Surveyors Marking Wand

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MCEN 5045: Design for Manufacturability

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1. Executive Summary

This report details the design process of a novel product called the Surveyor's Marking Wand. This product is the first low-cost version of such a product. The team designed it with the goal of increasing unit volume sold to the existing surveyor's wheel market of two million units per year. The surveyor's Marking Wand is a device which measures relatively large ground distances like surveyor's wheel, but which also has the ability to make paint marks on the ground via a trigger on the handle. It uses a standard inverted spray paint can, available at most hardware stores, and the user has a choice of permanent or non-permanent spray paint.

The efforts needed for the re-design of the wheel spanned a little under 2 months and the overall design was generated from existing measuring wheels. The first step in the team's ideation process was to brainstorm additional functions that would add on to the supplement functionalities of the product. The added function of the device when compared to the original product means that the number of parts, cost, and complexity of assembly would all inherently increase. The team made two notable changes to the design which aimed to mitigate the increase in these metrics of the new product.

The first design improvement was the removal of several fasteners throught the product. These connections were replaced by snap-fits. Specifically, five screws in the handles and four rivets in the pole sections were all replaced with snap fits. This had the side benefit of impriving the overall DFA scores. The second design improvement was the replacement of the two-piece hinge with a one-piece living hinge. This reduced the overall mass of plastic used in manufacturing as well. The net result was a decrease in assembly time and part count.

The team determined that, although the surveyor's marking wand, which costs $34.12 to manufacture, is more expensive than the original surveyor's wheel, which costs $32.95, the surveyor's marking wand will benefit fit from increased marketability. Economic goals for the project centered around increasing market penetration by differentiating the product from existing while maintaining the current price point. Research indicated that average surveyor wheel selling price was $50, which allows the team a 40% profit margin on each unit sold. However, per-piece costs were lowered on each part using large production runs: 500,000 of each part was manufactured at a time. To lower overhead costs related to storage, it was important to increase sales volume. Therefore, a 15% profit margin was accepted in order to sell the new product at $40, which would be more competitive on Amazon.

A thorough material analysis was conducted. This was followed by process selection analysis in order to effectively reduce cost wherever possible without compromising adding features. Reducing the number of fasteners used was set as one of the team's primary goals and other mechanisms, like snap fits, were incorporated in their place. Given control of conceptualization of the design and its manufacturing, the team was able to adapt the existing surveyor's wheel to add another function while also improving the DFA metrics in other areas of the design.

In summary, the team was able to redesign the surveyor's wheel to add the ability to make paint marks along the ground while maintaining all the product's original functionality. The surveyor's marking wand maintained similar results to the original surveyor's wheel when analyzing its DFA metrics and the price was kept low enough to remain competitive to similar products.

2. Reverse Engineering Project

Prior to the commencement of the redesign, the team completed a reverse engineering project for the surveyor's wheel. For this, the team disassembled the product, modeled the parts in SOLIDWORKS, and made engineering drawings for all of them. They also conducted material selection analysis, DFA analysis, DFM and process selection analysis.

A summary of the DFA table is given below. The team made changes to improve DFMA with respect to the handle shims, handles, and material.

Table 1: Summary table of DFA analysis of our Reverse Engineering project

Metric	Original Surveyor's wheel- Main assembly	Counter Sub-assembly of the surveyor's wheel
Number of parts	43	28
Total interactions	63	68
DFA Complexity factor	52.048	36.34
Total Aluminum parts	3	0
Total Cast iron parts	0	3
Theoretical Part Count Efficiency	46.5%	29%
Practical Part count efficiency	44.2%	32%
Total Unit cost	$32.95	
Break-even point	$26.52	

Building on this work, the team redesigned the surveyor's wheel to include a paint spraying wand. Changes to DFMA metrics are discussed in this report. For more detailed documentation of the original surveyor's wheel, and information on the redesign in our reverse engineering project, please see our "Reverse Engineering Report for Surveyor's wheel".

3. Economic Goals

The Surveyors Marking Wand seeks to achieve two primary economic goals. The first is to increase the volume of our units sold in the surveyor's wheel market as compared to the standalone Surveyor's Wheel on which its design is based. The surveyors wheel market is roughly US$100M measured by total revenue [1]. Still, this market is saturated with products, particularly in the sub-$50 range. This can be seen by searching for the product on Amazon, our intended retail sales channel. We thus seek to differentiate our product by adding a feature to it: a marking wand.

Purchasers may not be looking for a surveyor's wheel with a built-in marking wand, but this feature adds to the total product package and increases perceived value. Combined with the reputation and high customer satisfaction that selling on Amazon brings, we will be able to offer a higher total package value at a price point that is competitive with existing surveyors' wheels. According to Bottlieb Innovations, the average surveyor's wheel selling price is $50. In order make a 40% profit, we will need to produce our product for less than $35.

The second economic goal is to decrease manufacturing cost by increasing the volume of units that can be sold anywhere. We thus add the marking wand market to the addressable market that our product sells in. As reasoned above, marking wand buyers may not be looking for a surveyor's wheel, but the added feature makes the product more appealing than similar products that do not also measure distance. We do not anticipate that the marking wand sales volume for our product will be as large as the surveyor's wheel market, however, for two reasons.

The first comes down to application: oftentimes, a marking wand is wielded in a single hand and carried between markings – it is not rolled. Our product is too heavy and too bulky to be carried like this. The second is simply value: marking wands top out at about $40 on Amazon, with the average being closer to $30; unlike in the surveyor's wheel market, purchasers will have to pay for the added measuring feature because we cannot produce the product for less than that selling price.

Bringing all of this together, we seek to make profit on volume, not on profit margin. The new product should be priced competitively when compared to the average surveyor's wheel on Amazon, which is about $40. If we can achieve the $35 manufacturing target, this will leave 15% profit on each unit sold.

4. Preliminary Design Research

4.1. Design Motivation

The motivation behind the redesign of the surveyor's wheel was to increase the functionality of the product without significantly increasing the cost. The redesigned surveyor's wheel costs about $35 for the consumer. A one-wheeled paint striper which performs a similar task to the paint spraying function being added to our product costs somewhere between $20 and $40. Buying both products separately would cost the consumer around $60. Therefore, the team wanted to add these functions together into one product which costs less than $60. Additionally, having both functions integrated into one product allows the user to perform both functions simultaneously.

4.2. Market Analysis

Distance measurement has always been critical, especially in construction and agriculture. Since the invention of the modern measuring wheel in this century, demand has grown swiftly due to booms and constant overall growth in population and construction. Although the number of small farms has been declining in recent years, the need for precision application of new soil and chemical technologies has increased. As populations grow and the urban sprawl continues, the demand for distance and area measurement is estimated to at least exceed the growth rate to compensate for replacement demand and new demand. According to one analysis, the global revenue generated from the sales of measuring wheels is about $100M per year with an average selling price of $50 [1]. This implies that roughly 2 million distance wheels are sold per year worldwide. It has been estimated that ¼ of this amount is due to customer need to calculate area versus distance measurement only. Hence, it is safe to assume that there is potential demand for 600,000+ units per year in the area market with remaining sales in the distance-measurement-only market. The market segmentation of the measuring wheels in the current market is as follows:

1. Construction, including appraising, engineering, and small-scale surveying
2. Agricultural, including large-scale surveying
3. Niche

Small-diameter (4"-10") distance wheels are typically designed for measurement of shorter distances over paved ground. They offer excellent precision and are easy to carry because of their small size.

Manufacturers of this device have designed and tailored the measuring wheel keeping in mind decorators, appraisers, painters, realtors and other related professionals.

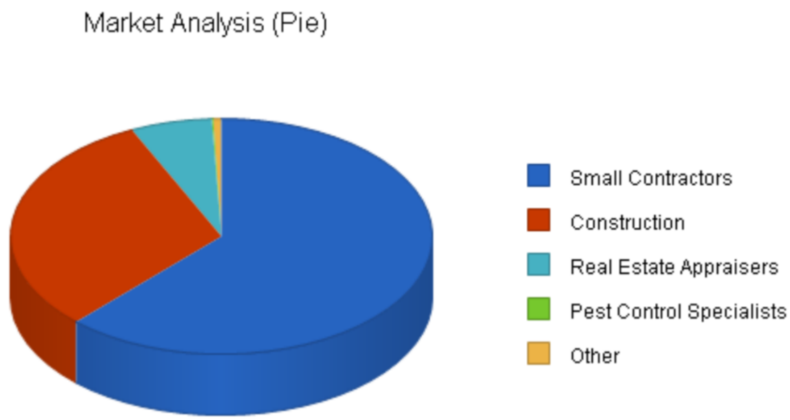


Figure 1: Pie chart distribution of the measuring wheels market

4.3. Black Box and Glass Box Diagrams

4.3.1 Black Box Diagram

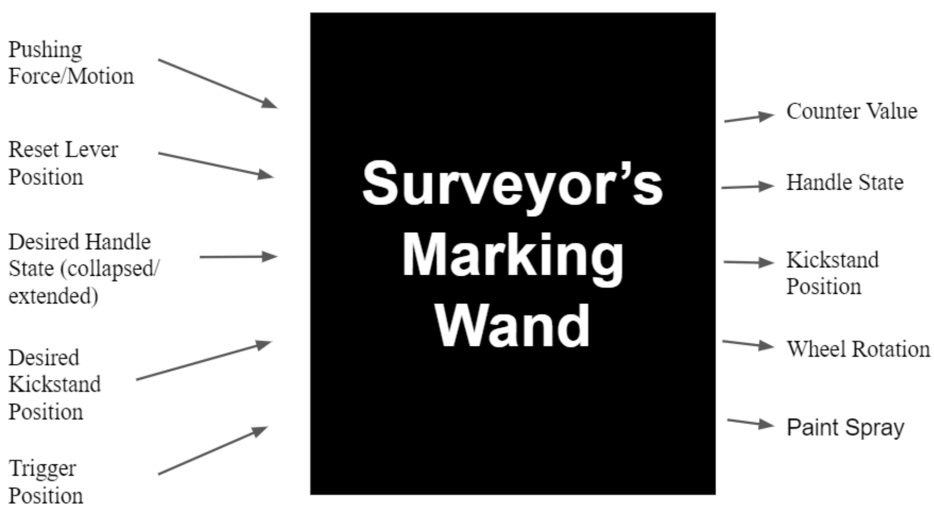


Figure 2: Surveyor's Marking Wand Black Box Diagram

A good place to start when analyzing a product is determining the inputs and outputs of the system. To do that, the team constructed a Black Box Diagram, shown in Figure 2: Surveyor's Marking Wand Black Box prior to disassembling the product. The black box represents the surveyor's wheel, the inputs are on the left, and the outputs are on the left. The inputs and outputs shown in this diagram only include the ones that are pertinent to the function of the product. These do not include items such as heat from friction and sounds that are generated.

The team decided to add the ability to spray the ground with paint. This change is reflected in this diagram. In comparison to the original product's black box diagram, this diagram has an added input of spray trigger position and an added output of pain spray.

