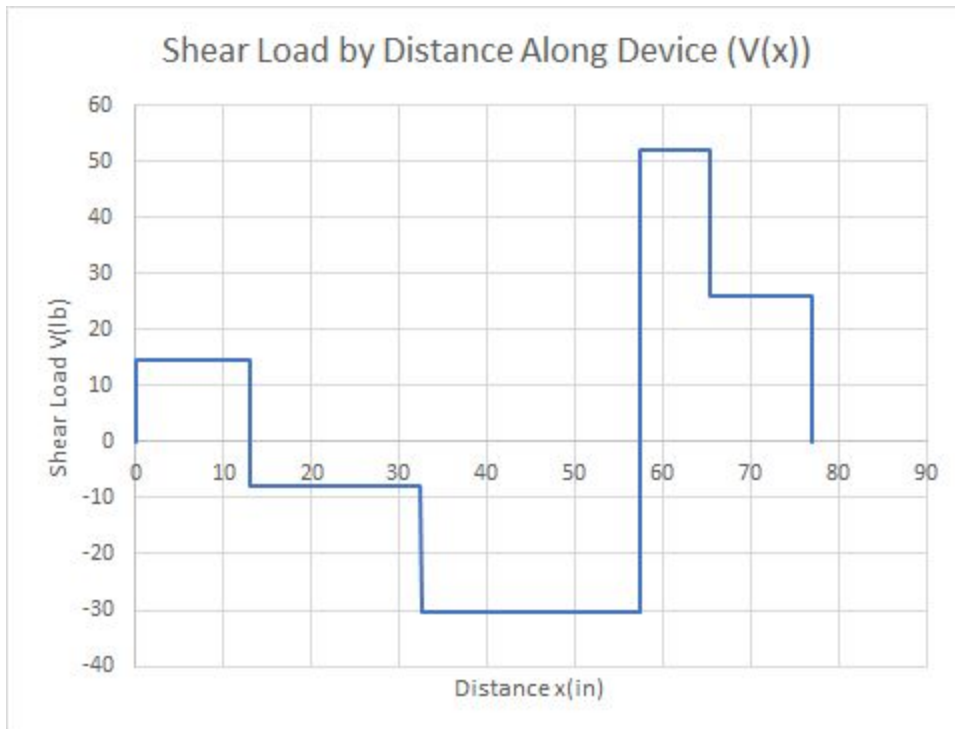
Shear load as a function of distance from the hitch

$$V(x) \;=\; 40.5 <x>^{0} - 62.4 <x-12.94>^{0} - 62.4 <x-32.51>^{0} + 229.5 <x-57.37>^{0}$$

$$- 72.6 <x-65.36>^{0} - 72.6 <x-76.93>^{0}$$
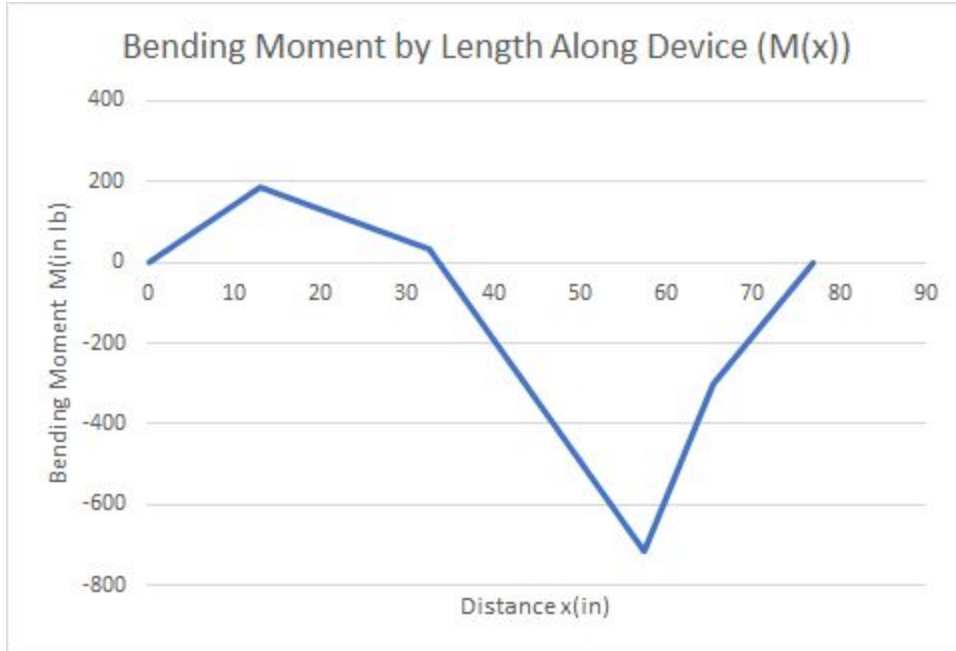
Bending moment as a function of distance from the hitch

$$M(x) = 40.5 <x>^1 - 62.4 <x - 12.94>^1 - 62.4 <x - 32.51>^1 + 229.5 <x - 57.37>^1$$

$$- 72.6 <x - 65.36>^1 - 72.6 <x - 76.93>^1$$
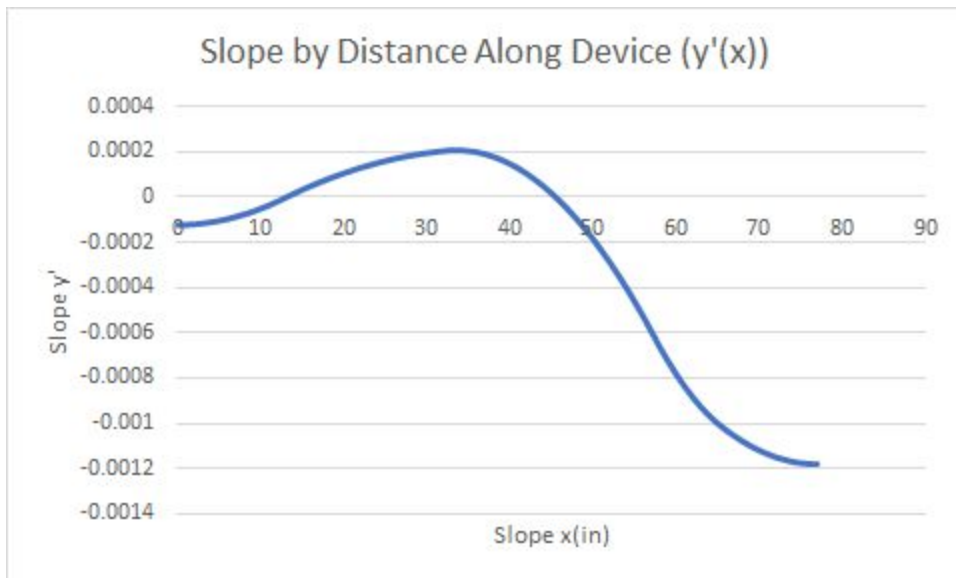
Slope as a function of distance from the hitch

$$EIy'(x) = 20.25 <x>^2 - 32.2 <x-12.94>^2 - 32.2 <x-32.51>^2 + 114.75 <x-57.37>^2$$

$$- 36.3 <x-65.36>^2 - 36.3 <x-76.93>^2$$
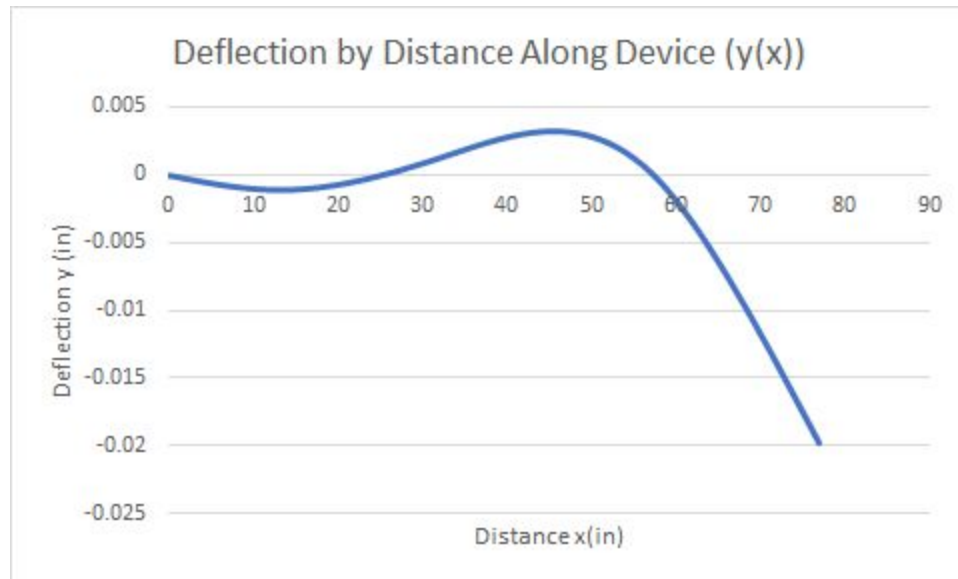
Deflection as a function of distance from the hitch

$$EIy(x) = 6.75 <x>^3 - 10.4 <x-12.94>^3 - 10.4 <x-32.51>^3 + 38.25 <x-57.37>^3$$

$$- 12.1 <x-65.36>^3 - 12.1 <x-76.93>^3$$

A maximum deflection on the order of .80" can be observed at the back of the trailer

Maximum moment occurs at a point of zero shear: where forces are applied

Solving for M(12.94), M(32.51), M(57.37), M(65.36), M(76.92)

$$M(max) = M(57.38) = 40.5lb(57.37in)^1 - 62.4lb(57.37in - 12.94in)^1 - 62.4lb(57.37in - 32.51in)^1$$

$$+ 229.5lb(57.38in - 57.37in)^1$$

$$M(57.38) = -2000.15 \ in \ lb$$

$$\sigma = -\frac{M*r}{I} = \frac{2000.15 \ in \ lb * .847 \ in}{.0654 \ in^4} = 25893.9 \ \frac{lb}{lb^2}$$

$$n_{ut} = \frac{S_{ut}}{\sigma} = \frac{35000 \ psi}{25893.3 \ psi} = 1.74$$

$$n_y = \frac{S_y}{\sigma} = \frac{50800 \ psi}{25893.3 \ psi} = 1.35$$

Appendix I: Bill of Materials for Prototype

BOM for Material Stock and Off-the-Shelf Parts			
AFE: Accounted for elsewhere, stock material used across functional areas			
Functional Area	Component Name	Quantity	Off-The-Shelf
Bin	Conveyor belt axle	1	N
	conveyor belt rubber	1	N
	rubber flap	1	Y
	large gear	1	Y
	small gear	1	Y
	gear axles	1	N
	3/8 sleeve bearing	3	Y
	1/2 sleeve bearing	4	Y
	3/4 sleeve bearing	8	Y
	1/2 bearing clamp	1	Y
	3/4 bearing clamp	1	Y
	tree hooks	1	N
	bin siding	2	N
Wheels	axle	2	N
	bearing	4	Y
	plate for wheel-axle attachment	AFE	N
	frond gear/plate/peg gear material	AFE	N
	sprocket	2	Y
	small gear (1:8)	1	Y
	large gear (1:8)	1	Y
	14" wheel	2	Y
Planting arm	arm	AFE	N
	Torsional Spring	2	Y
	axle	AFE	N
	rails	1	N

	sprocket	1	Y
	chain	1	Y
Digging arm	cone	1	N
	arm	AFE	N
	axle	0	N
	sprocket	1	Y
	chain	1	Y
	Rollers		
Chassis	T-slot framing	1	N
	90 degree attachments	0	Y
	Metal plate for angled attachments	1	N
	3/4 inch sprocket	1	Y
	3/8 inch sprocket	2	Y
	T-slot nuts (50)	2	Y
	Threaded rod	1	Y
	Plywood for peg gear/frond gear and bin	1	N

Appendix J: Cone Test Results

1 year fallow dirt		
Mass (lb)	**Depth sunk (in)**	**Notes**
1	1.5	Mass of cone
4	2	Mass of cone and platform
9	2.125	5 lb
14	2.25	10 lb
19	2.375	15 lb
24	2.75	20 lb, moved stake
29	3	25 lb
34	2.875	30 lb
44	3.125	40 lb
54	3.5	50 lb, platform collapsed
135	5.75	Body weight standing on cone

Measurements at 4 and 20 lbs are less accurate because platform placement wiggled the cone into the ground. Readjusting the support stakes had a similar effect.