4.3.2 Glass Box Diagram

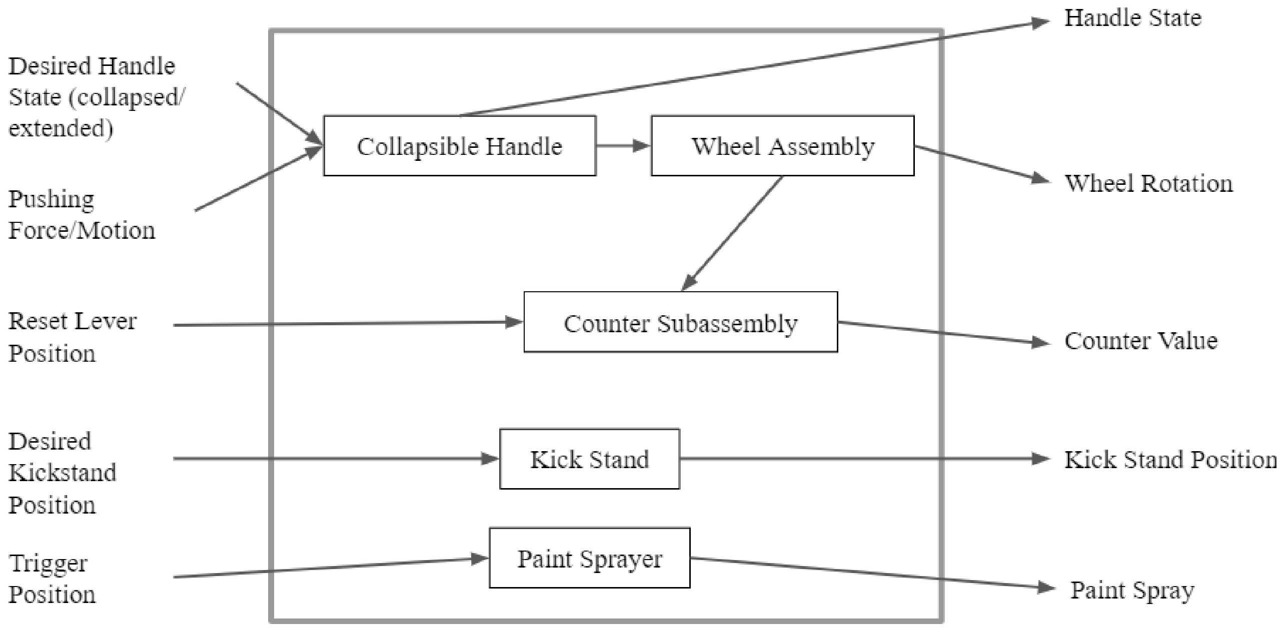


Figure 3: Glass Box Diagram

The next step in analyzing this product is to "look inside" the black box to view the subsystems within the surveyors' wheel. That can be done by creating a Glass Box Diagram. The Glass Box Diagram for the surveyors' wheel is shown in Figure 3. In it, the inputs and outputs from the Black Box Diagram are connected via the subsystems in the glass box. The subsystems we chose to sort our product into are the collapsible handle, the wheel assembly, the counter subassembly, and the kickstand, as well as the new subsystem, the marking wand.

Collapsible Handle

The Collapsible Handle subsystem allows for the surveyors' wheel, a relatively long device, to be folded for ease of storage and transportation. It has two hinge joints along the length of the handle that are locked into place when the handle is fully extended.

Wheel Assembly

The Wheel Assembly includes the wheel and a position indication arrow, both of which are mounted to the driving shaft of the counter subassembly. The wheel rolls along the ground while the user pushes the device. This rotation drives the counter subassembly. The position indication arrow is loosely mounted on the driving shaft so that it always hangs down, thus pointing to where the wheel contacts the ground. This makes it easy for the user to see where they should start and stop measuring.

Counter Subassembly

The Counter Subassembly is the mechanical brain of the surveyors' wheel. It takes in the rotation of the wheel and outputs a distance via a plastic gear train. There are small circular parts with numbers 0 through 9 printed on the circumference and extruded gear teeth on one side which are coupled to the final gear in the gear train. The gears/counter gears in this subsystem rotate about multiple steel/ABS shafts. This subsystem also includes a distance reset lever, shown in the foreground of the left image below. When the lever is depressed, the counter gears are decoupled from the drivetrain and a torsional spring causes the counter gears to move back to displaying a value of 0. The Counter Subassembly internals are shown on the right in Figure 4: Rendering of the counter.

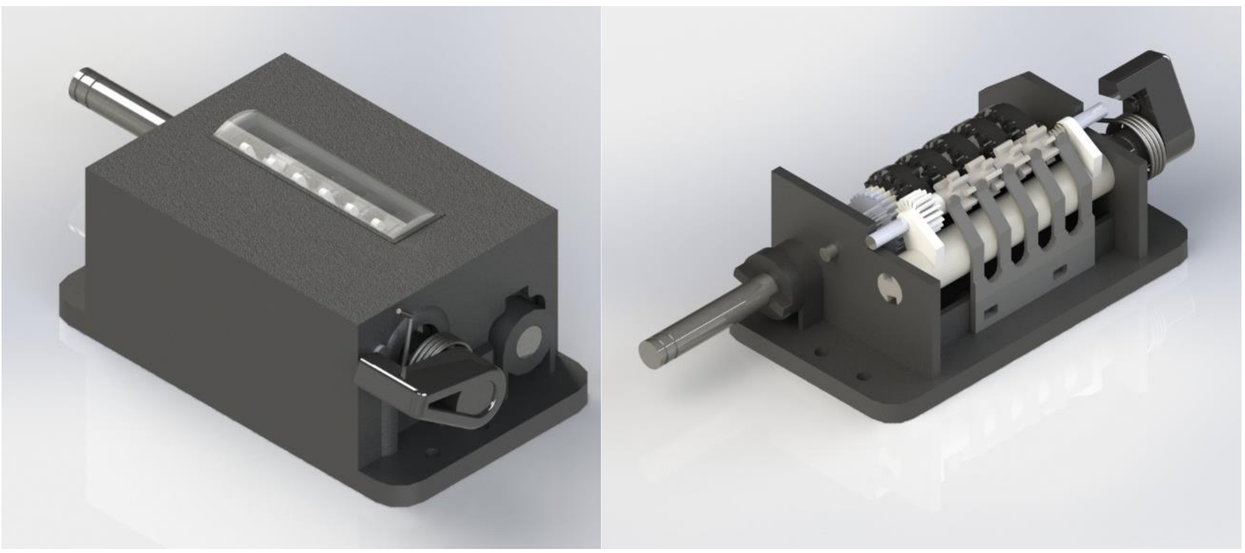


Figure 4: Rendering of the counter

Kickstand

The surveyor's wheel also includes a retractable kickstand which allows the device to stand upright so that the user can take their hands off without having to bend down to pick it up again. It folds up underneath the counter subassembly when not in use.

Marking wand

The marking wand is a new subsystem which the team added to the existing surveyor's wheel. This allows for the user to make marks or lines on the ground with spray paint while they are pushing the device along the ground. This subsystem includes a trigger on the handle, a cable system, mounting features for a spray paint can, and a depressor mechanism to press the valve of the can.

4.3.3 Fishbone Diagrams

After understanding which subassemblies are responsible for which inputs and outputs, it is useful to analyze which components are used in which subsystem. To do this, the group created two fishbone diagrams—one for the main subassembly and one for the counter subassembly—because there are too many parts for just one fishbone diagram. Additionally, creating the diagram for the counter subassembly alone is useful since it is the most complex subsystem by far. Both diagrams were created after disassembly and can be seen in Figure 6 and Figure 5.

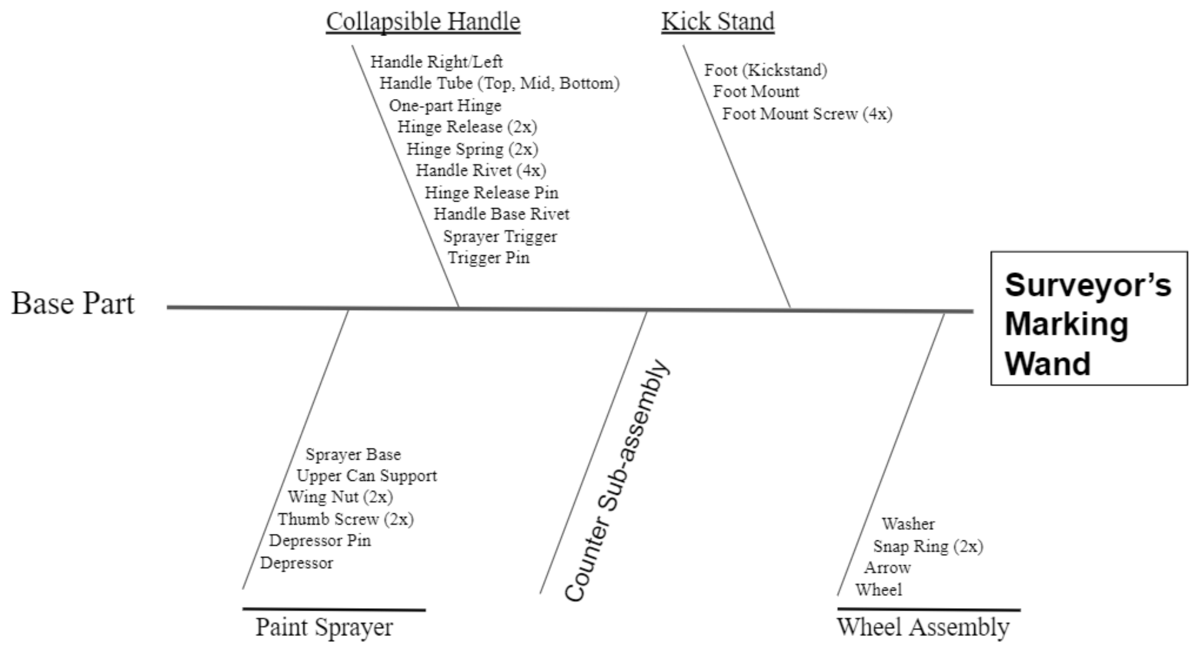


Figure 6: Fishbone Diagram of the main assembly

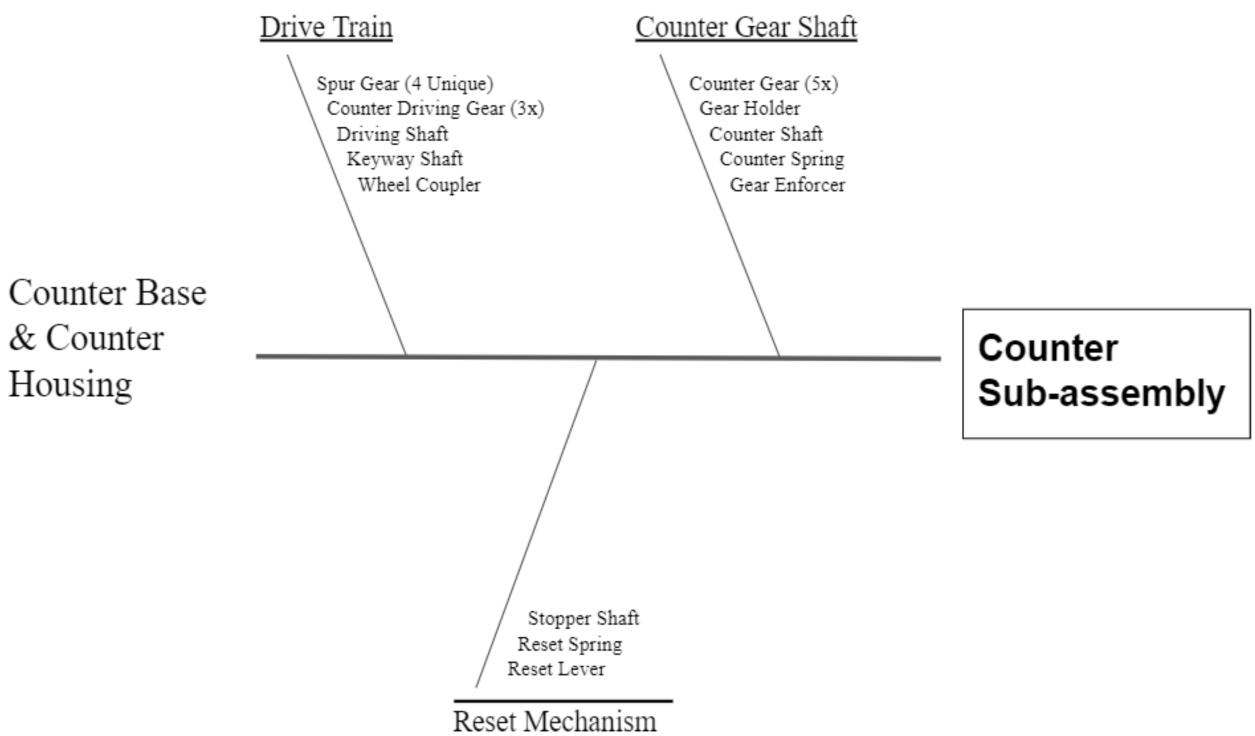


Figure 5: Fishbone Diagram for the Counter Subassembly

The design changes made to the product are reflected only in the Fishbone Diagram for the main assembly. They did not affect the counter subassembly. In the main assembly, another rib on the diagram was added to show the parts in the new Marking wand subsystem. Additionally, the part count reductions related to adding snap hooks to the handle and changing the hinge to a one-part design are reflected in the Collapsible Handle rib of the main assembly Fishbone Diagram.