Appendix H: Fabrication Drawings

The following drawings are included to give detailed views of each unique sub assembly and unique parts. They are ordered as listed below:

1. Entire Mechanism
2. Entire Mechanism Exploded View
3. Chassis
4. Chassis Exploded View
5. Hole Digging Mechanism
6. Hole Digging Mechanism Exploded View
7. Tree Separator
8. Tree Separator Exploded View
9. Tree Placer
10. Tree Placer Exploded View
11. Hole Filler
12. Hole Filler Exploded View
13. Wheel & Gear Assembly
14. Wheel & Gear Assembly Section View
15. Wheel & Gear Assembly Exploded View
16. Digging Linkage
17. Digging Cone Head
18. Retention Wall
19. Tree Funnel
20. Planting Linkage
21. Planting Support Linkage
22. Packing Wheels
23. Frond Gear
24. Peg Gear

2

1

B

B

34.44

85.49

74.54

A

A
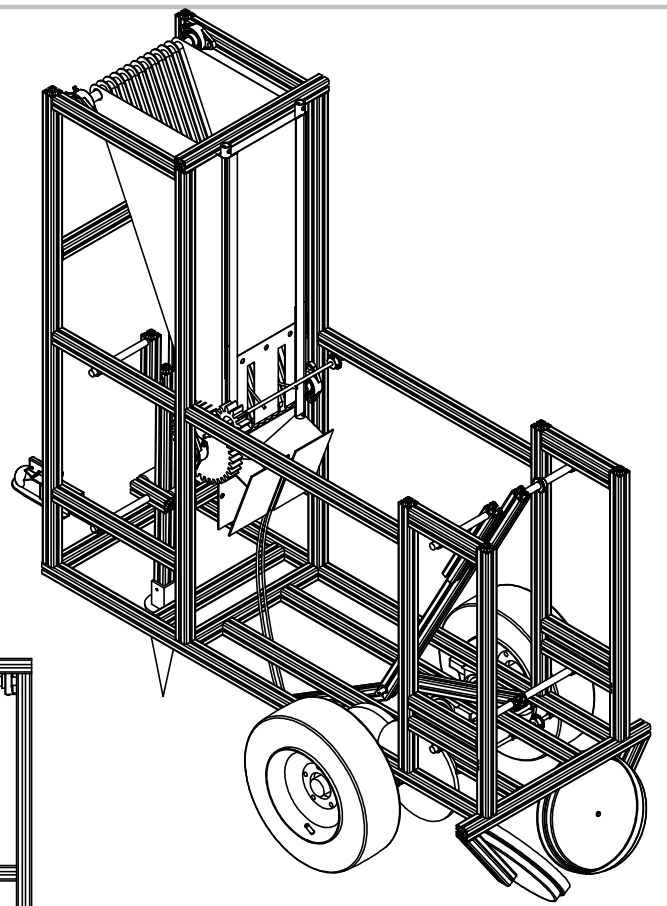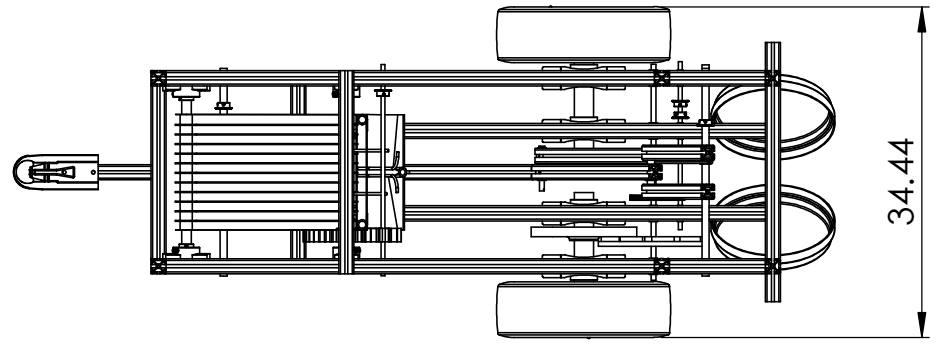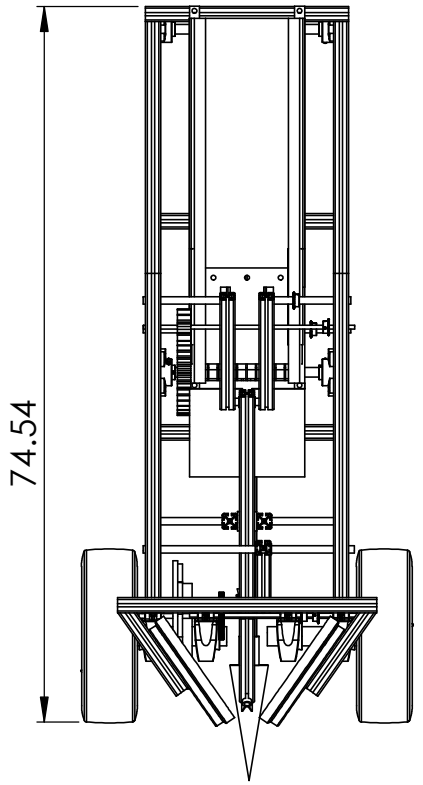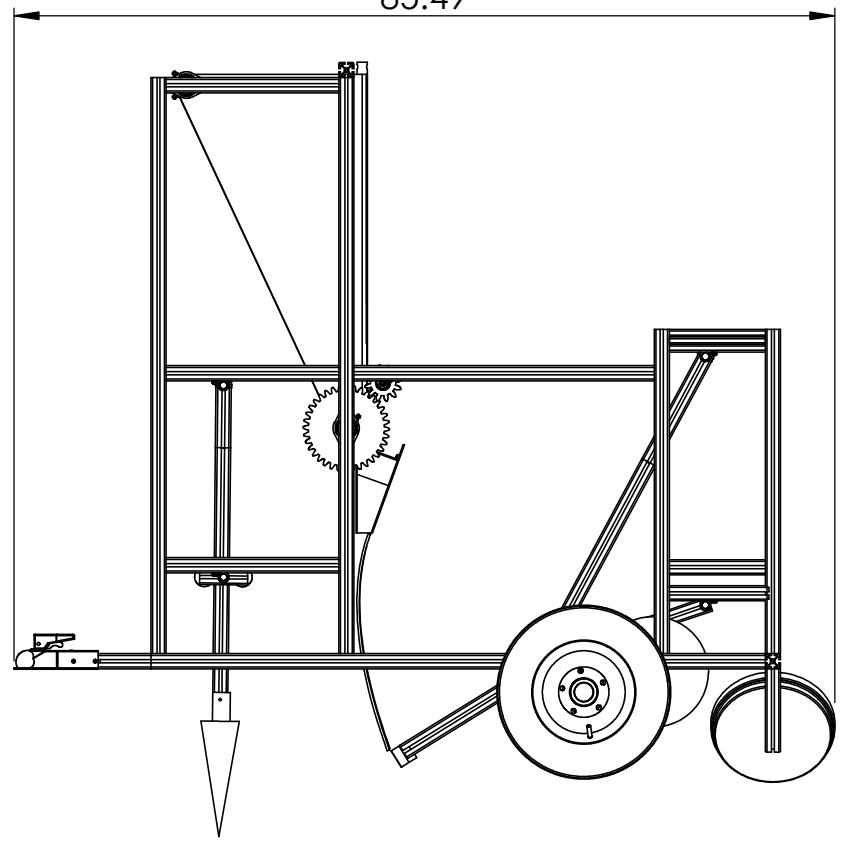
Tree Seedling Planter

COMPONENT: ENTIRE MECHANISM

SCALE: 1:20

SHEET 1 OF 1

2

1

ITEM NO.	PART NUMBER	QTY.
1	Chassis	1
2	Wheel & Gear Assembly	1
3	Packing Wheels	1
4	Tree Separator	1
5	Tree Placer	1
6	Hole Digger	1
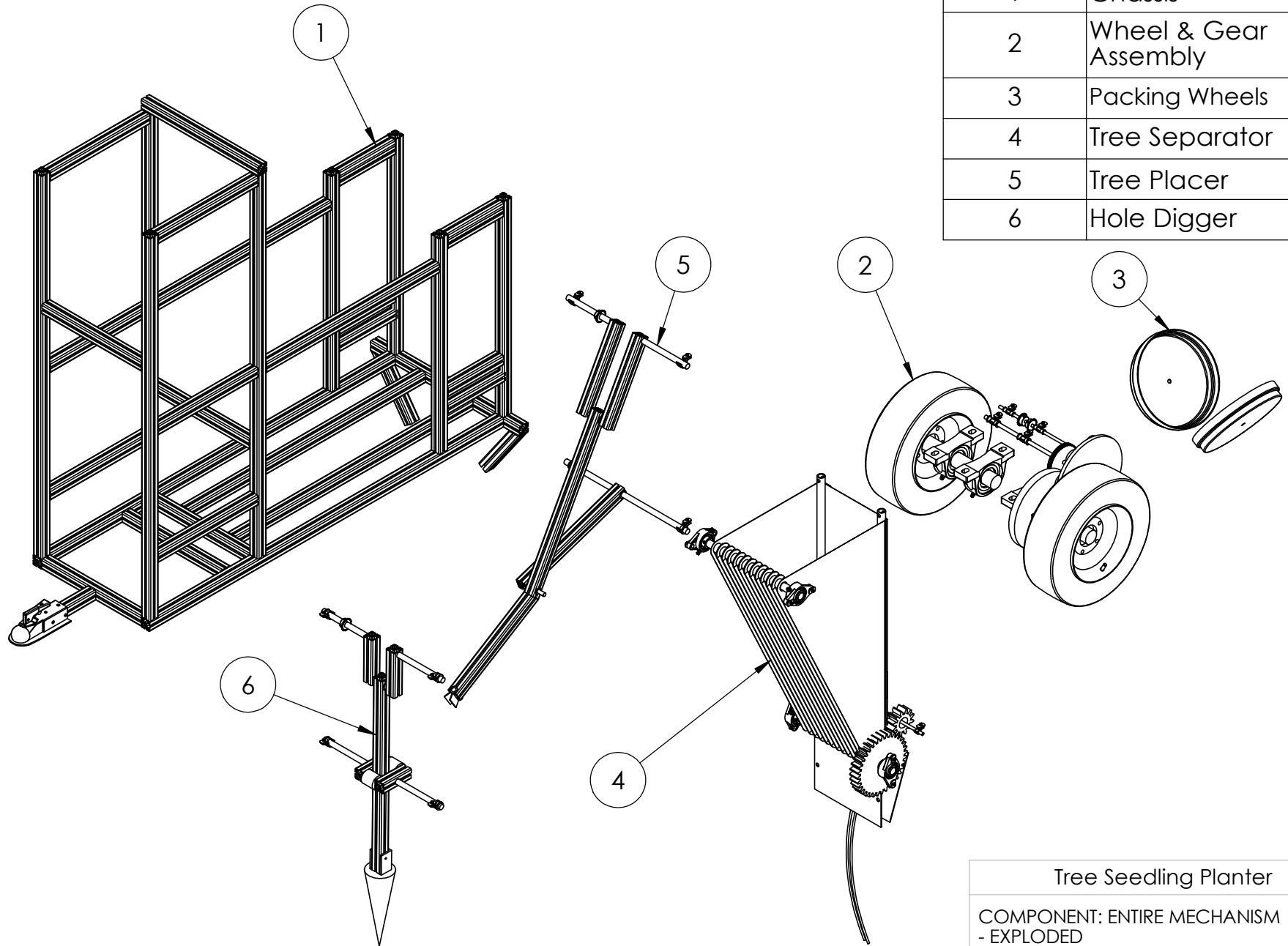
	Tree Seedling Planter
	COMPONENT: ENTIRE MECHANISM - EXPLODED
SCALE: 1:18	SHEET 1 OF 1

2

1

B

B

27.00

74.40

70.15

A

A
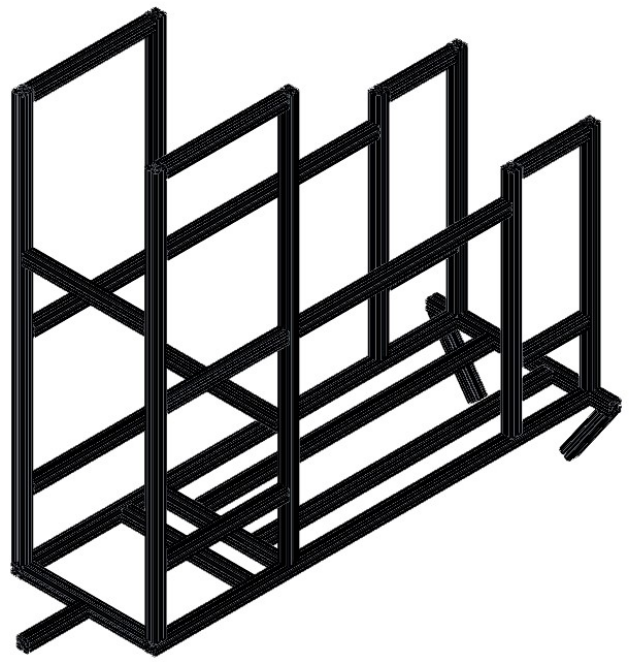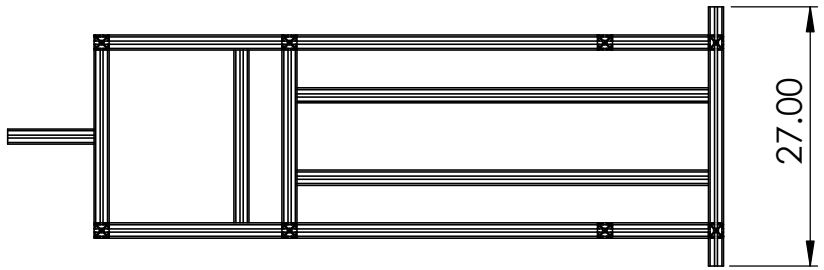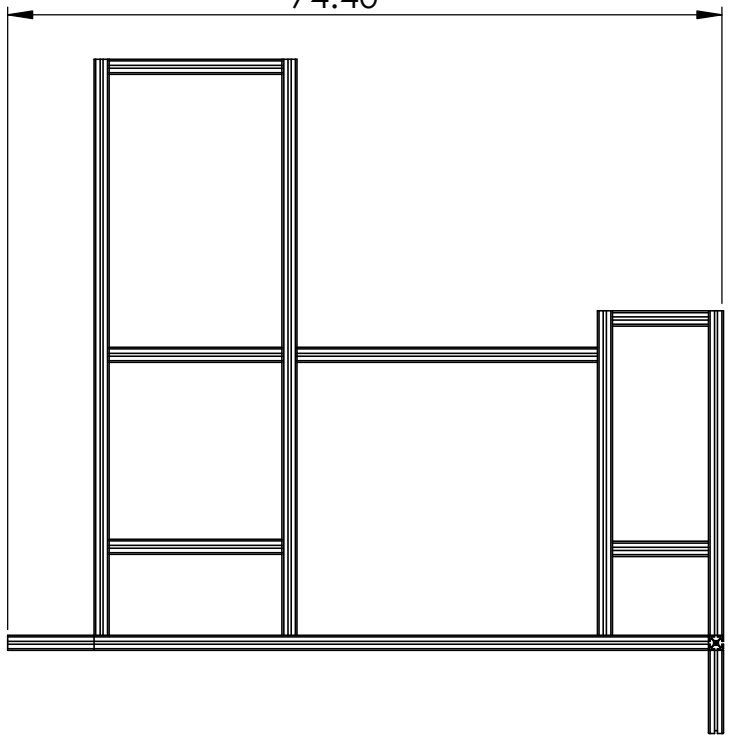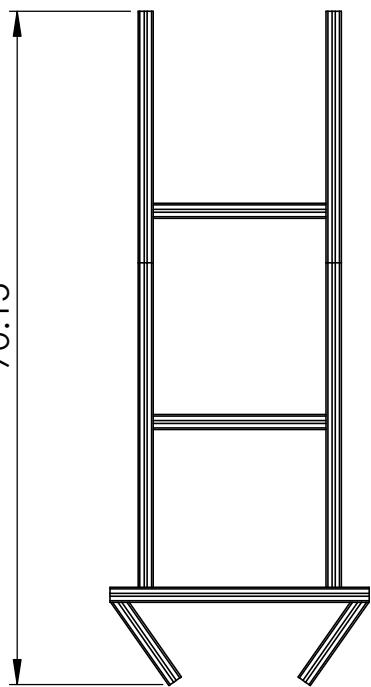
Tree Seedling Planter	
COMPONENT: CHASSIS	
SCALE: 1:20	SHEET 1 OF 1