4.4 Patent Search

A patent search was conducted in order to gain insight of the products that are already on the market to redesign our wheel efficiently. This was also done to understand if there would be any legal issues pertaining to the product. The designs used for reference have been displayed in the sections 4.4.1-4.4.3. The first design initiated our ideation phase which revolved around adding a feature which allows marking of the distance travelled. Digging deeper into the research we found the designs that were pertaining primarily to distance measurement and having spraying unit as an added feature. The second and third design listed here is relevant to our design. Our research showed us how the incorporation of a spraying unit would be a first for a measuring wheel having 12-inch diameter.

4.4.1 Marking Device with distance measuring capability US 5749522

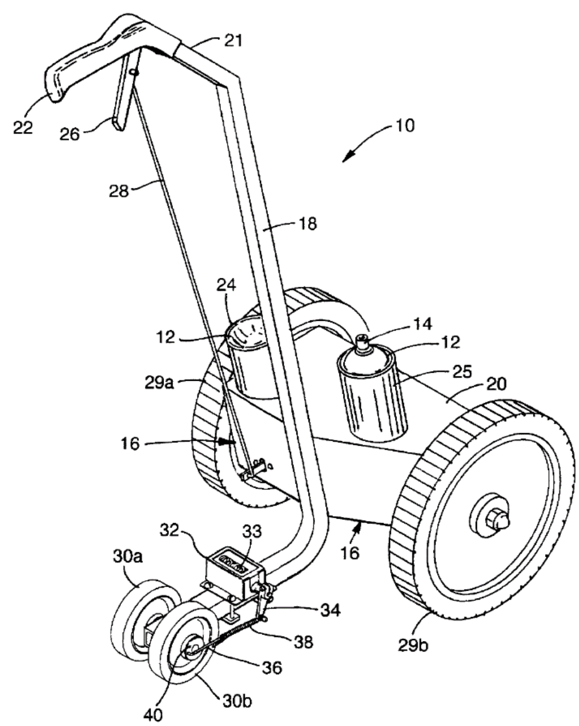


Figure 7: Patent 5749522 - measuring and marking device

This device discharges the contents of an aerosol container onto a surface. The invention of this marking device was to solve the problem pertaining to making marks or stripes which extend only for pre-determined distance. Hence, it also shows the operator the distance travelled when moved relative to a surface. It comprises of a housing, means disposed on the housing for holding a container. There is an actuator mounted on the container that moves between charging and discharging positions, means provided to switch between the discharging and non-discharging position, a container, rotatable wheels on the housing that rotates as the device moves relative to the surface, and lever-operated counter on the device for counting the number of revolutions in order to mark the distance is shown in the lower left of Figure 7. The counter's implementation is not completely clear, as Figure 8 is the only insight the patent gives into its integration with the wheel (next page.)

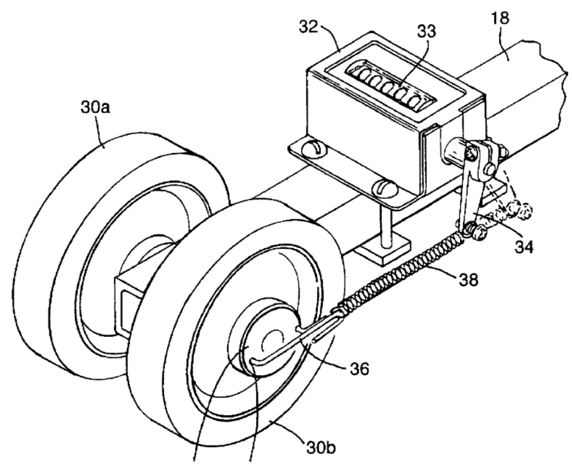


Figure 8: Marking device and detail view of counter

4.4.2 United States Patent US 20110190626 A1

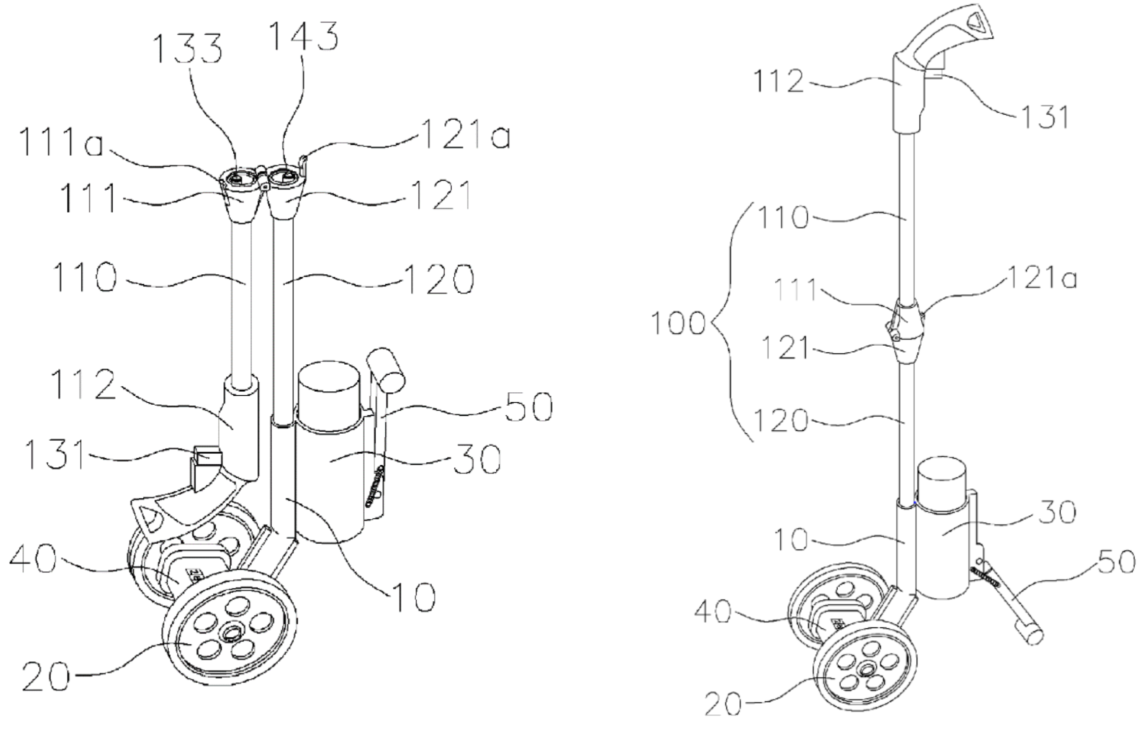


Figure 9: Design that utilizes spraying unit and has foldable handle

This measuring wheel consists of upper and lower pipe sections which can be folded and unfolded to form the assembly. The operation is quite like the measuring wheel we have where in the input is from the upper side and then is transmitted to the lower side through transmission rods. This wheel encompasses a spraying wheel unit along with the foldable assembly for easy storage and use. There is an operation lever on the upper handle at the grip portion. This operation lever controls the switch connected to the nozzle of the spray can for the purpose of spraying paint. The same idea has been used in many measuring wheels which use this kind of mechanism for installing brakes onto the measuring wheel. This assembly consists of the following sub-units: a frame, a rotary wheel mounted on the frame, a catch for the spray can to be mounted on the frame, extension pipes consisting the upper and lower sections detachably coupled through hinge, upper and lower transmission rods, operation input on the upper portion of transmission rods and output on the lower side of the transmission rod.

4.4.3 Adapter for Coupling a Paint Marking Stick to a Digital Counter - US 7163353B2

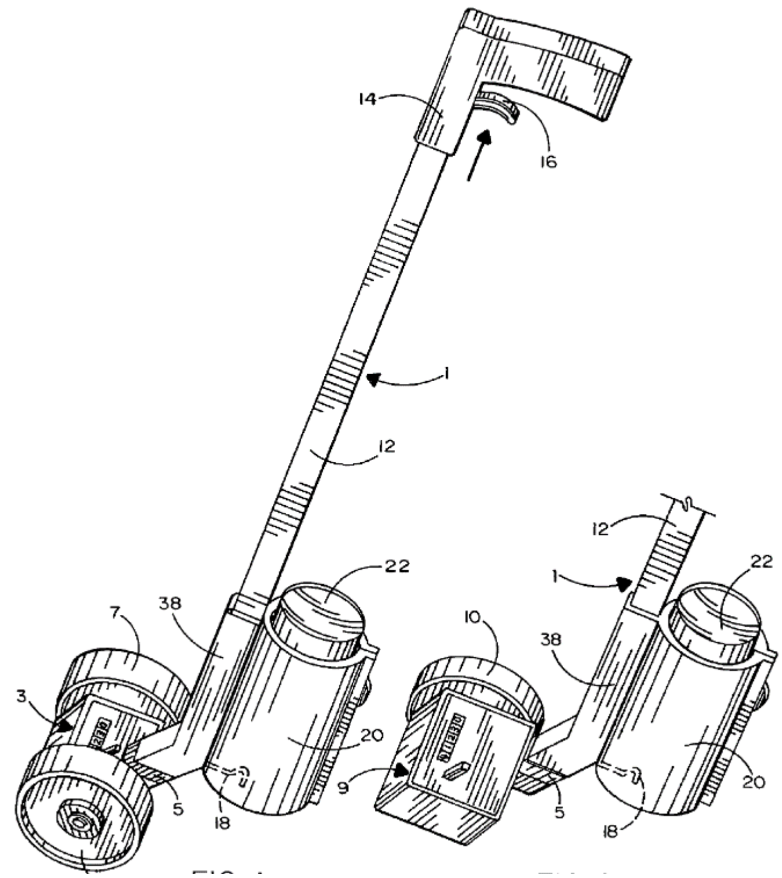


Figure 10: Design of the detachable adapter connected to the measuring device`

This design is again very similar to the one we plan on implementing. It is a modular design in which the base has a pair of legs extending outwards and a cylindrical post projecting in the opposite direction. The pair of legs of the adapter are received into a hollow container that encompasses the paint marking stick. The paint marking adapter is detachable as shown on the right side of **Error! Reference source not found.**. This device is not foldable. However, it does have a trigger mechanism attached to it in order to control the spraying unit.

5. Novel Design Overview

Although the original surveyor's wheel was already a very well-engineered and useful product, the team decided to make a few modifications to it. These changes can be broken out into two categories: adaptive redesign (adding new functionality to the existing product) and DFA improvements.

5.1 Adaptive Redesign: Marking wand

The surveyor's wheel is very useful in measuring relatively long distances along the ground. However, the device features no way for the user to mark informative lines on the ground to reference these measurements at a later time or for other people to use the measurements. Therefore, the team decided that a good feature to add to the surveyor's wheel would be a mechanism which allows the user to make marks on the ground at any desired point with spray paint.

The new marking wand system that the team designed is activated using a trigger built into the handle, allowing the user to make spray paint marks on the fly. The system was designed as to not impede on the ability of the surveyor wheel's existing handle to fold. The spray paint can is held upside down at the bottom of the surveyor's wheel. When the trigger is pressed, the can is depressed, expelling paint towards the ground. The user can make marks at specific intervals or make a long line along the ground that has a measured length. In particular, the team expects that this functionality would be useful for applications such as construction, athletic events, traffic management, etc.

5.2 DFA Improvements

In addition to the added functionality described above, the team made some changes to the surveyor's wheel that improve its DFA metrics. The first change was to replace the handle screws with snap hooks. This change removed six total screws from the part count, theoretically decreasing the time and cost of assembly. This change is reflected in the DFA analysis as well as the drawings shown in APPENDIX. The team also redesigned the hinges for the collapsible handle. This design and its effects on the DFA metrics are described in the next section of the report. It is also visualized in the drawings in APPENDIX.

6. Bill of Materials

Table 2: Bill of materials for the Surveyor's Marking Wand

S. No.	Part Number	Description	Material	Qty.	Manufacturing Method
1	1101	Base Part	ABS	1	Injection Molding
2	1105	Counter Foot Wireframe	Plain Carbon Steel	1	Bending (Metal Working)
3	1107	Right Handle	ABS	1	Injection Molding
4	1108	Left Handle	ABS	1	Injection Molding
5	1109	Paint Spray Trigger	ABS	1	Injection Molding
6	1110	Cable	1060 Alloy	1	Drawing (Metal Working)
7	1207	Position Arrow	ABS Plastic	1	Injection Molding
8	1209	Hinge	PE High Density	2	Injection Molding
9	1210	Wheel	PE High Density	1	Injection Molding
10	1301	Top Tube	1060 Alloy	1	Extrusion & Drilling
11	1302	Middle Tube	1060 Alloy	1	Extrusion & Drilling
12	1303	Bottom Tube	1060 Alloy	1	Extrusion & Drilling
13	1304	Depressor Pin	1060 Alloy	1	Extrusion & Drilling
14	1307	Hinge Release	PE High Density	2	Injection Molding
15	1309	Can Support	ABS	1	Injection Molding
16	1310	Depressor	PE High Density	1	Injection Molding
17	1350	Foot Mount	ABS	1	Injection Molding
18	1408	Spray Base	1060 Alloy	1	Machining
19	2100	Counter Cover	ABS PC	1	Injection Molding
20	2103	Reset Switch	ABS	1	Injection Molding
21	2202	Gear Mount	ABS	1	Injection Molding
22	2203	Keyway	Nylon 101	1	Injection Molding
23	2203	Counter Increment Gear	ABS	4	Injection Molding
24	2211	Counter Spring	Brass	2	Winding
25	2320	Counter Gear	ABS	5	Injection Molding
26	2340	Wheel Coupler	ABS	1	Injection Molding
27	2392	Second Gear	Nylon 101	1	Injection Molding
28	2394	Spur Gear B	Nylon 101	1	Injection Molding
29	2401	Counter Driving Gear	ABS	1	Injection Molding
30	2403	Driving Shaft	PE High Density	2	Injection Molding
31	2404	Mechanical Counter Gear Holder	ABS	1	Injection Molding
32	2405	Mechanical Counter Stopper	Nylon 101	1	Injection Molding
33	2406	Reset Spring	AISI 1020 Steel, Cold Rolled	2	Winding
34	2407	Stopper Shaft	AISI 304	1	Machining
35	2410	Spur Gear	Nylon 101	1	Injection Molding

7. Critical Components and Design Additions

7.1 Spray Base and Modified Base Part

Since the team decided to add the ability to paint the ground using a spray paint can, the can needed a place to be retained somewhere on the surveyor's wheel. The team decided that the option for this would be to modify the original base part to accept a part called the "spray base". The spray base has a cylindrical space for the can body to rest in. The bottom of the spray base is designed in such a way so that when the can body is pressed down, the tip is kept in place, thus depressing the valve and releasing pain. There is a small hole at the bottom of this which allows for the paint to escape towards the ground. The spray base and modified base part are shown in Figure 11: Spray base rendering.

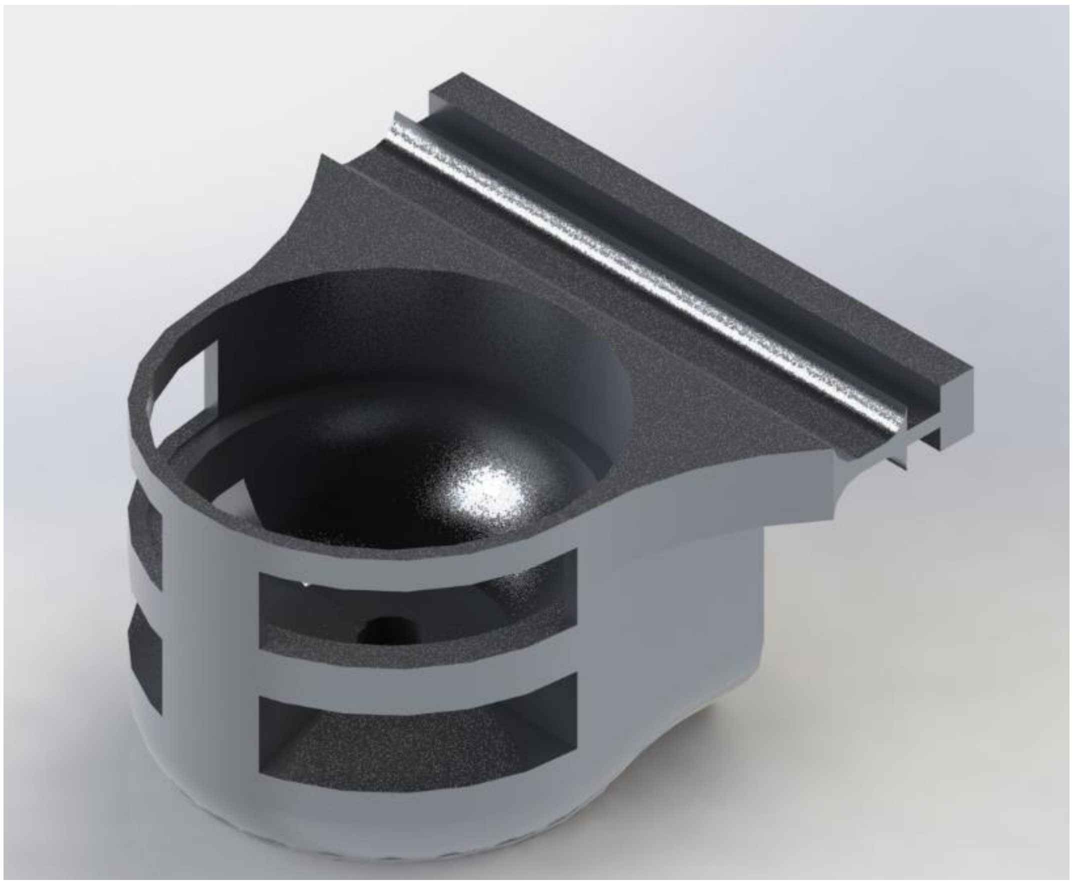


Figure 11: Spray base rendering

The base part is modified so that it has a rectangular slot in the front. This slot matched the male rectangular extrusion on the spray base. This feature allows the spray base to be slid into place. The inside of the slot on the modified base part has a wall towards one side which is designed to be a stop so that the spray base cannot be slid past a specific point. These features constrain the spray base in 2 axes relative to the base part and constrains it in one direction in the third axis. The spray base will be kept from sliding back out once the can is in place and supported by the Upper Can Support.

7.2 Upper Can Support

In order to support the spray paint can from a second point along the can so that it is not cantilevered, the team decided that an upper can support was a necessary component. Since this component had to be there anyways, the team decided that the easiest place to add the mechanism to depress the can was on this upper can support. This critical component is shown in Figure 12.

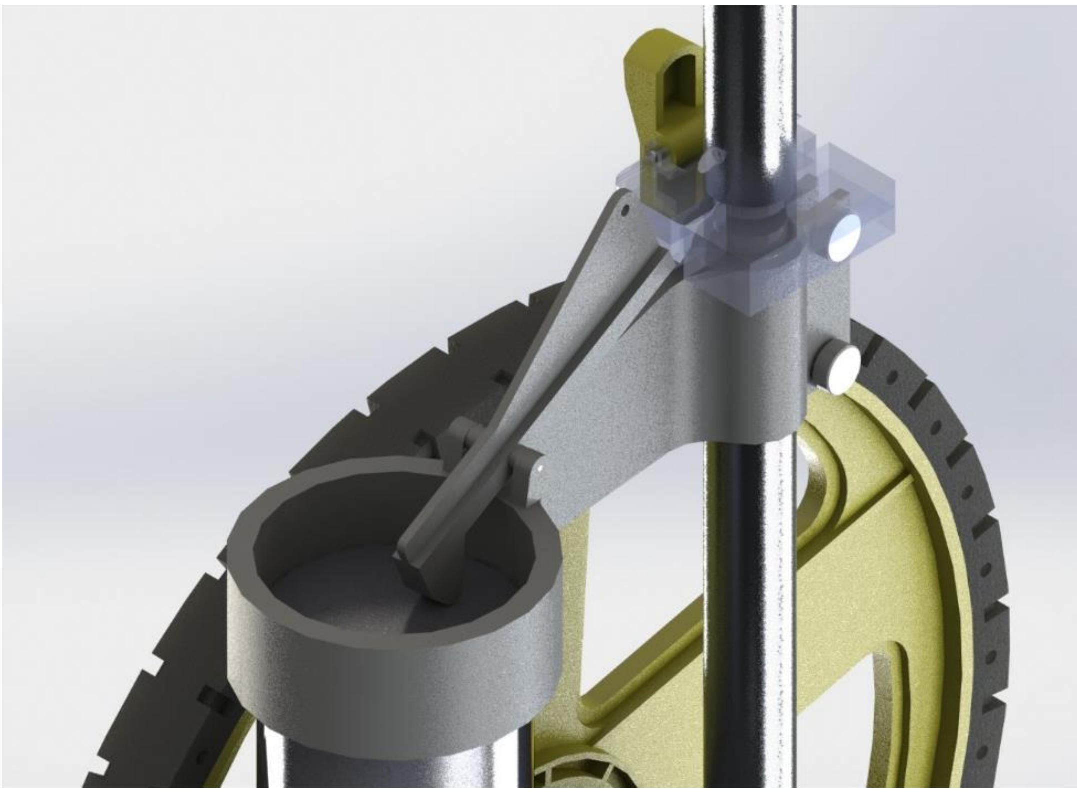


Figure 12: Upper can support and depressor

The support has two large cylindrical holes; one is for the body of the can and the other is to slip over the lowest column of the handle. In order to grip the handle column tightly to remain axially in place, the support has a split around the column that has flanges for a thumb screw and a wing nut to be tightened. When these fasteners are tightened, the flanges are pulled closer together, gripping the handle column. When the fasteners are loosened, the support can slip axially along the column so that the height can be adjusted and so that it can be moved out of the way to remove and insert paint cans.

The support also has mounting features for the can depressor. This component is pulled by the cable attached to the trigger at one end. This force causes the can side of the depressor to rotate down towards the ground, thus depressing the can causing it to expel paint. The depressor rotates about a pin that is pressed into the mounting features on the support.

7.3 Trigger Mechanism

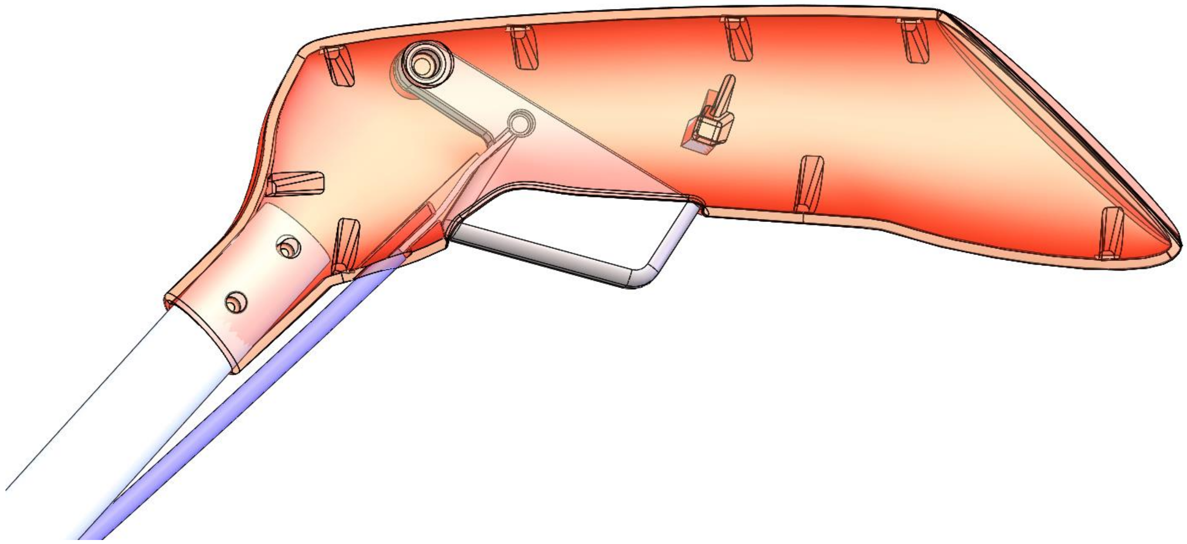


Figure 13: Internal handle view showing trigger supports and cable routing

The original handle design was optimized using DFA to reduce assembly time and complexity by adding snap hooks. It was then modified again to accommodate the addition of a trigger that retracts into the handle and pulls a standard bicycle brake cable when depressed. The trigger is the grey piece in the center of Figure 13: Internal handle view showing trigger supports and cable routing and the purple piece is the brake cable that actuates the can depressor. Eight snap hooks and the trigger stop can also be seen.

The big challenge here was to add the trigger's pivot and stop, as well as the cable boss, without requiring the use of fasteners, which had been entirely eliminated in the first revision. This was achieved through the use of mating bosses on either handle have. During assembly, the assembler attaches the brake cable to the trigger, lays the trigger into the right handle halve, places the cable housing into its boss, and then simply snaps the left handle half on, securing all the parts in place.