2

1

ITEM NO.	QTY.	LENGTH (in)
1	1	9
2	11	18
3	2	64
4	1	27
5	4	33.79
6	2	42.85
7	4	10
8	2	10.59
9	4	60
10	2	31.28
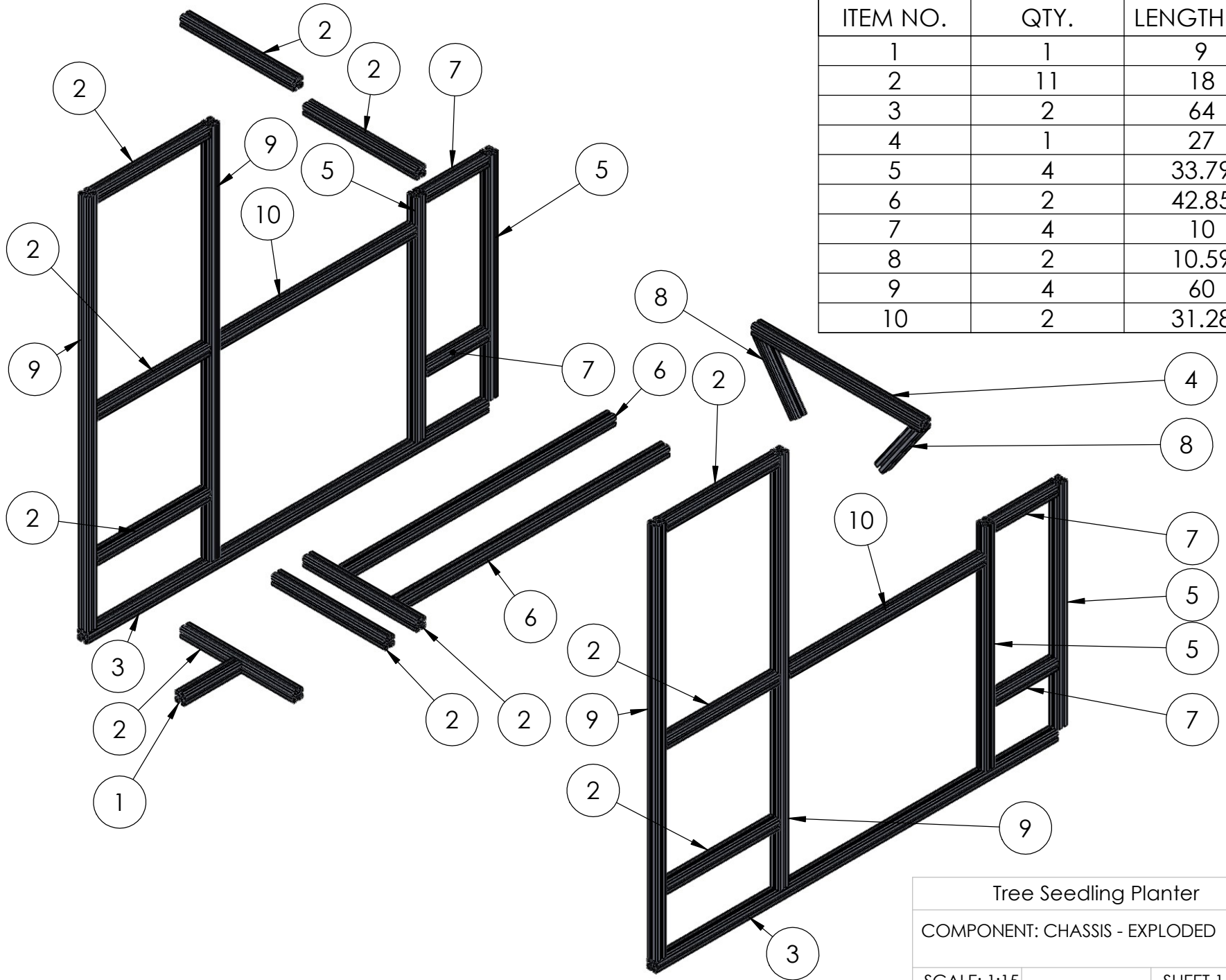
Tree Seedling Planter

COMPONENT: CHASSIS - EXPLODED

SCALE: 1:15   SHEET 1 OF 1

2

1

B

B

6.00

21.65

6.00

14.00

47.00

A

A
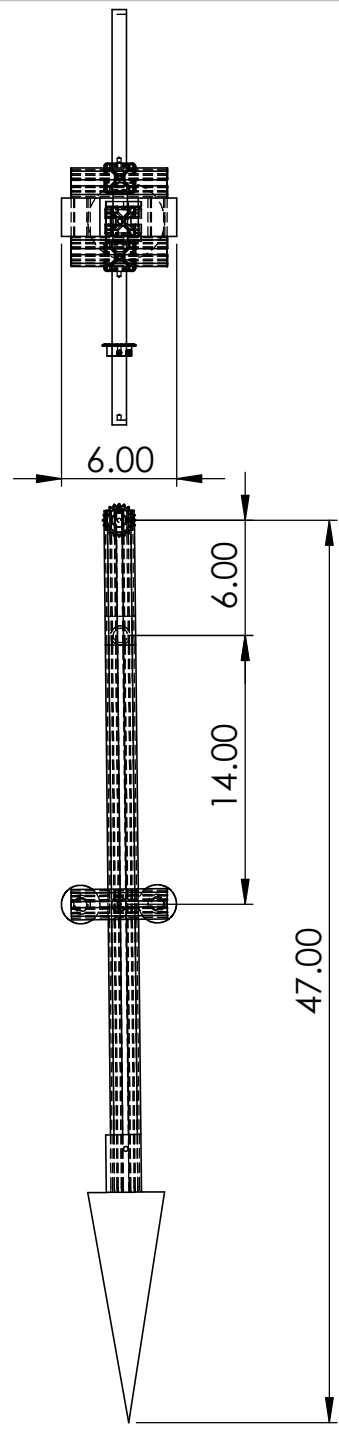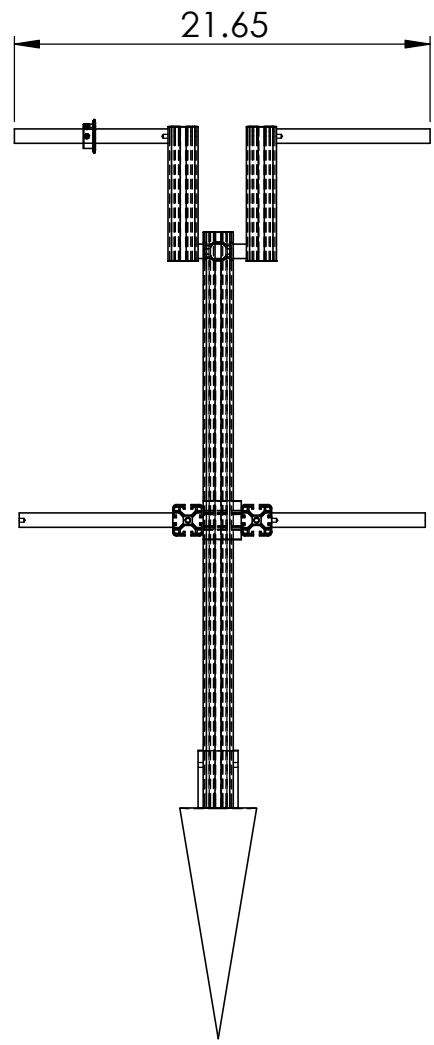
Tree Seedling Planter

COMPONENT: HOLE DIGGER

SCALE: 1:10

SHEET 1 OF 1

2

1
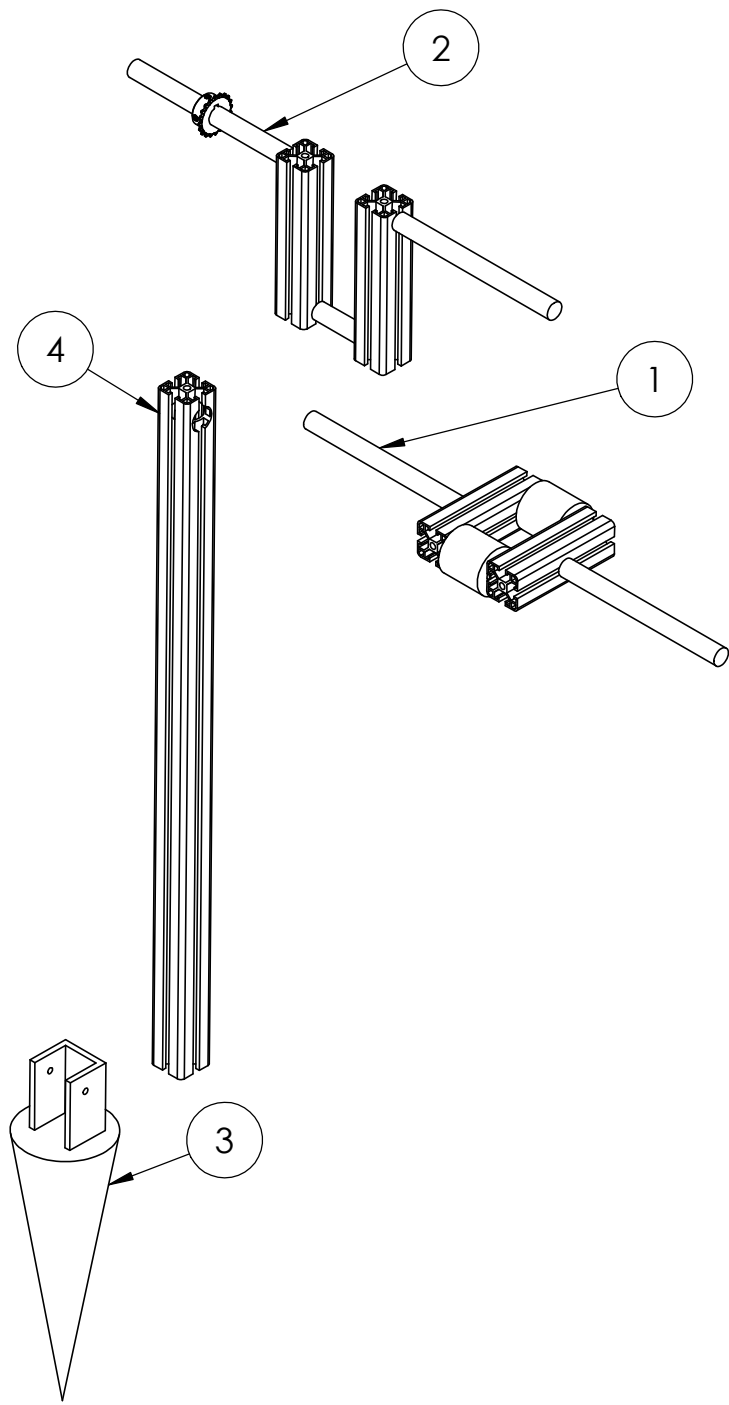
ITEM NO.	PART NUMBER	QTY.
1	Bearing Arm	1
2	Driving Arm	1
3	Digging Cone Head	1
4	Digging Arm	1