Also of interest, the trigger was optimized using DFM. It is hollow, which reduces its mass by .15 oz. Internal draft angles of 3° allow the trigger to be easily injection molded. All parts are specified with light texture, PM-T1, for easy operation. This gives the handle and trigger a quality feel and prevents them from slipping in the user's hand.

7.4 One Piece Hinge

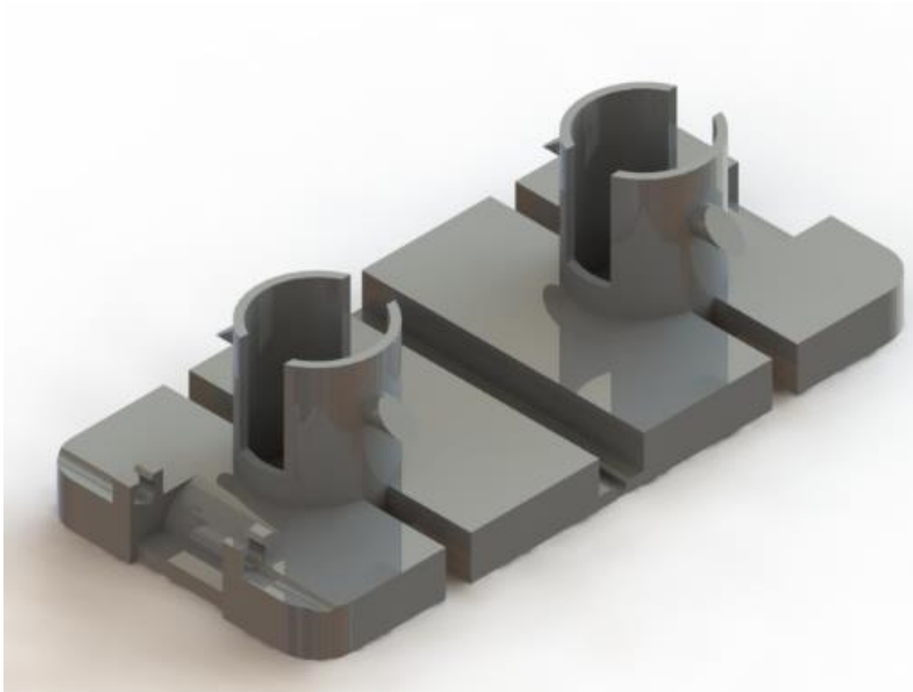


Figure 14: One-piece hinge

On top of adding functionality to this product, the team also wanted to reduce parts where possible. One of the easiest places to do this was at the two hinges of the collapsible handle. Originally, each hinge assembly had two plastic halves, two pins to hinge about, a release, the return spring for the release, a pin for the release, and rivets to connect each half of the hinge to the handle columns. In total, each hinge assembly had 9 components, meaning the product had 18 components just for the hinges. The team designed a new hinge to reduce this part count. The main part of this design is shown in Figure 14.

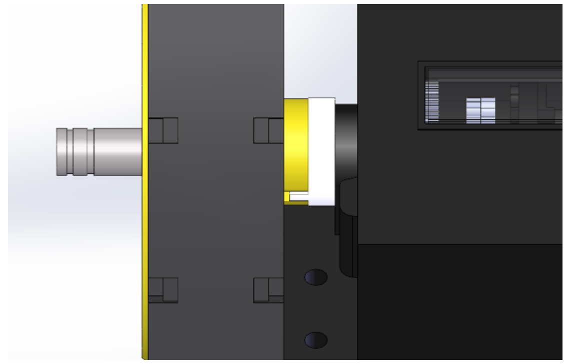
The new hinge design features a living hinge. The part is injection molded with a thin extrusion located between the two sides of the part. After the part comes out of the mold, that section of plastic is thin enough to be very flexible, acting like a hinge. This takes away the need for one of the halves of each hinge assembly and the need for the two hinge pins.

The design also incorporates a feature which allows the handle columns to be snapped onto the hinge rather than be riveted in place. This reduces the number of parts by two on each hinge assembly. Additionally, it negates the need for the assembler to use a rivet gun for this step.

Overall, the new hinge design reduces the part count of each hinge from 9 to 4, meaning the overall part count for this subsystem is reduced from 18 to 8.

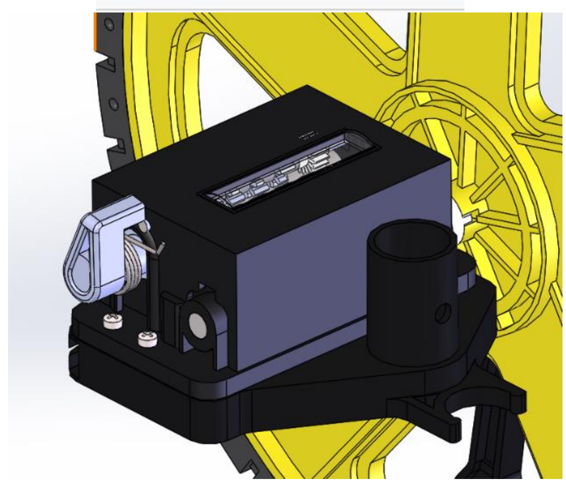
8. Assembly Procedure

1. Counter is fitted to wheel using the wheel coupler located inside the counter.

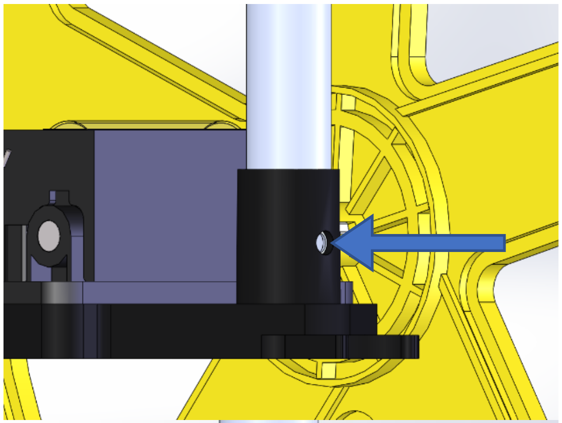


2. Arrowhead is inserted in the groove on the wheel axle shaft.

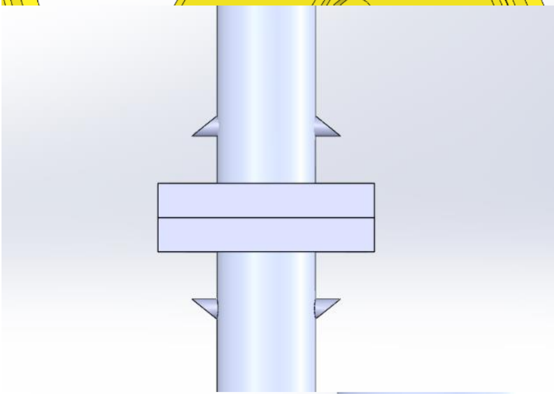
3. Base part is attached to the counter using 4 machine screws and captive nuts in the base.



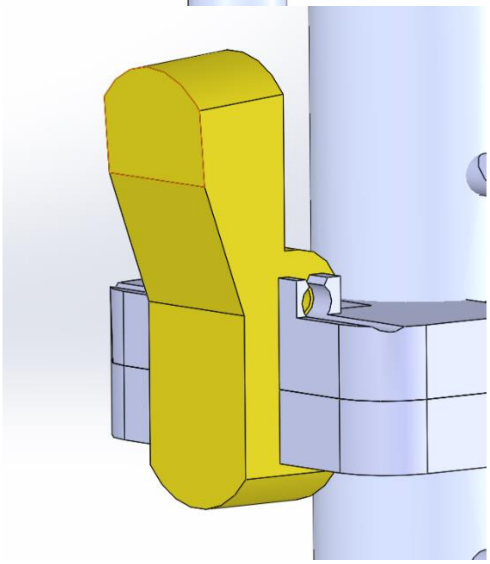
4. Bottom tube is attached to the base part and riveted with a single ¼” rivet as indicated by the arrow.



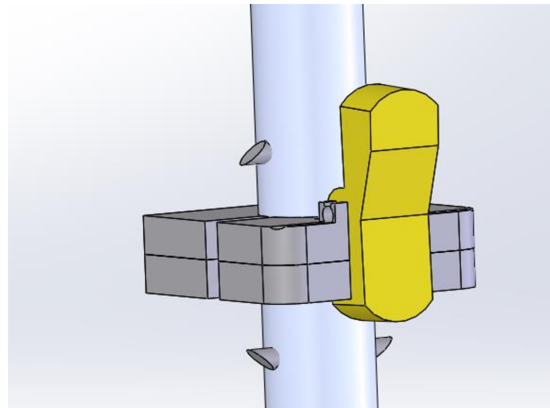
5. Bottom tube and middle tube are slid on to hinge.



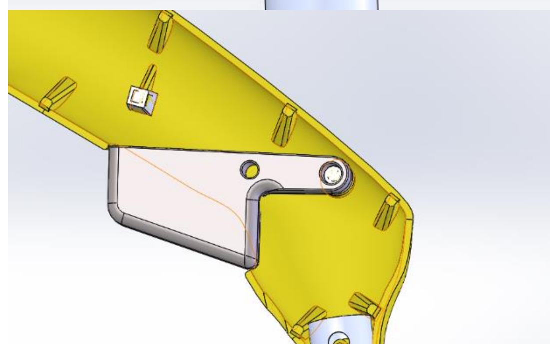
6. Hinge release pin is slid into the trigger and fitted in the groove by applying some pressure.



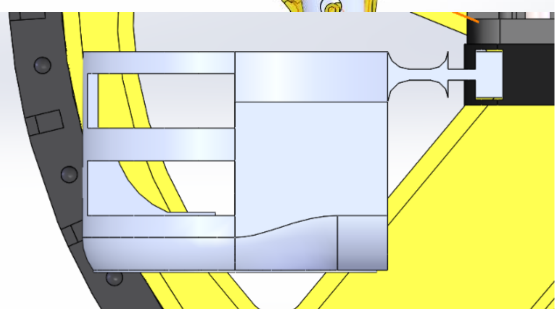
7. Steps 6 and 7 are repeated to place hinge between top tube and middle tube as well.



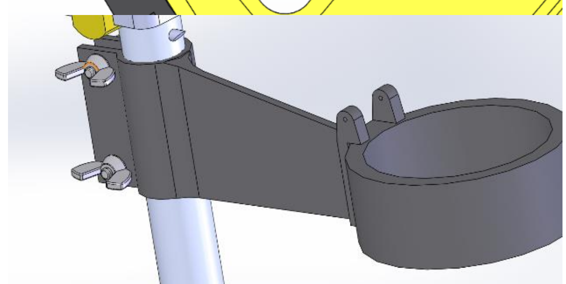
8. Trigger is fit inside the left handle halve and the cable is attached. The right handle halve is snapped in place.



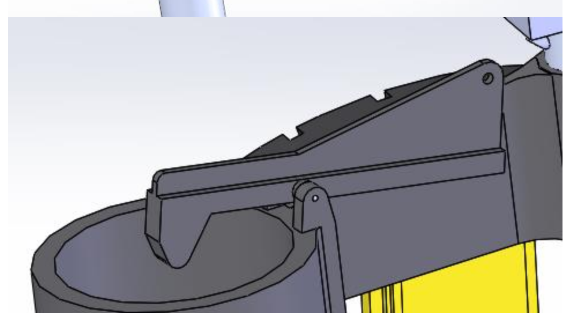
9. Spray base is slid onto the base part.



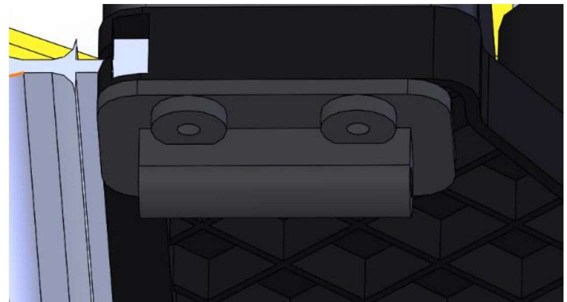
10. Top housing is inserted on the bottom tube and tightened with wing nuts.