B

B

2

4

1

A

3

A

Tree Seedling Planter

COMPONENT: HOLE DIGGER - EXPLODED

SCALE: 1:7   SHEET 1 OF 1

2

1

B

B

26.92

22.00

25.00°

48.96

A

A
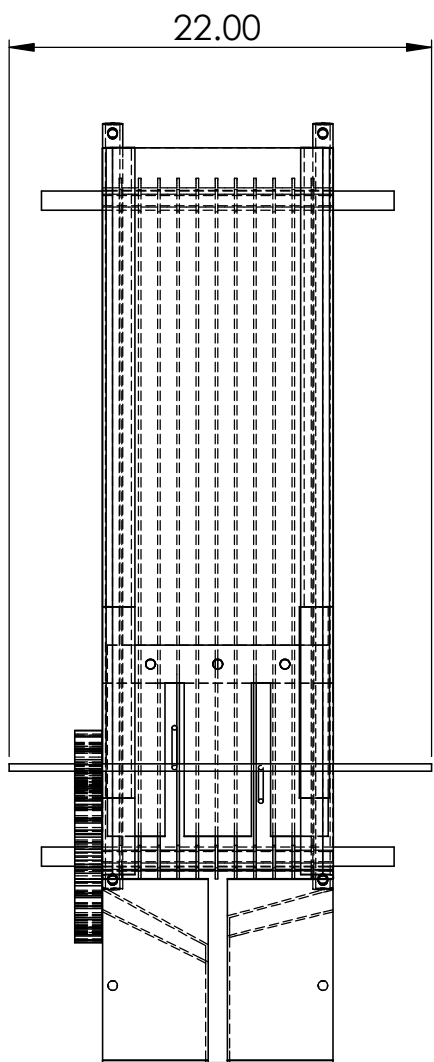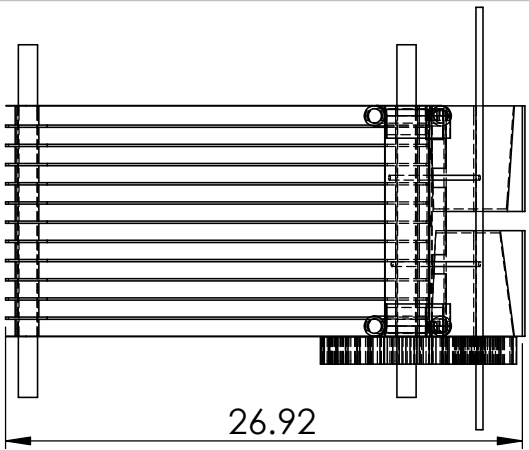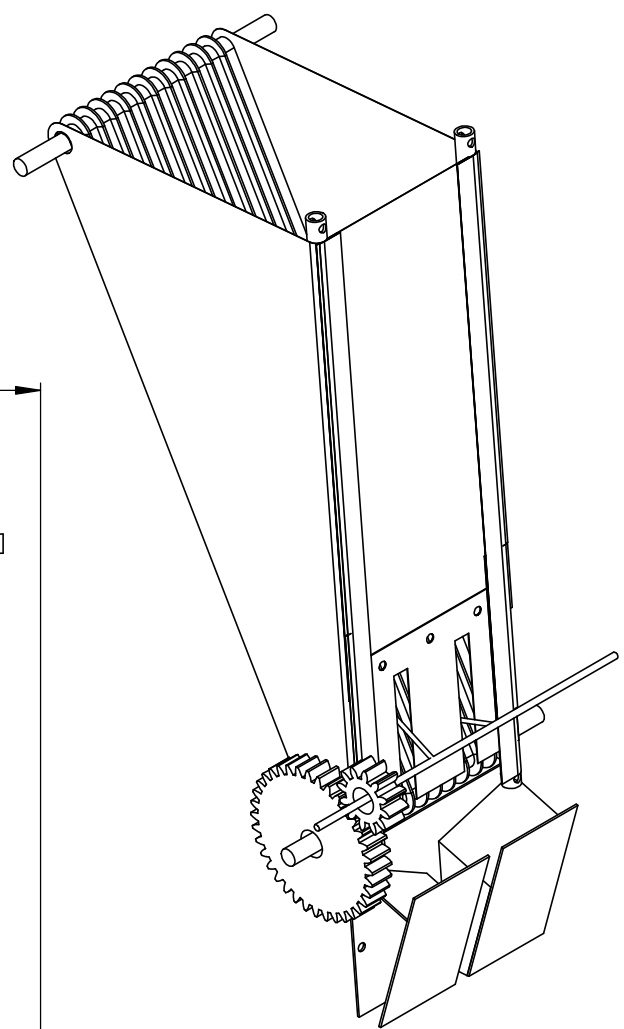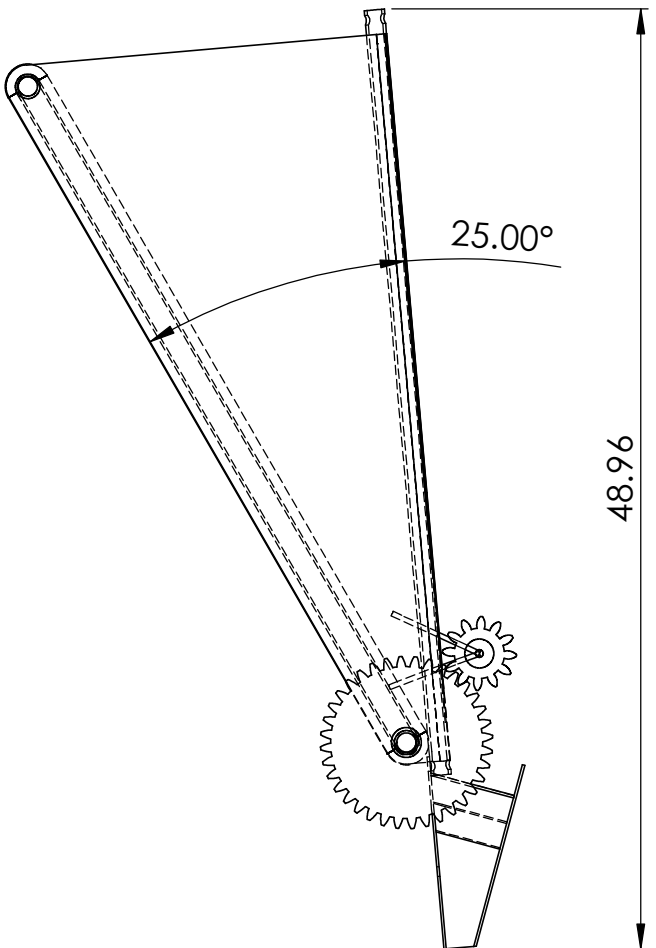
Tree Seedling Planter

COMPONENT: TREE SEPARATOR

SCALE: 1:10

SHEET 1 OF 1

2

1

ITEM NO.	PART NUMBER	QTY.
1	Conveyor Belt Axle	2
2	Separator	1
3	Conveyor Belt	1
4	Funnel	1
5	Large Spur Gear	1
6	Small Spur Gear	1
7	Cloth Wall	1
8	Retention Wall	1
9	Cloth Support Rod	2
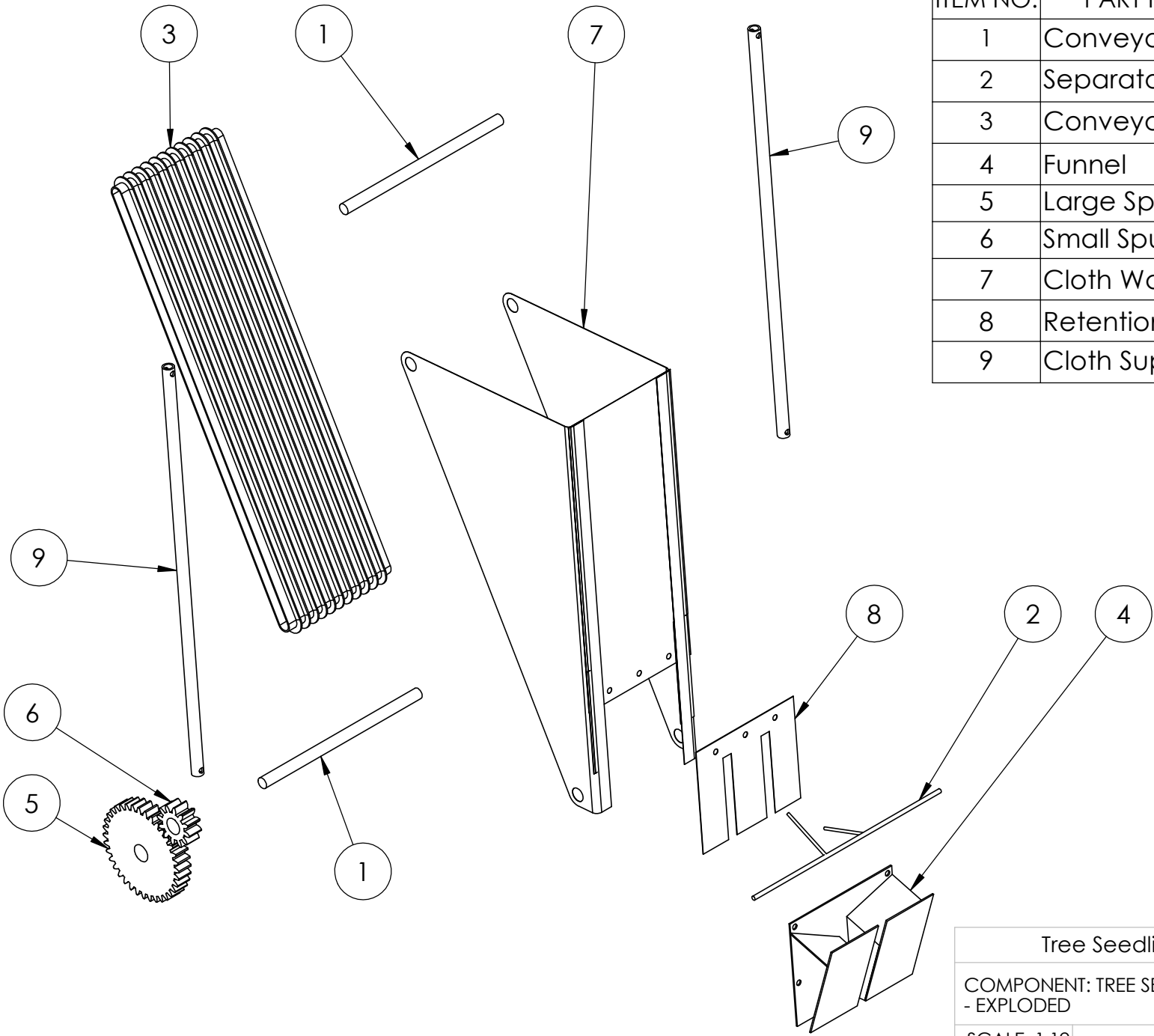
Tree Seedling Planter

COMPONENT: TREE SEPARATOR - EXPLODED

SCALE: 1:12

SHEET 1 OF 1

33.50

12.00

24.00

18.00

43.50

22.00
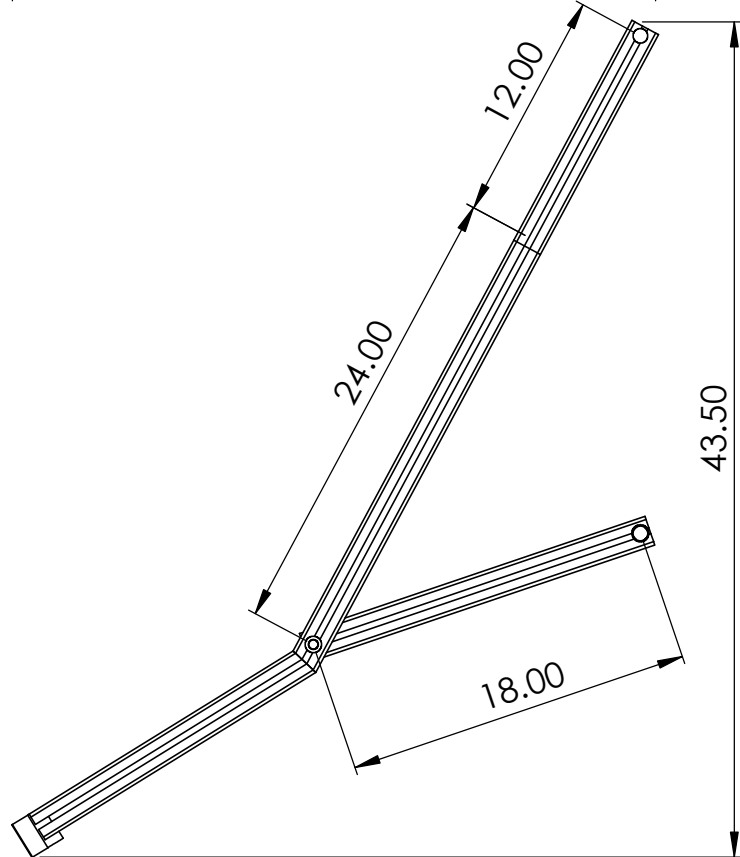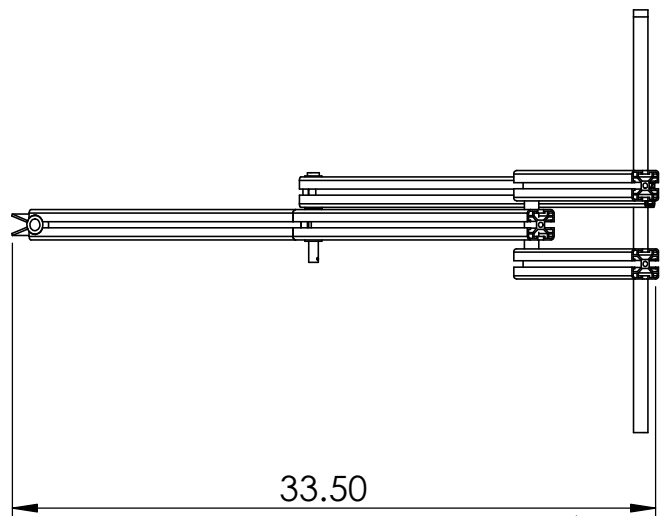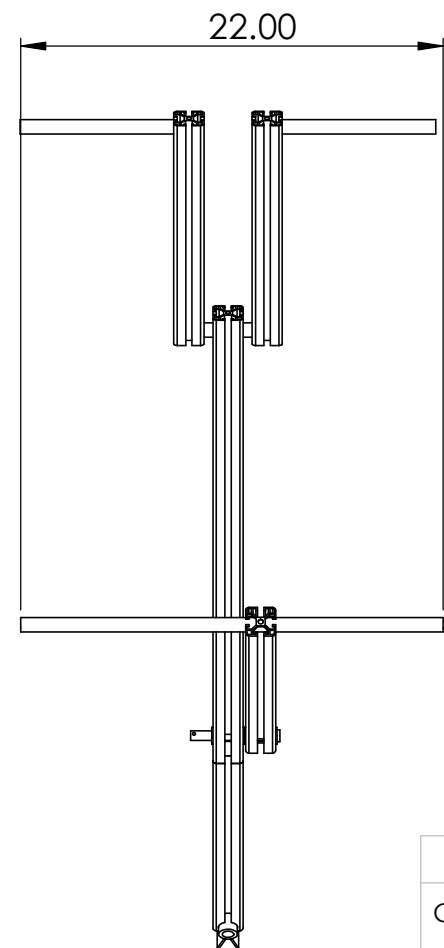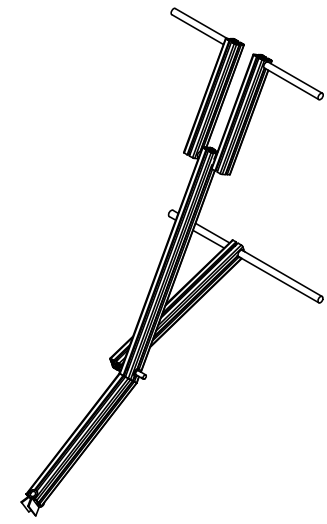
Tree Seedling Planter

COMPONENT: TREE PLACER

SCALE: 1:10

SHEET 1 OF 1

2

1

B

B

A

A

B

B
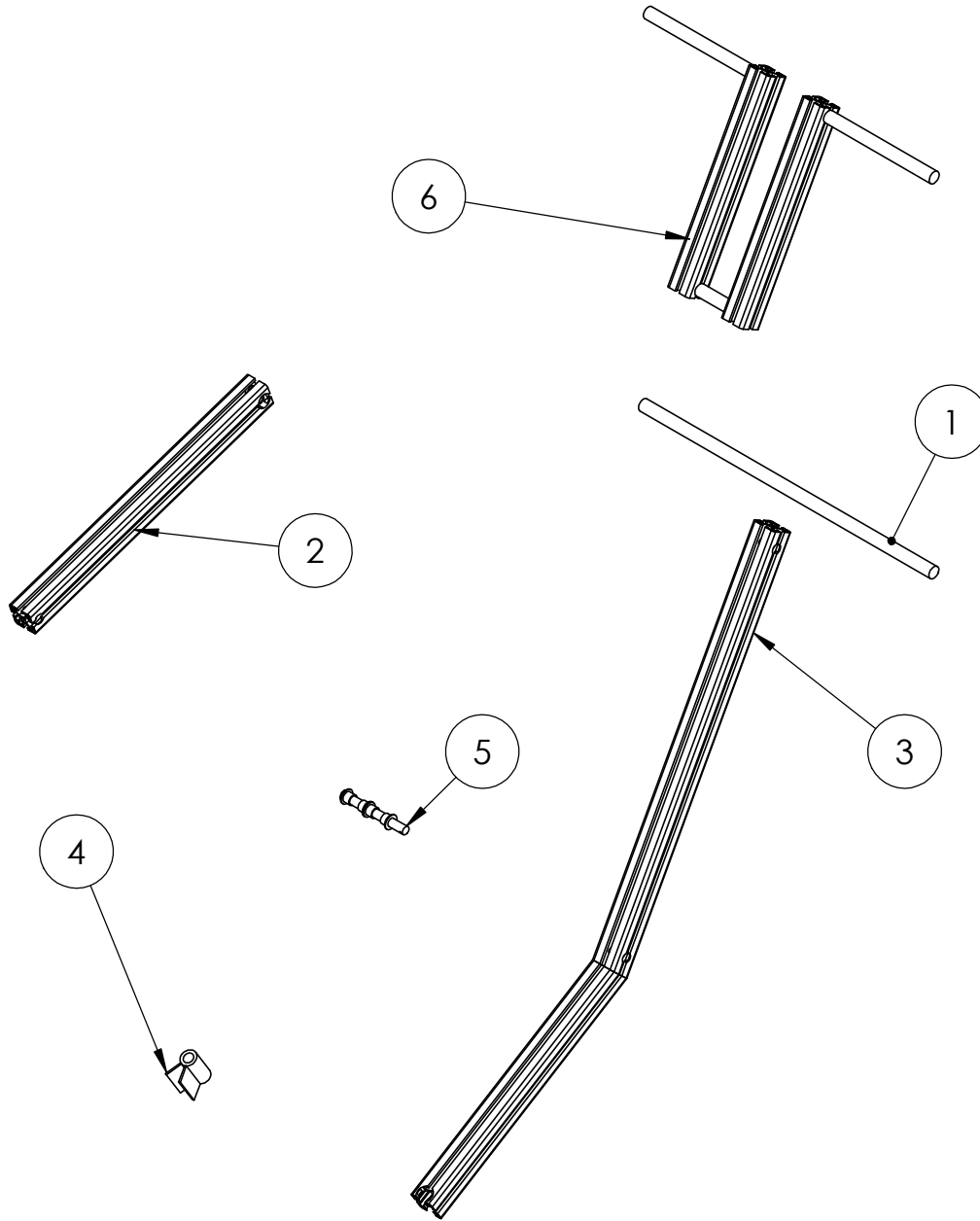
ITEM NO.	PART NUMBER	
1	Supporting Linkage Axle	1
2	Supporting Linkage	1
3	Placing Linkage	1
4	Torsional Spring Clamp	1
5	Pin & Bearing Assembly	1
6	Driving Arm Assembly	1

A

A

	Tree Seedling Planter
	COMPONENT: TREE PLACER - EXPLODED
SCALE: 1:10	SHEET 1 OF 1

2

1

B

B

27.00

⌀12.90

13.37

A

A
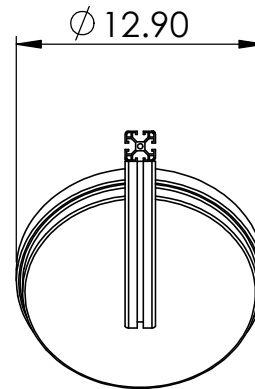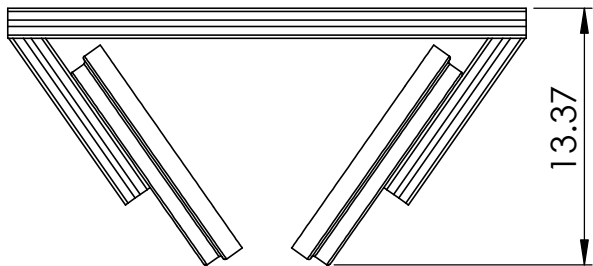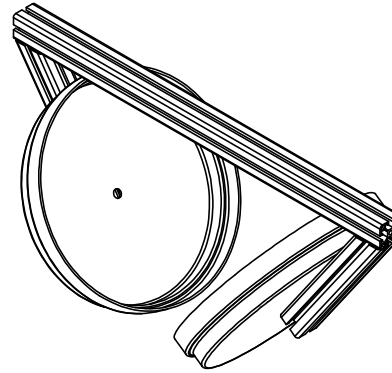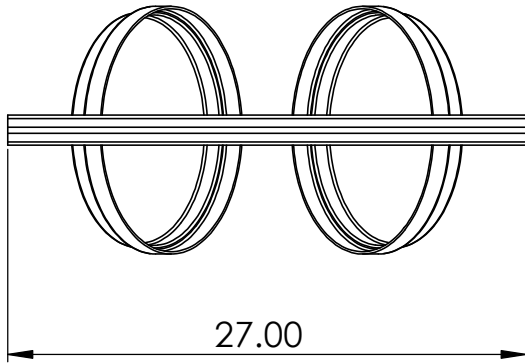
Tree Seedling Planter

COMPONENT: HOLE FILLER

SCALE: 1:10

SHEET 1 OF 1

2

1

ITEM NO.	PART NUMBER	QTY.
1	Weldment Base	1
2	Packing Wheel	2

B

B

1

A

A

2

2
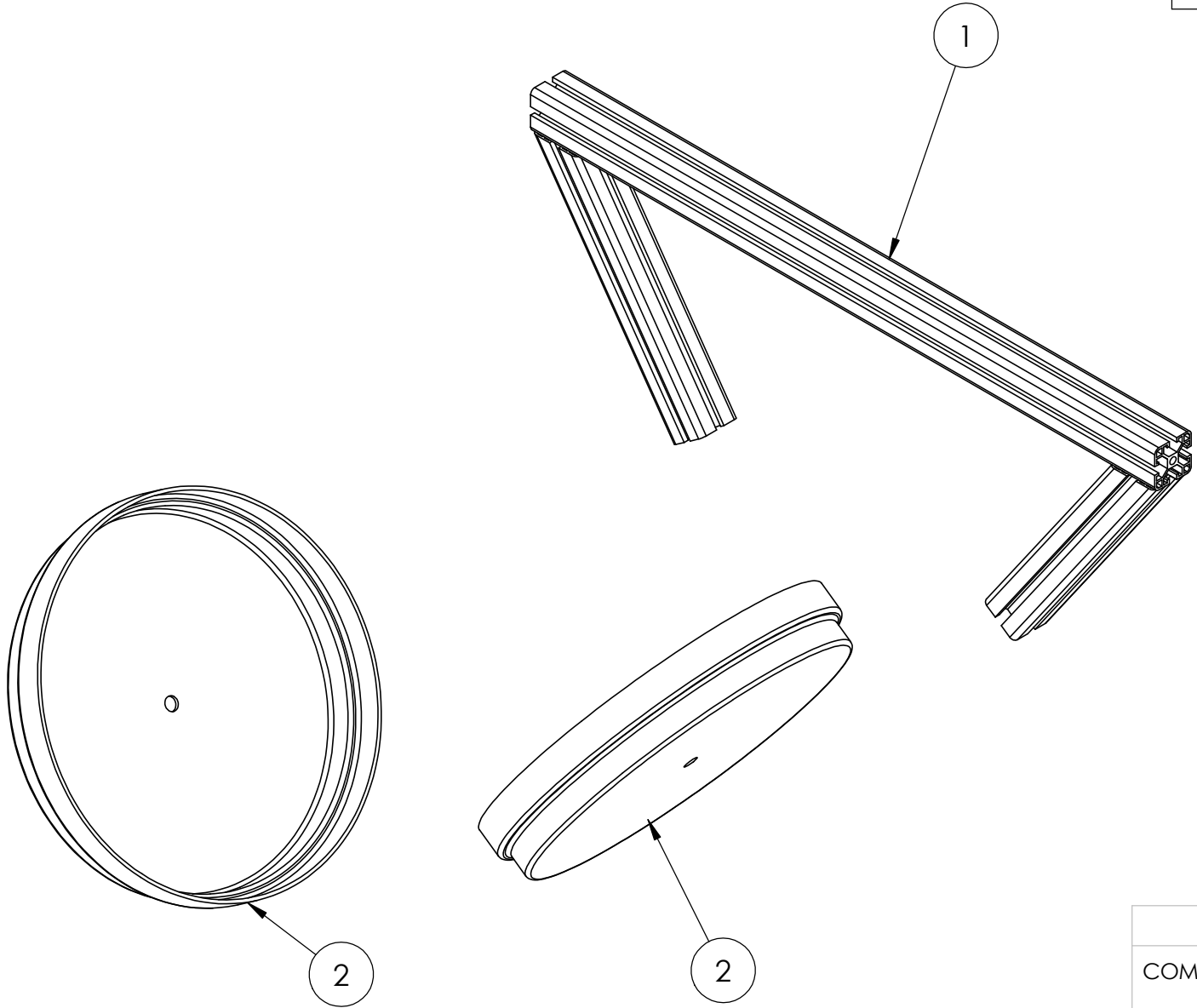
Tree Seedling Planter

COMPONENT: HOLE FILLER - EXPLODED

SCALE: 1:5

SHEET 1 OF 1

2

1

B

B

A

A
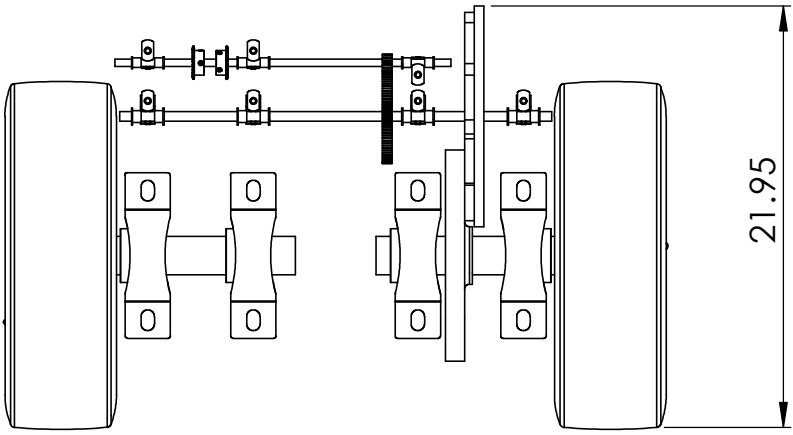
21.95

33.87
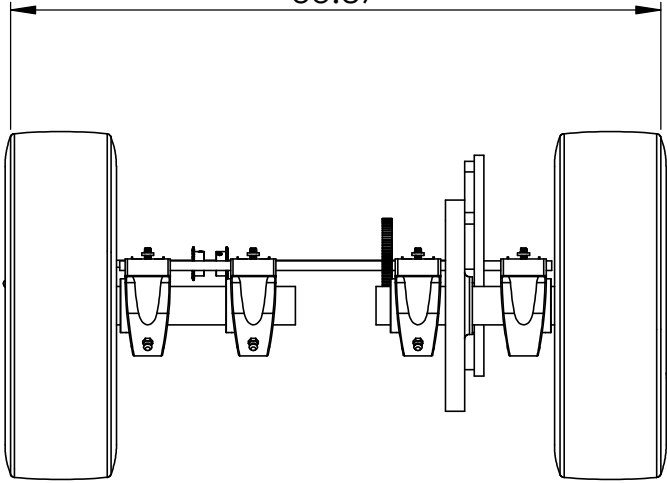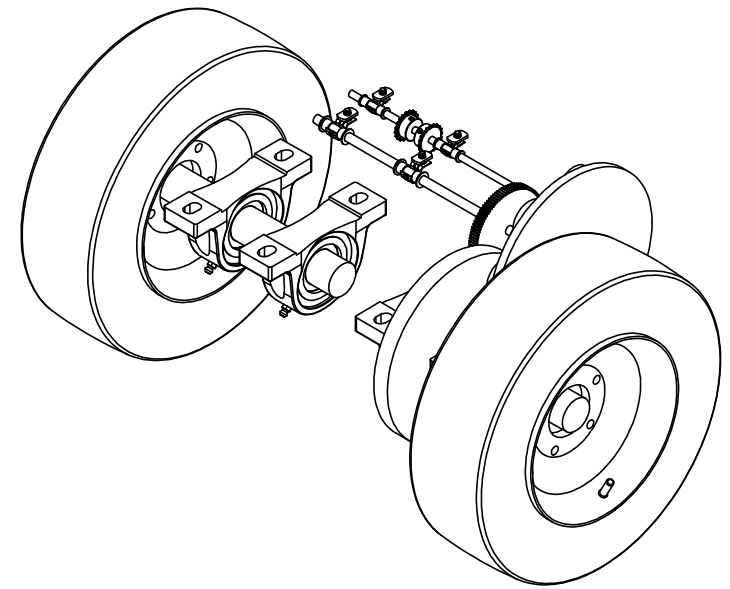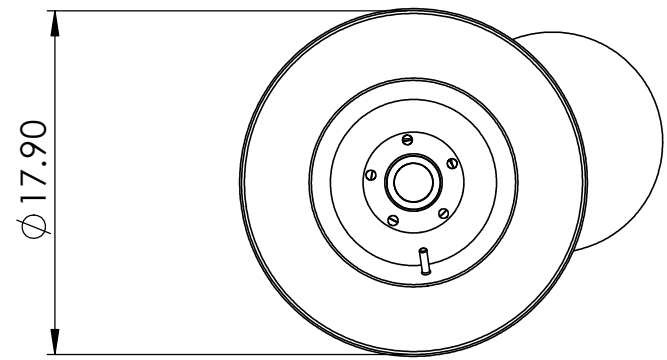
$\varnothing$ 17.90