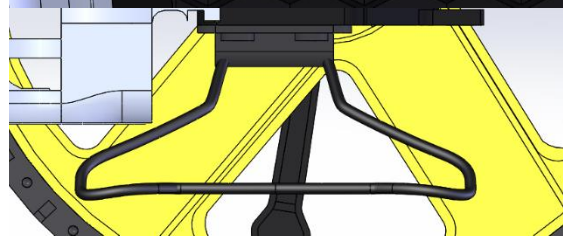
11. Depressor is attached to the top housing by using the depressor pin



12. Foot mount is attached to the base part using the nuts and bolts.



13. Counter foot wire is attached to the base by applying pressure.



9. Product Manufacturing

9.1 Materials selection

9.1.1 Spray Can base

Figure 15: Spray Can Base

Function:
This base holds the spray unit and is also coupled to the base of the counter providing means of attachment of the counter base to the spraying unit.

Constraints:

1. Weight
2. Strength
3. Easy manufacturability
4. Excellent lifetime

Geometric parameters:

Thick walls (0.1 in thickness), simple geometry, small holes and precise shapes are required for this part.

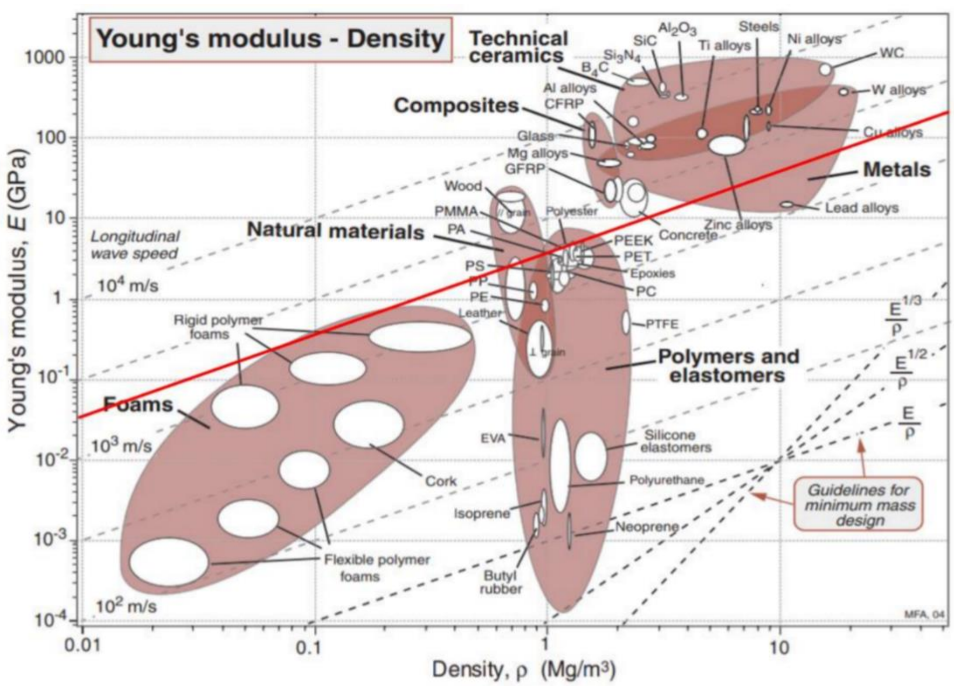


Figure 16: Ashby chart for Young's modulus vs density

The material selection of the spray base was largely determined by the weight and strength needed to hold the parts that is encompasses together. Also, the stiffness of the base needed to be considered so that the base of the counter can be rigidly mounted to it. This led us to the Ashby chart of Modulus vs Density as shown in Figure 16. This was used in order to determine a proper material. Since the weight of the part is important to us along with the stiffness, E/ϱ chart was used. From our observation of the same, we found out that polymers, natural materials, foams and metals satisfy our requirements. Given the aforementioned function, we decided that our part requires optimal stiffness. Almost all the components of the surveyor's wheel are made with injection molded parts apart from the foldable rods. However, we realized that it was better to have this part made from metal than plastics given the amount of stiffness needed. Using this information along with the process selection analysis carried out in Section 9.2, we came to the conclusion that aluminum, steel or cast iron would be possible alternatives in terms of cost and manufacturability.

9.1.2 Hinge

Function: The hinge not only folds the assembly to make it into a compact shape, but also controls the length of the assembly. During the operation of this product, hinge is subjected to tension forces.

Constraints:

1. Lightweight
2. Flexible
3.
4. Strength
5. Excellent lifetime
6. Easy manufacturability

Geometric parameters:

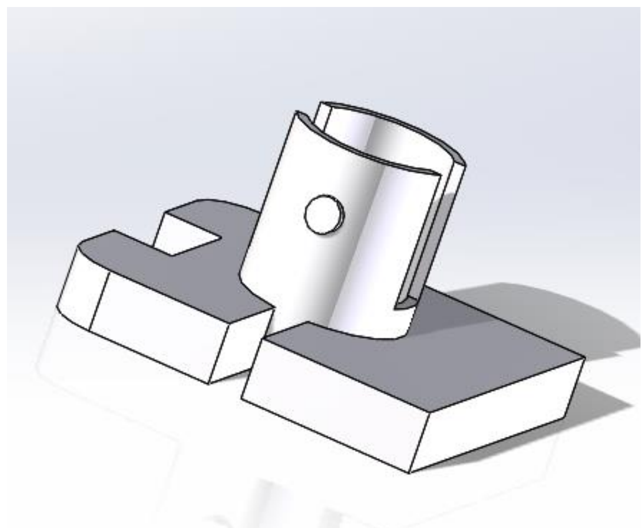


Figure 17: One-piece hinge

The part is complex and has thin walls. Precision is needed for this part given its function of holding the upper and lower portion of the assemblies and its extensible nature.

The DFMA goal for this is to have a durable part with enough stiffness to hold the assembly keeping in mind the weight. Hence, we look at the Young's modulus vs density curve.

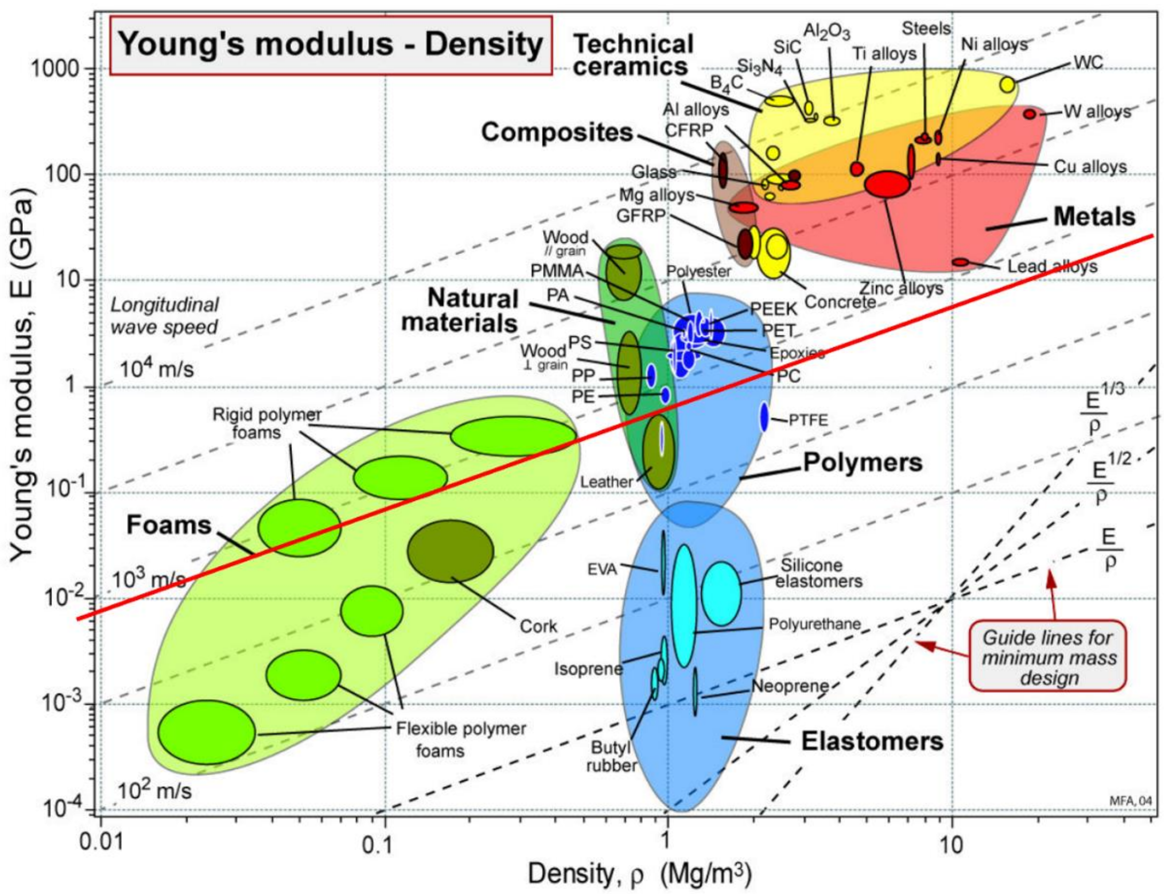


Figure 18: Ashby chart for Young's modulus vs density

For this analysis, we referred to the Young's modulus vs Density chart as shown in Figure 18.

The material here, in terms of weight can be substituted with many polymers/plastics without compromising the function. Most of the parts of the Surveyor's wheel have been injection molded and ABS and HDPE are the two primary materials used. This chart Figure 18 allowed us to minimize the weight of the hinge while not compromising on the function of the part. Foams, polymers and elastomers, composites, ceramics; all of them fit the criteria. But many materials like Polycarbonate, ABS, Polypropylene, Polystyrene can be used. Using them will not compromise the functional requirements. Many materials fit on the line, including rigid foams, PE, PMMA, PET, PS, ceramics. But we find HDPE to be the best alternative given its durability, temperature resistance, lightweight and low cost.

9.1.3 Upper can support

Function: The top housing of the assembly is connected to the tube of the lower portion of the main assembly through 2 pins. It provides a housing for the spray can so that the can is not cantilevered. It also has a mounting feature for the depressor and can be adjusted axially by removing and re-fitting two pins that hold it to the tube.

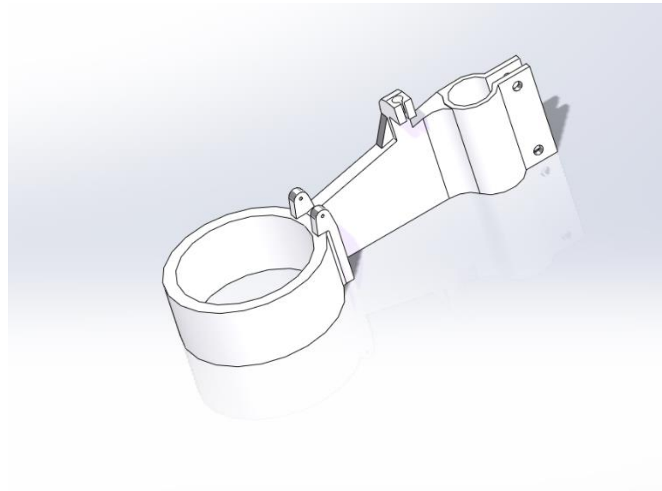


Figure 19: Upper can support

Constraints:

- Lightweight
- Stiff
- Easy to manufacture
- Cheap

The DFMA goal for this part is having a stiff part that is inexpensive. As before, we used Ashby to help us with the process. The Young's modulus vs Relative cost chart is guided by indices that encompass modulus, strength, cost.