Tree Seedling Planter

COMPONENT: WHEEL & GEAR ASSEMBLY

SCALE: 1:10

SHEET 1 OF 1

2

1

2   1

C   C

B   B

B   A   A   B
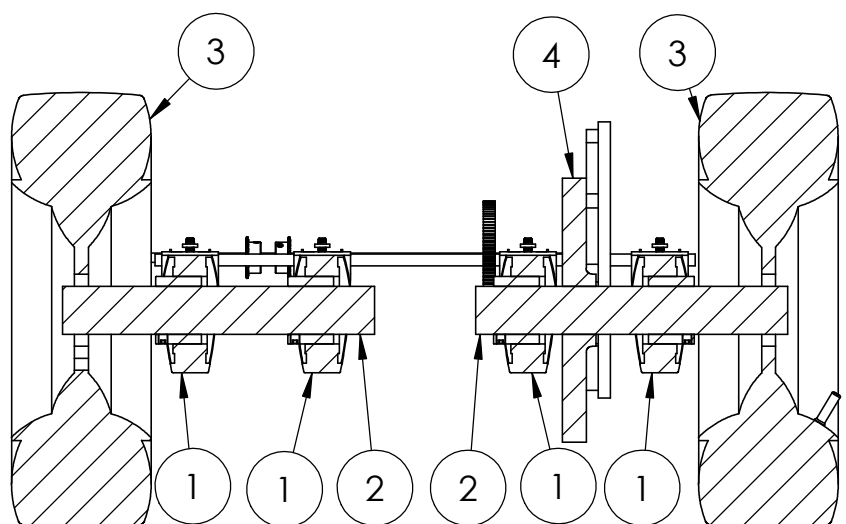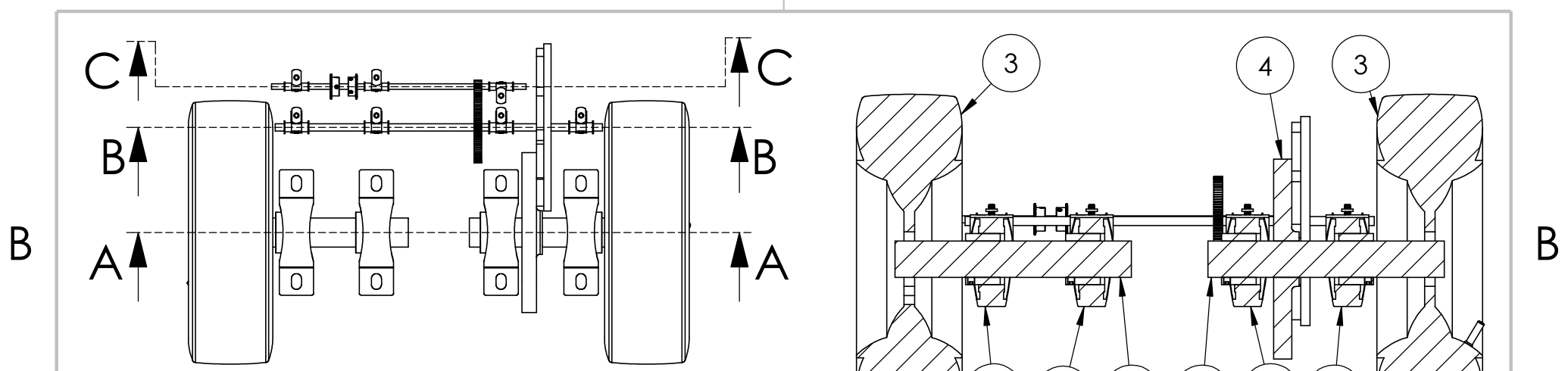
SECTION A-A

SCALE 1 : 8

3   4   3

1   1   2   2   1   1

9   9   5   6   8
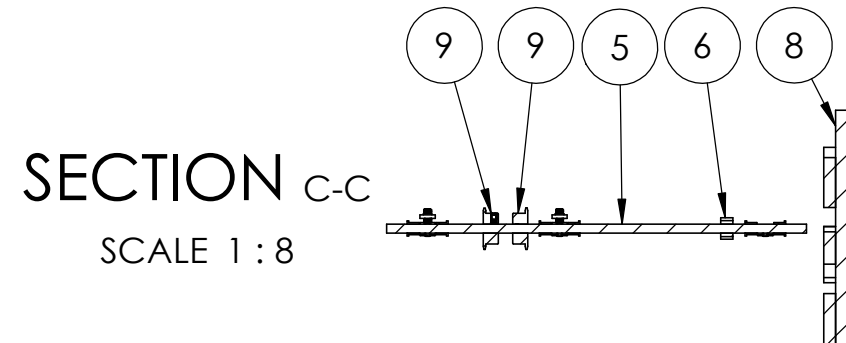
SECTION C-C

SCALE 1 : 8

3   5   7   8

3
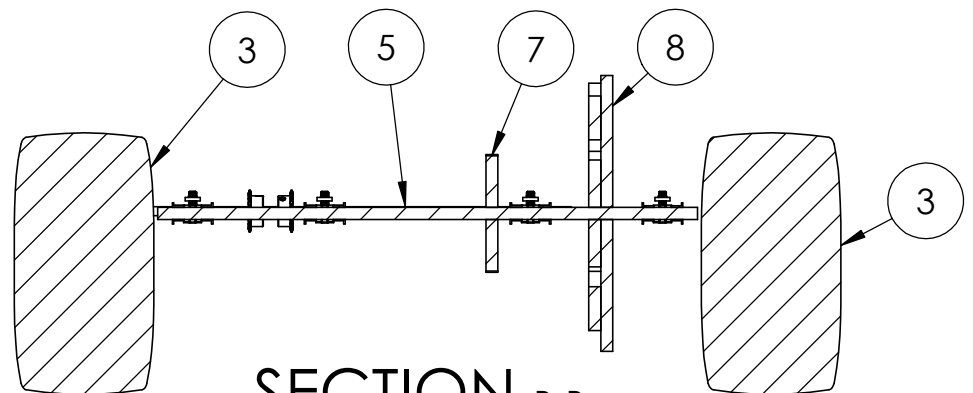
SECTION B-B

SCALE 1 : 8

ITEM NO.	PART NUMBER	QTY.
1	Mounted Bearing	4
2	Wheel Axle	2
3	Wheel	2
4	Peg Gear	1
5	Gear Axle Assembly	2
6	Small Spur Gear	1
7	Large Spur Gear	1
8	Frond Gear	1
9	Sprocket	2

Tree Seedling Planter	
COMPONENT: WHEEL & GEAR ASSEMBLY - SECTION VIEW	
SCALE: 1:10	SHEET 1 OF 1

A   A

2   1

B

8

8

9

9

6

7

2

1

5

1

3

4

2
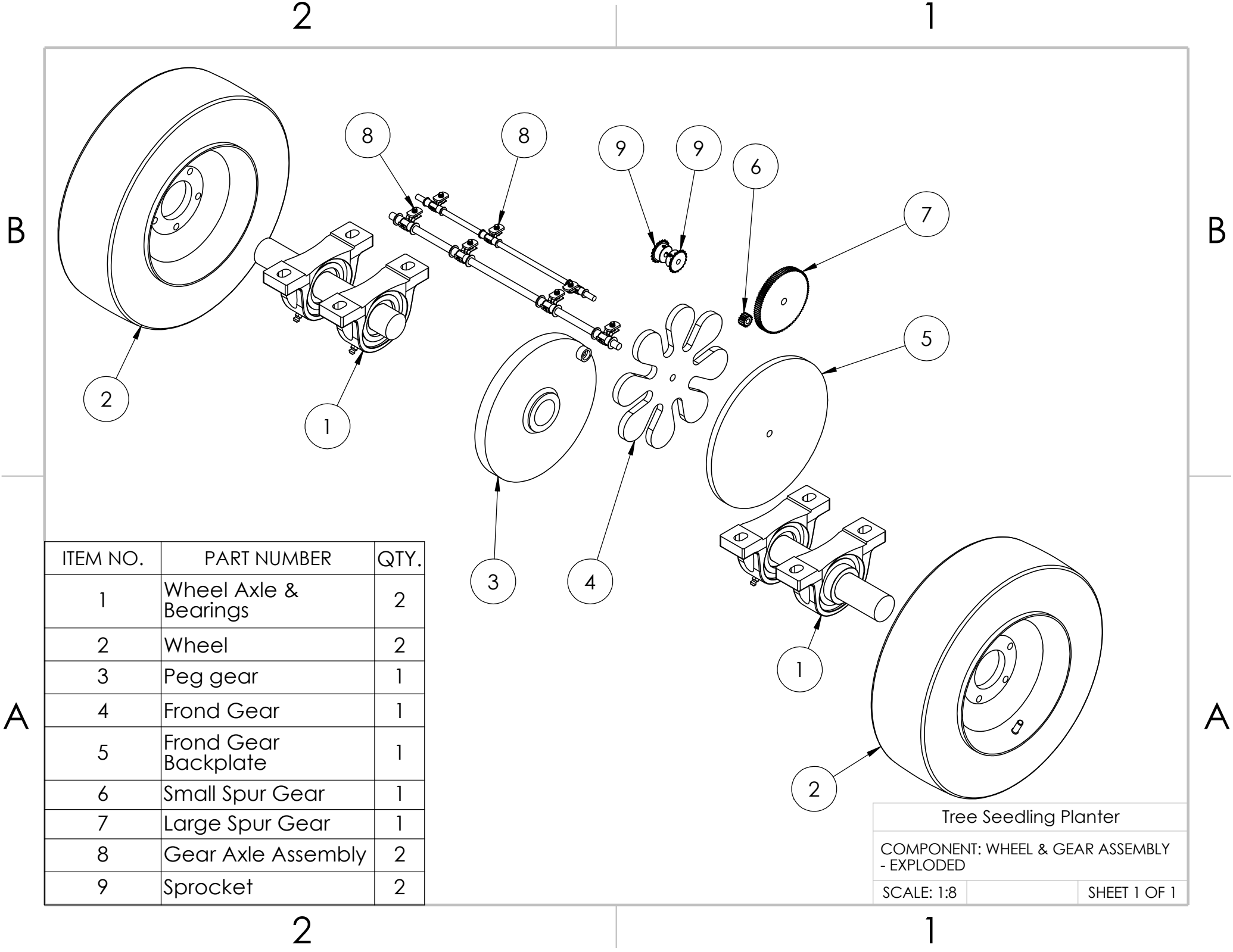
ITEM NO.	PART NUMBER	QTY.
1	Wheel Axle & Bearings	2
2	Wheel	2
3	Peg gear	1
4	Frond Gear	1
5	Frond Gear Backplate	1
6	Small Spur Gear	1
7	Large Spur Gear	1
8	Gear Axle Assembly	2
9	Sprocket	2

A

Tree Seedling Planter

COMPONENT: WHEEL & GEAR ASSEMBLY
- EXPLODED

SCALE: 1:8   SHEET 1 OF 1

⌀ 1.00 THRU ALL

0.79

1.00

30.00

2

1

B

B

A

A
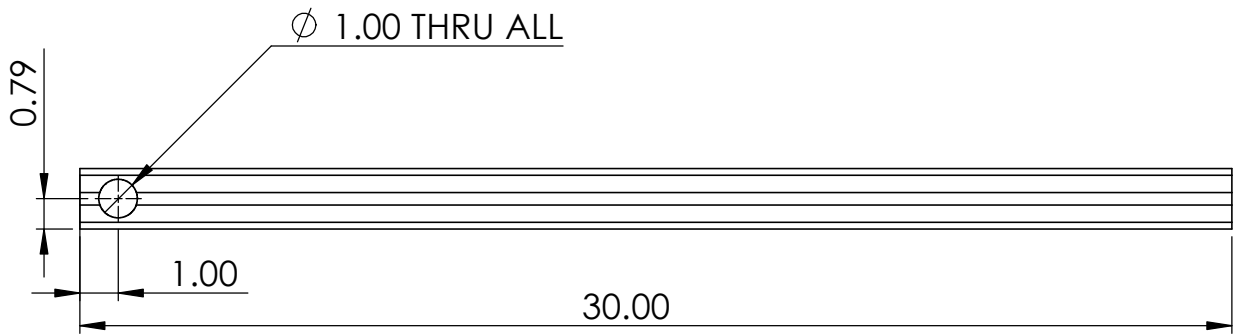
Tree Seedling Planter

COMPONENT: DIGGING LINKAGE

SCALE: 1:5
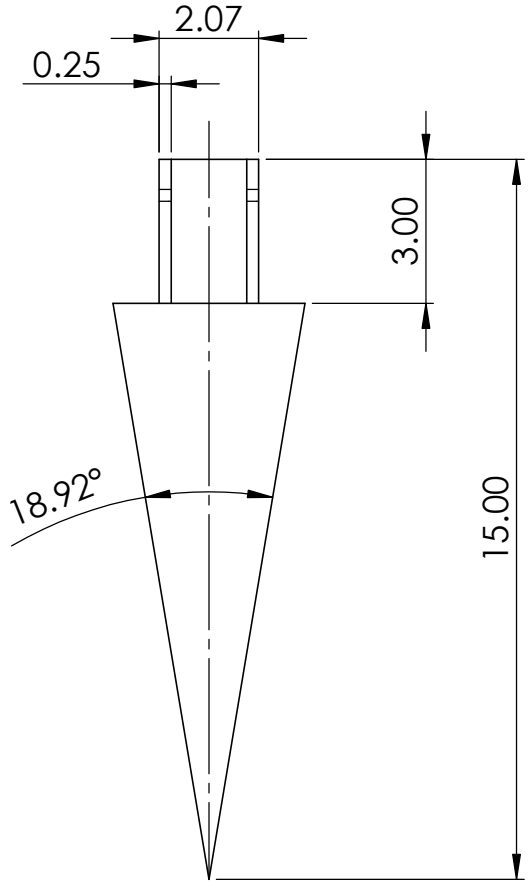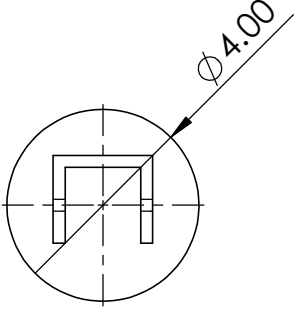
SHEET 1 OF 1

Ø4.00

2.07

0.25

3.00

18.92°

15.00

1.82

0.79

0.75

Ø 0.25 THRU ALL
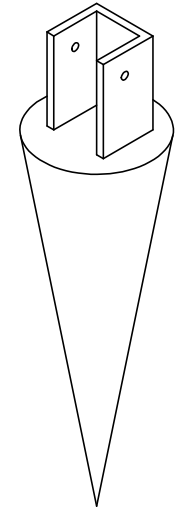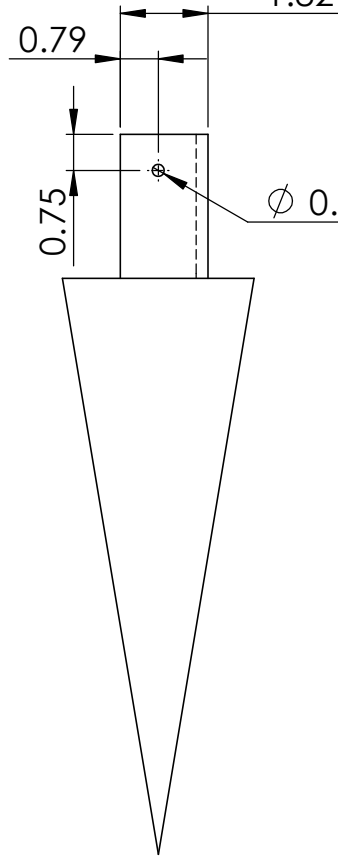
	Tree Seedling Planter
	COMPONENT: DIGGING CONE HEAD
SCALE: 1:4	SHEET 1 OF 1

2 — 1

B — B

A — A
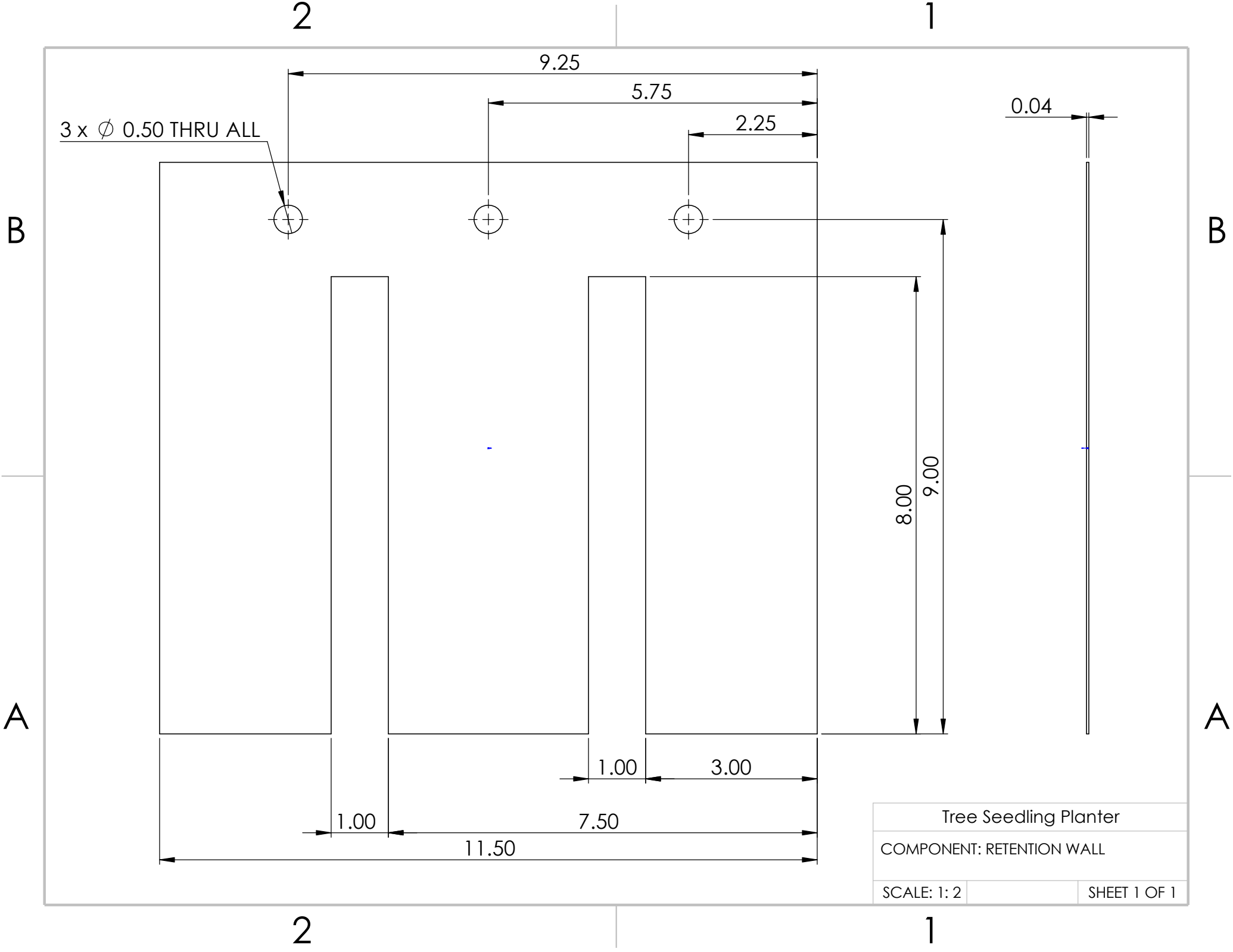
3 x Ø 0.50 THRU ALL

9.25

5.75

2.25

0.04

8.00

9.00

1.00

3.00

1.00

7.50

11.50

Tree Seedling Planter
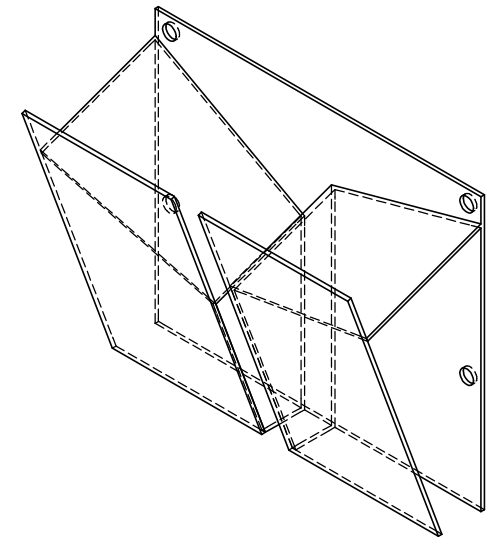
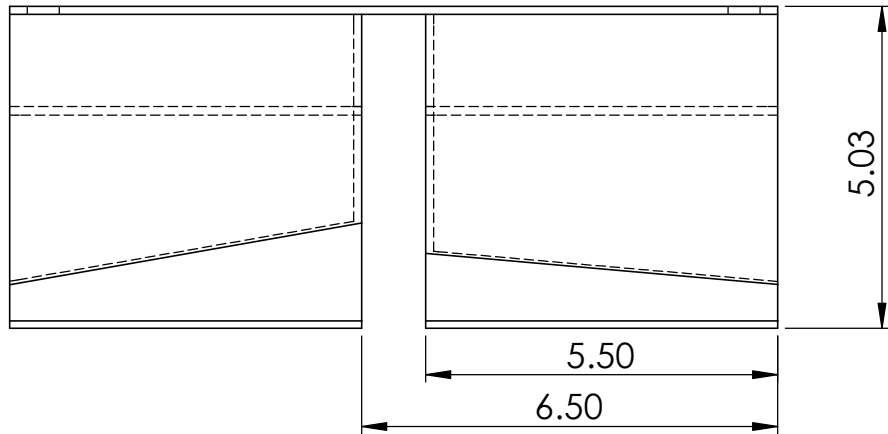COMPONENT: RETENTION WALL
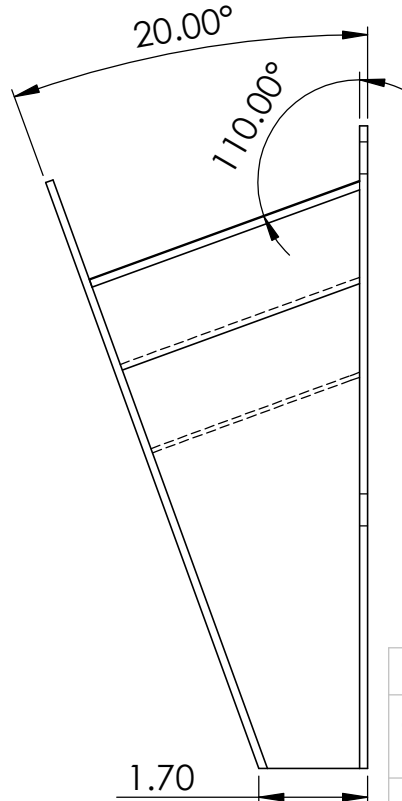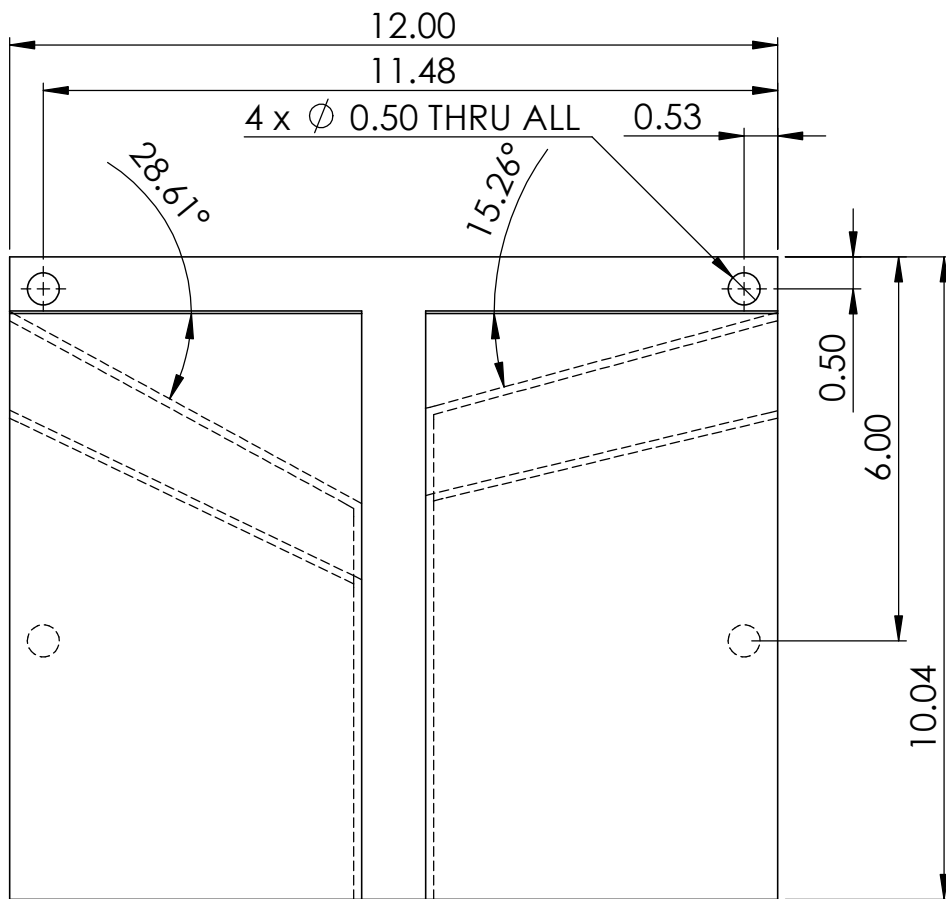
SCALE: 1: 2