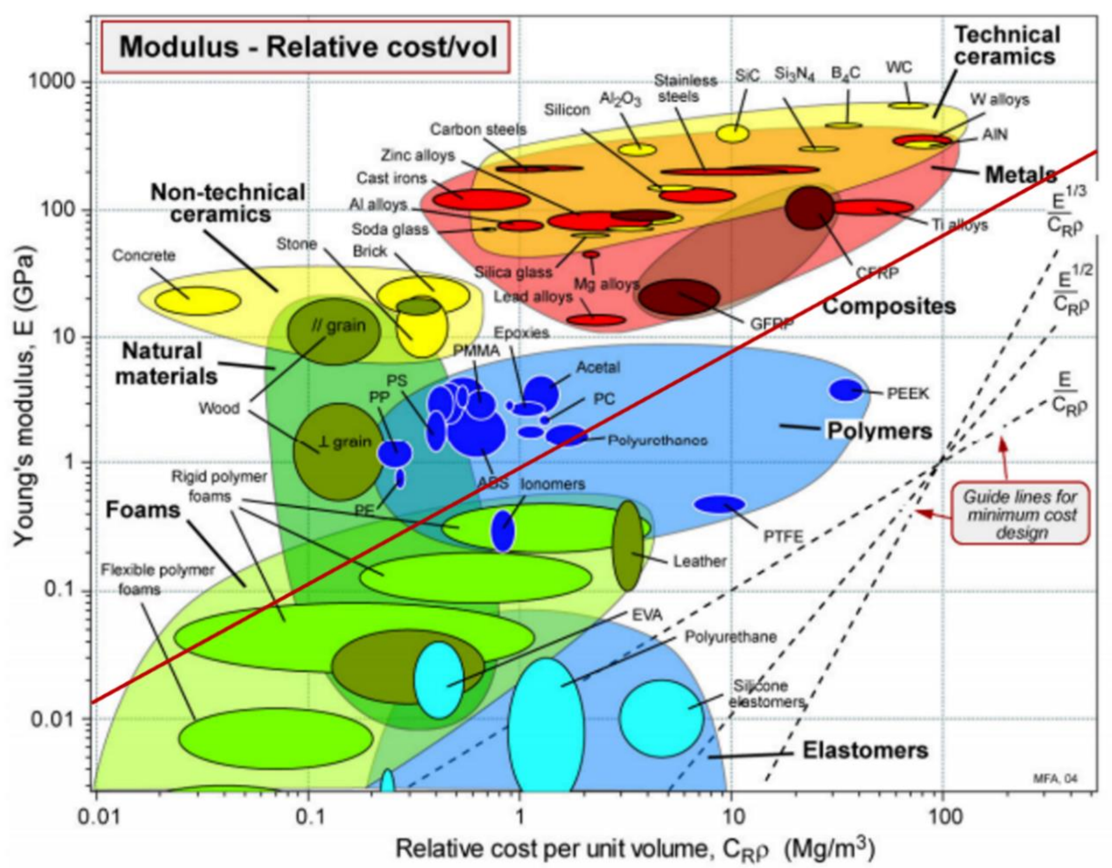


Figure 20: Ashby chart for Young's modulus vs relative cost per unit volume.

Discussion

In Figure 20 we see that plastics, ceramics, natural materials, foams, Mg alloys, Ti alloys emerge as possible material candidates. However, we eliminate foams and Mg, Ti alloys as they are not strong enough. This leaves us with polymers like ABS, PET, PMMA, Al alloys etc. The material can be substituted with many polymers/plastics without compromising its function. Also, most of the surveyor's wheel parts have been injection molded. Also, their cost per unit volume is cheaper as compared to other candidates. We finally go ahead with selecting ABS as it turns out to be cheapest alternative given its cost, lightweight and durability.

9.1.4 Nylon and ABS components:

Through our Reverse Engineering project and from our analysis, we went with the selection of plastics like PP, PVS, Nylon and ABS. In the re-design of this device, we have chosen and incorporated plastics in most of our parts. The product itself has many parts made from injection molded plastics. The two main plastics that have been used are ABS and Nylon. In the main assembly, most parts are made from ABS. However, in the counter sub-assembly, there are many moving parts. Although ABS is a lower cost alternative to Nylon, these parts need a low coefficient of friction to move against each other. For these parts, Nylon has been utilized. This will allow for low coefficient of friction and hence supports our choice for moving plastic parts. Figure 21 displays the coefficient of friction of various plastic components and it can easily be seen that nylon's coefficient of friction is nearly half that of ABS.

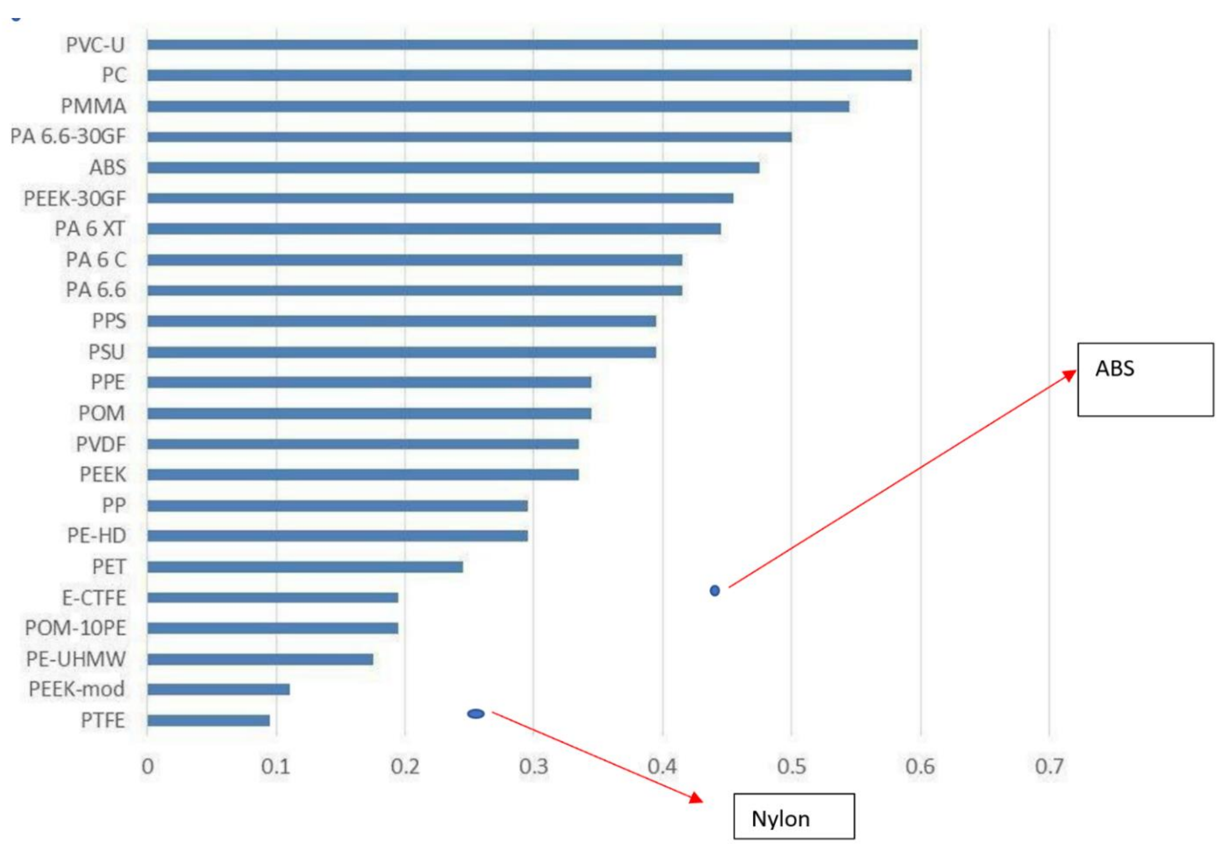


Figure 21: Coefficient of friction of different polymers

9.2 Process selection

Process selection is significant because this is what is going to decide if it is feasible to manufacture the product with this material. In theory, you might have the product design ready, but the success of your business depends on a lot of parameters with this parameter being one of them. If done in a wrong manner, this could potentially ruin your business idea. For any given product, we have a plethora of manufacturing processes to choose from and narrowing them down to a selected few requires us to refer to something called as process selection drivers. Following are those:

- Labor rate
- Quality
- Throughput time
- Quantity of product needed
- Level of automation needed
- Processing time
- Tooling cost
- Cost of material
- Maintenance cost
- Energy consumption
- Size of the product
- Material cost

Material selection helps a lot in narrowing down from the manufacturing processes. For example: if we choose sheet metal, then bending, blanking, drawing, casting, shearing etc. are some of the processes we have to choose from while ignoring the rest of the processes like polymer processing, casting, deformation etc. (chosen from Professor Dan Riffell's slides). When coming to investigation of the processes, we should also have an understanding about whether the process is going to be repetitive or intermittent, whether o the process is going to be a batch process or continuous process. The following general criteria is adopted for the selection of the manufacturing processes:

STEP 1: Material choice

As mentioned above, this option is very efficient in initial screening of the manufacturing processes.

STEP 2: Identify processes

Since we already have a smaller range of processes to work with, the next step should be to classify them according to size, geometry.

STEP 3: Assess the processes

This process is done to investigate fewer broad parameters such as tooling time, automation, labor skill, assembly etc.

This selection must be done for every part but herein, we are going to the selection criteria adopted for only the base of the spray paint unit. The spray paint assembly is one of the most important additions that holds the container and connects it to the base part of the counter sub-assembly. Since the design of the base part turned out to be simple, and since it needs enough stiffness, our choice (as mentioned in section 9.1) for the base is using metal part that could be machined or cast. The analysis was then completed using the charts and figures provided by Prof Dan Riffle. Pitching the processes against each other, analysis was done for a batch size of 100,000 units. Once the processes were selected on the basis of geometry, batch size, characteristics etc., a cost analysis was done to finalize the process.

The first step as mentioned was to research the processes capable of manufacturing metals. The metals that we decided to choose from was aluminum 1060 alloy, steel and cast iron. Reason being these three metals are very flexible in terms of manufacturability.

Table 3: Initial screening of the candidate processes for the base of the spraying unit

	Aluminum		**Steel**		**Cast Iron**		
Process	**Yes or No**	**Reject**	**Yes or No**	**Reject**	**Yes or No**	**Reject**	**Reason**
Sand Casting	Y		Y		Y		
Investment Casting	Y		Y		Y	R	Not common for cast iron
Die Casting	Y		N		N		
Injection Molding	N		N		N		
Impact Extrusion	Y		Y		N		
Hot Extrusion	Y		Y	R	N		Not common for steel
Sheet metal	Y		Y		N		
Machining	Y		Y		Y		

From the research collected, The first step as mentioned was to research the processes capable of manufacturing metals. The metals that we decided to choose from was aluminum 1060 alloy, steel and cast iron. Reason being these three metals are very flexible in terms of manufacturability.

Table 3, we discarded two manufacturing processes for the candidate materials chosen and hence narrow down the processes we think are most valid for the materials. Based on this research, we hence choose sand casting and machining as our processes. Essentially, the base of the spray unit is of a simple geometry with some holes and cut-outs and hence can be manufactured through sand casting or machining. Moving forward with these, we now go ahead with our analysis. The next step is to utilize the process based on certain characteristics like cycle time, material waste, flexibility etc. Table 4: Rating characteristics of manufacturing processes in consideration shows the rating scale and *Table 5* shows the rating characteristics for the casting and machining process.

Table 4: Rating characteristics of manufacturing processes in consideration

Process	Shape	Cycle Time	Flexibility	Material Utilization	Quality	Equipment Tooling Costs	Handbook Reference
Casting							
Sand casting	3-D	2	5	2	2	1	AHB, vol. 15, p. 523
Machining							
Single-point cutting	3-D	2	5	1	5	5	AHB, vol. 16
Multiple-point cutting	3-D	3	5	1	5	4	AHB, vol. 16
Grinding	3-D	2	5	1	5	4	AHB, vol. 16, p. 421
Electrical discharge machining	3-D	1	4	1	5	1	AHB, vol. 16, p. 557

Table 5: Rating scale of manufacturing processes in consideration

Rating Scale for Ranking Manufacturing Processes

Rating	Cycle Time	Flexibility	Material Utilization	Quality	Equipment Tooling Costs
1	>15 min	Changeover very difficult	Waste >100% of finished part	Poor quality	High machine and tooling costs
2	5 to 15 min	Slow changeover	Waste 50 to 100%	Average quality	Tooling and machines costly
3	1 to 5 min	Avg changeover and setup time	Waste 10 to 50%	Average to good quality	Tooling and machines relatively inexpensive
4	20 s to 1 min	Fast changeover	Waste < 10% finished part	Good to excellent	Tooling costs low
5	<20 s	No setup time	No appreciable waste	Excellent quality	Equip. and tooling very low
Rating scale: 1, poorest; 5, best					

Once the manufacturing processes in question have been ranked for the various important factors, the columns can be totaled. As the above table shows the total for sand casting is 13 and for machining is 18. This says how machining could be a more efficient process. However, mass and cost needed for the manufacturing have not yet been taken into consideration. Therefore, we now look at these factors to further assess the processes. This is shown in Figure 22 and Figure 23.