SHEET 1 OF 1

B

B

A

A

2

1

2

1

2   1

B   B

5.03

5.50

6.50

12.00

11.48

4 x ⌀ 0.50 THRU ALL   0.53

28.61°

15.26°

20.00°

110.00°

0.50

6.00

10.04

A   A

1.70

Tree Seedling Planter

COMPONENT: TREE FUNNEL

SCALE: 1:3   SHEET 1 OF 1

2   1

2

1

B

B

105.00°

16.57

0.79

75.00°

2 x ∅ 0.63 THRU ALL

0.79

1.21

1.00

26.21

A

A

∅ 1.00 THRU ALL

0.81

0.39
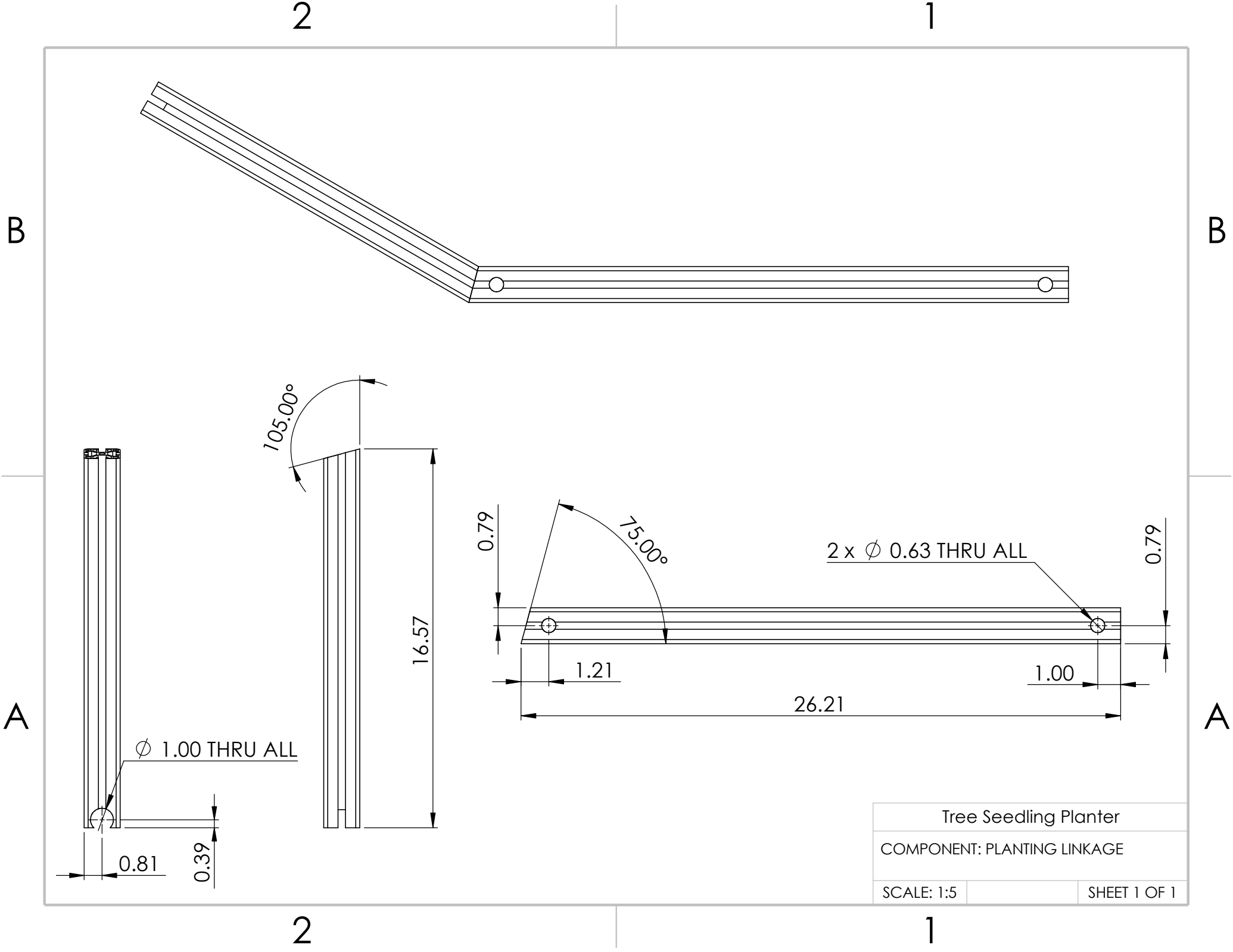
Tree Seedling Planter

COMPONENT: PLANTING LINKAGE

SCALE: 1:5

SHEET 1 OF 1

2

1

0.50

0.79

⌀ 0.88 THRU ALL

19.00

⌀ 0.63 THRU ALL

0.50

0.79

B   B

A   A

2   1
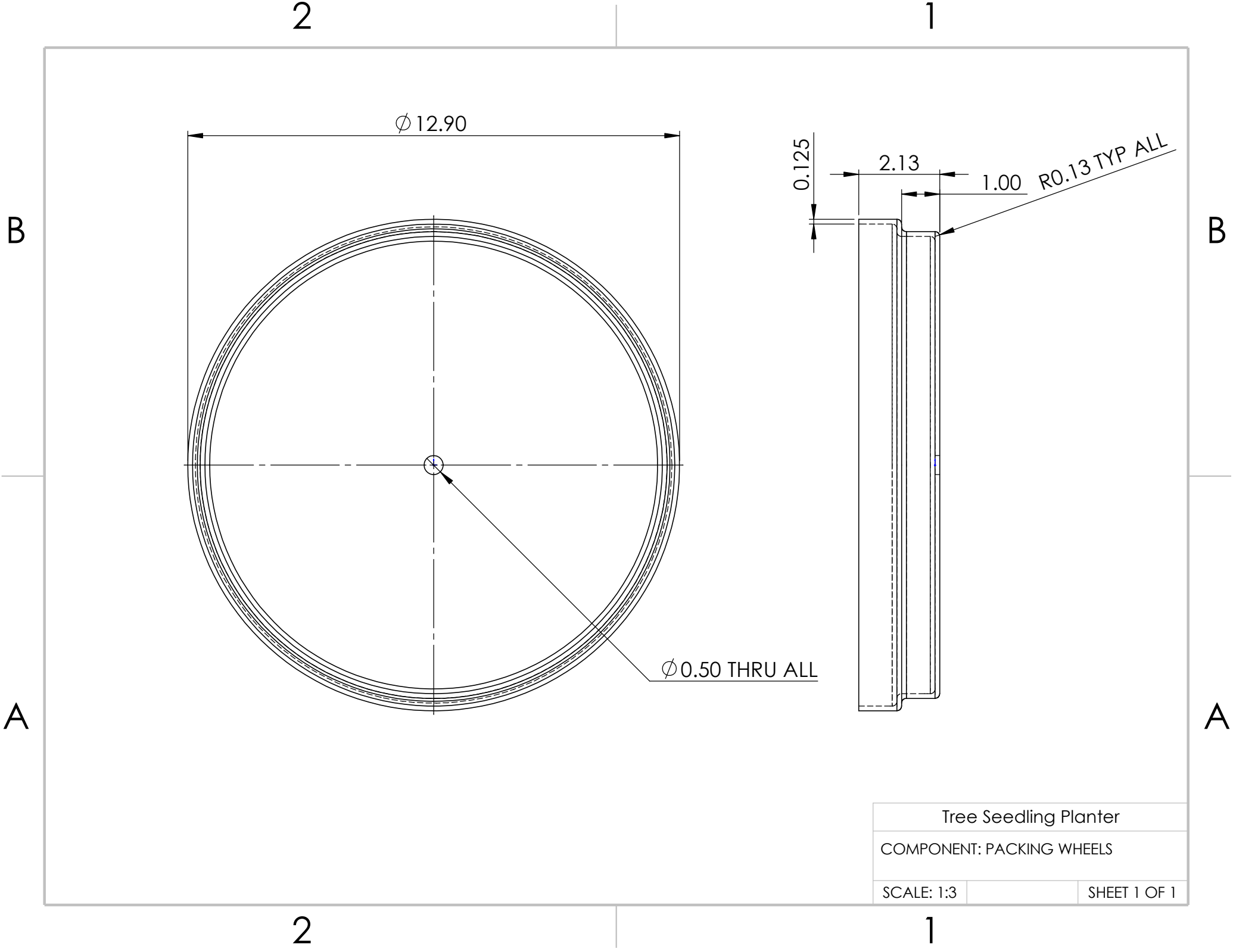
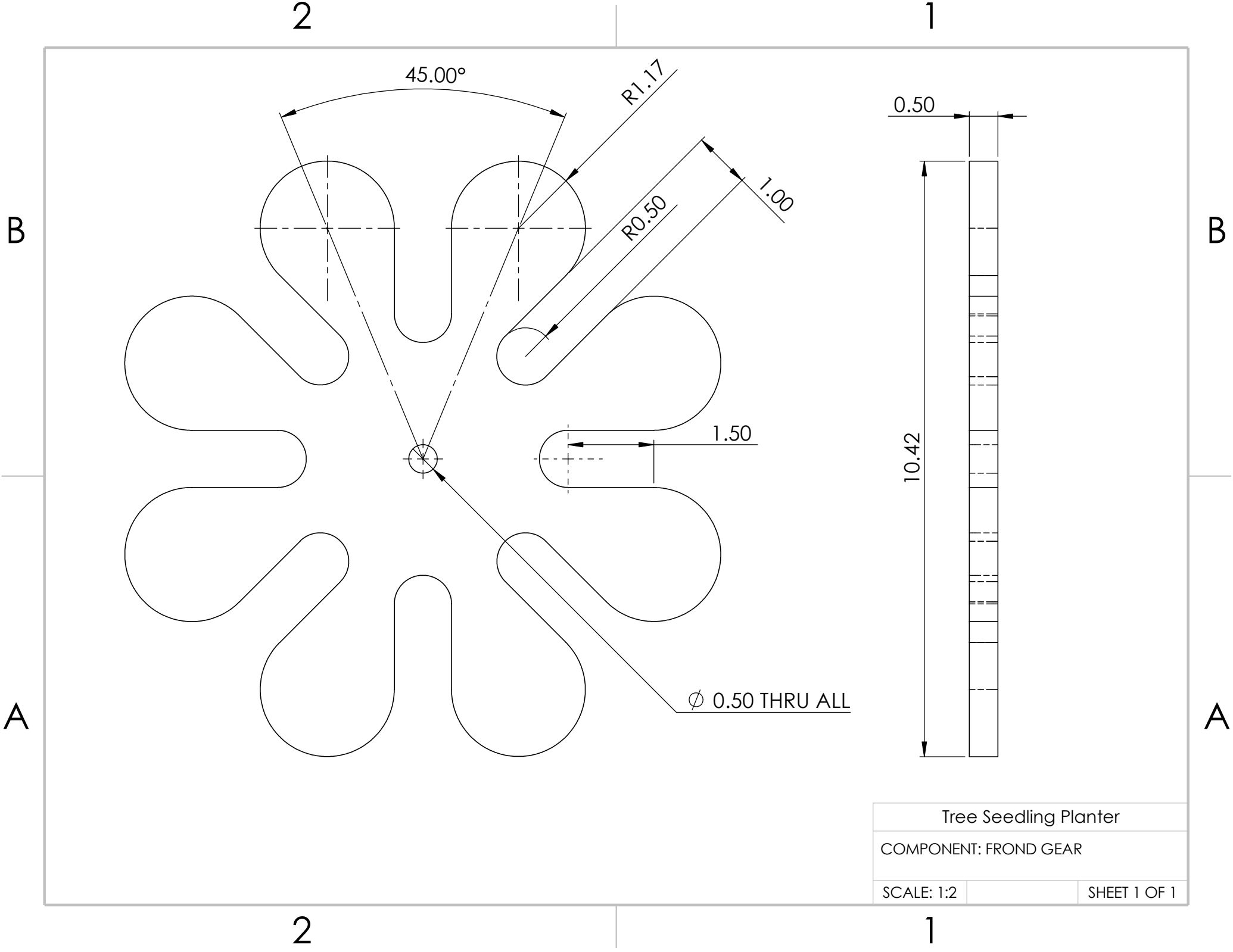Ø12.90

0.125

2.13

1.00

R0.13 TYP ALL

Ø0.50 THRU ALL

B

B

A

A

2

1

2

1

Tree Seedling Planter

COMPONENT: PACKING WHEELS

SCALE: 1:3

SHEET 1 OF 1

45.00°

R1.17

R0.50

1.00

1.50

Ø 0.50 THRU ALL

0.50

10.42

2

1

B

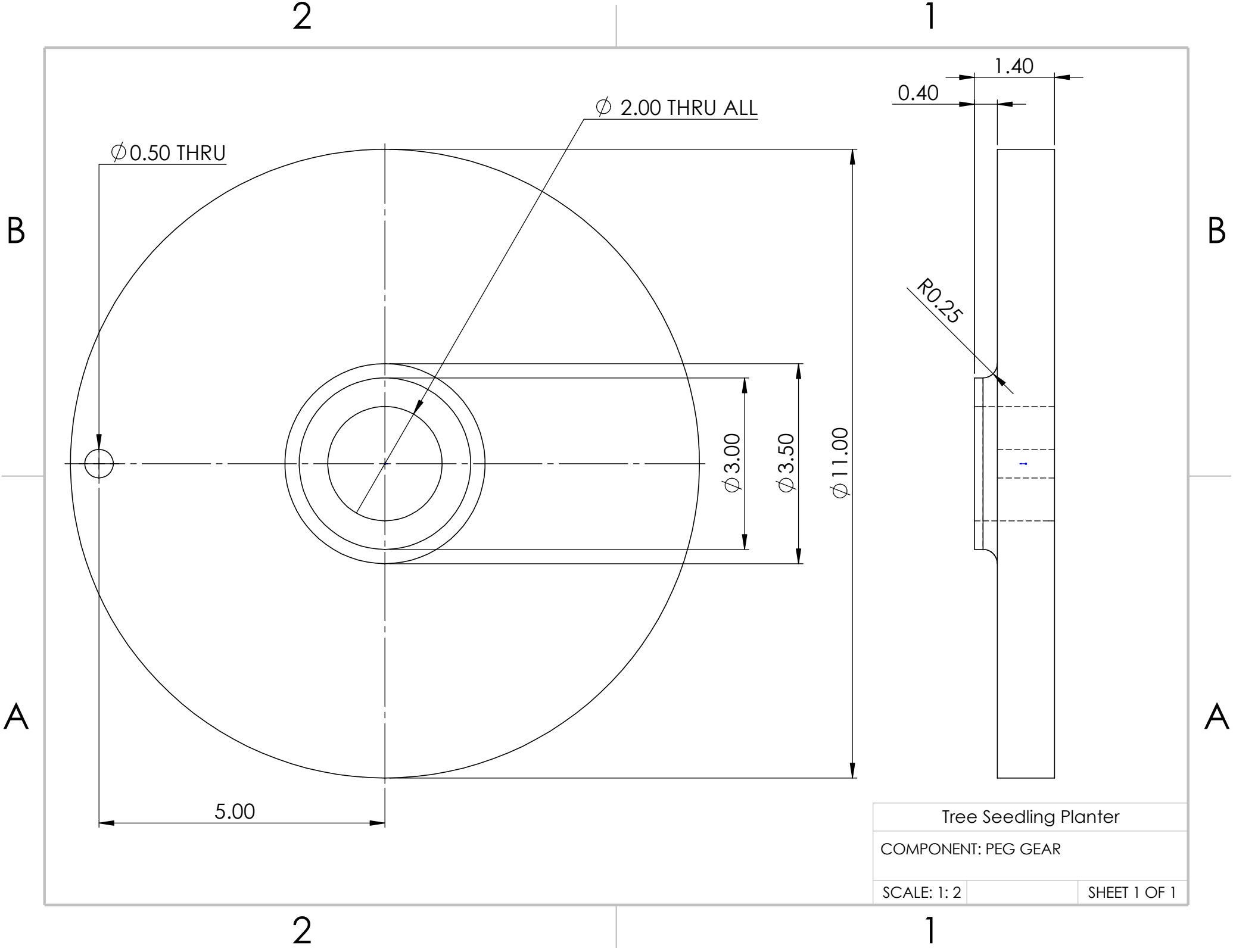B

A

A

Tree Seedling Planter

COMPONENT: FROND GEAR

SCALE: 1:2

SHEET 1 OF 1

Ø 2.00 THRU ALL

Ø 0.50 THRU

1.40

0.40

R0.25

B

B

A

A

2

1

Ø 3.00

Ø 3.50

Ø 11.00

5.00

Tree Seedling Planter

COMPONENT: PEG GEAR

SCALE: 1:2

SHEET 1 OF 1

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