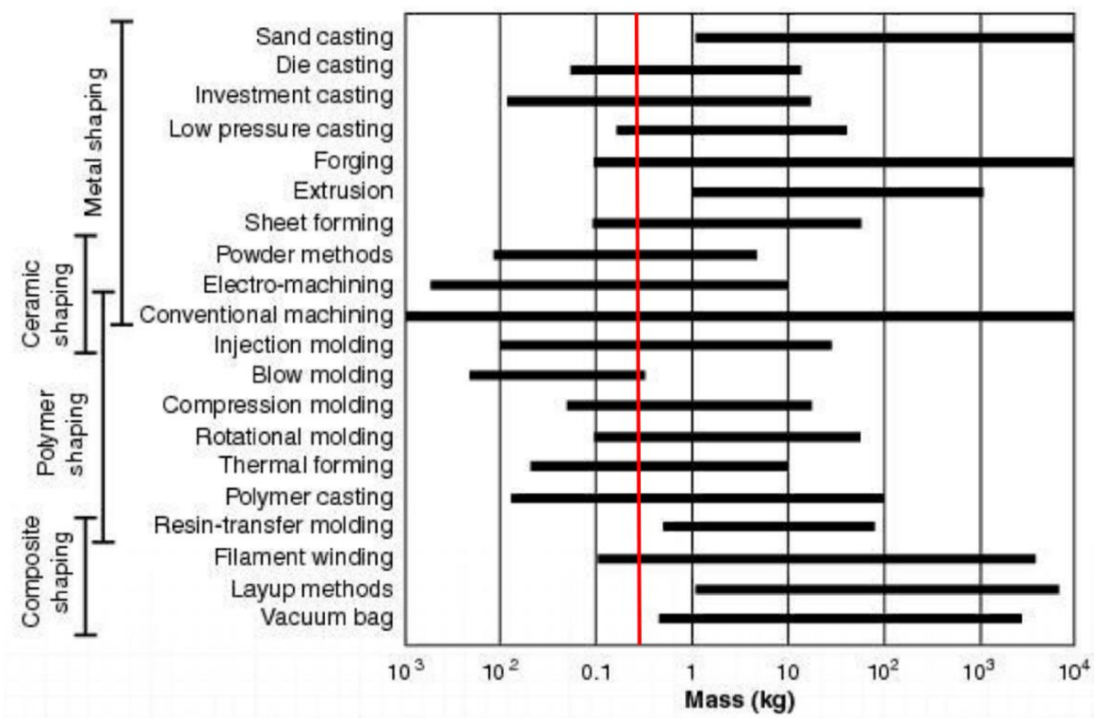


Figure 22: Displays the process to be selected for the mass in manufacturing processes

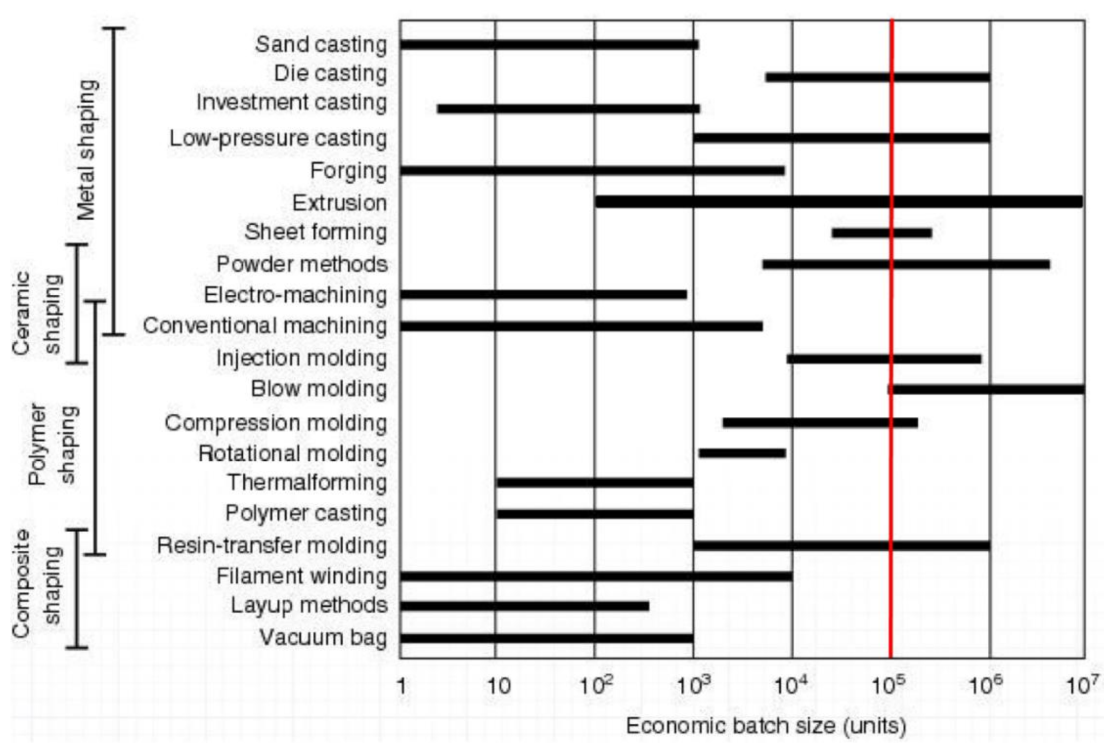


Figure 23: Displays the manufacturing process to be taken for various economic batch sizes

The mass of our base part is 0.44 lbs which is equivalent to 0.2 kgs. From the chart displayed in Figure 22, we see that conventional machining is more favorable as compared to sand casting. Sand casting makes sense for parts that weigh more than a kg. We further analyze the process for economic batch size. The batch size we aim for with this designed product is 100,000. From Figure 23, we reached a conclusion that the machining comes out to be the better of the two processes and hence we go ahead with that. Finally, we do a cost analysis to understand how much it would cost to make the base part. This is given in Table 6.

Table 6: Unit Cost of the Spray Base

Full Cost Calculation			
Value Name	Variable	Inputs	Outputs
Material Cost ($/lb.)	c_m	$0.99	
Scrap fraction	f	0.05	
Part Mass (lb.)	m	0.8	
Unit Cost of Material ($)	C_M		$0.83
Labor cost ($/hr)	c_w	35	
Production rate (Units/hr)	n_dot	124	
Unit cost of labor ($)	C_L		$0.28
Tooling cost ($/set)	c_t	$2,936.00	
Total Production Run (Units)	n	5000	
Tooling life (Units)	n_t	200000	
Sets of Tooling Required	k	1	
Unit cost of tooling ($)	C_T		$0.20
Capital Cost ($)	c_e	$1,000,000.00	
Capital Write-Off Time (yrs)	t_wo (yrs)	5	
Capital Write-Off Time (Hrs)	t_wo (hrs)	43800	
Load fraction	L	1	
Load sharing fraction	q	1	
Unit cost of capital equipment ($)	C_E		$0.18
Factory overhead, cOH, ($/hr)	c_oh	60	
Production rate (Units/hr)	n_dot	124	
Unit cost of factory overhead ($)	C_OH		0.4838709677
Total Unit cost	C_U		$1.98

10. Design for Assembly

This phase was one of the most important phases for our final project. The factors considered which affect the functionality of product are as follows:

1. Complexity Factor
2. Functional Analysis
3. Error proofing
4. Handling
5. Insertion
6. Secondary Operation

We recognized the components that must be integrated with other components and tried to reduce the number of interfaces thus improving the overall efficiency. Once we performed the analysis, we identified the areas of improvement and worked on them to reach the targets desired.

The metrics for DFA are given in **Error! Reference source not found.**

Table 7: DFA Metrics for Surveyor's Marking Wand

DFA Analysis Worksheet

Assembly Name: Surveyor's Wheel **Team:** Kyle R, Ryan W, Ayush B, Ninad M **Date:** 10/2/2019

If the answer is Yes to any of the metrics or questions enter a 1. If the answer is No then enter 0. Each cell must have a number.

Part		DFA Complexity		Functional Analysis / Redesign Opportunity				Error Proofing		Handling			Insertion				Secondary Operations				
Part Number	Part Name	Number of Parts (Np)	Number of Interfaces (NI)	Theoretical Minimum Part	Part Can Be Standardized (If not already standard)	Cost (Low/Medium/High)	Practical Minimum Part	Assemble Wrong Part/ Omit Part	Assemble Part Wrong Way Around	Tangle, Nest, or Stick Together	Flexible, Fragile, Sharp or Slippery	Pliers, Tweezers, or Magnifying Glass Needed	Difficult to Align/ Locate	Holding Down Required	Resistance to Insertion	Obstructed Access/ Visibility	Re-orient Workpiece	Screw, Drill, Twist, Rivet, Bend, or Crimp	Weld, Solder, or Glue	Paint, Lube, Heat, Apply Liquid or Gas	Test, Measure or Adjust
1101	Base Part	1	11	1	0	M	1	0	0	1	0	0	0	1	0	1	1	1	0	0	0
1309	Top Housing	1	5	1	0	L	1	0	1	0	1	0	0	1	0	0	0	1	0	0	0
1408	Spray Base	1	2	0	0	H	1	0	0	0	0	0	0	1	1	0	0	0	0	0	0
1306	Depressor trigger pin	1	2	0	1	L	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
1109	Handle trigger pin	1	3	0	1	L	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
1105	Trigger	1	3	0	0	L	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1310	Depressor	1	3	0	1	L	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0
1209	Hinge	1	4	0	0	M	0	0	1	0	0	0	1	1	1	0	1	1	0	0	1
2000	Counter Subassembly	1	2	1	0	H	1	0	0	1	1	0	0	1	1	0	1	0	0	1	1
	Wing nut	2	2	1	1	L	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Thumb screw	2	2	1	1	L	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0
1100	Handle Left	1	0	1	0	L	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1110	Handle Right	1	0	1	0	L	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1301	Top Tube	1	6	1	1	M	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0
1302	Middle Tube	1	6	1	1	M	1	1	0	0	0	0	0	0	1	0	0	0	0	0	0
1303	Lower Tube	1	5	1	1	M	1	1	0	0	0	0	0	0	1	0	0	0	0	0	0
1307	Hinge Release	2	3	0	0	L	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
1308	Hinge Release Pin	2	2	0	1	L	0	1	0	0	0	0	0	0	1	0	1	1	0	0	0
1401	Hinge Spring	2	2	0	0	M	0	0	0	1	0	0	0	1	1	0	1	0	0	0	0
	Handle Base Rivet	1	2	0	1	L	0	1	0	0	0	0	0	0	0	0	1	1	0	0	0
1105	Foot (Kick Stand)	1	1	1	0	L	1	0	1	1	0	0	0	1	1	0	1	0	0	0	0
1150	Foot Mount	1	5	0	0	L	0	0	1?	0	0	0	0	0	0	0	1	0	0	0	0
	Foot Mount Screw	4	2	0	1	L	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0
	Counter SubAssy Screw	2	2	0	1	L	1	1	0	0	1	0	0	0	0	0	1	0	0	0	0
1207	Position Arrow	1	1	1	0	L	1	1	0	0	0	0	0	0	0	0	1	0	0	0	0
	Snap Ring	2	1	1	0	L	1	1	0	0	0	1	1	0	1	0	0	0	0	0	0
1210	wheel	1	1	1	0	H	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	#10 Nut	2	2	1	0	L	1	0	0	0	0	0	1	1	0	0	1	0	0	0	0
	Totals	33	71	15	12	0	19	8	3	4	4	2	3	9	10	1	11	8	0	0	2
	Design for Assembly Metrics	**48.40454524**		**45.0%**	←Theor. Effy. Pract. Effy.→		**57.6%**	**0.73**		**0.67**			**1.53**				**1.40**				
	Targets	**50**		**>60%**			**>50%**	**0.00**		**0.00**			**0.00**				**0.50**				

*smaller is better

10.1 DFA Complexity Factor

While re-designing the wheel, number of interfaces were analyzed by the team. We tried on reduction of interfaces by eliminating unnecessary interactions. By incorporating snap fits on the handles, press fit on hinges and re-designing our base part, the team arrived at a complexity factor of 48.40.

10.1.1 Functional Analysis

In order to understand if the part type could be standardized, the team conducted a functional analysis. The theoretical minimum part count was 15 while the practical minimum part count was 19. We felt the need to minimize non-standard parts in order to achieve an efficient assembly process. We found out that we could standardize around 12 parts and hence reduce production cost. The theoretical part count efficiency achieved was 45% while the practical part count efficiency was 57.6%.

10.1.2 Error Proofing and Handling

This was one of the important areas of DFA analysis. We identified few areas which were prone to incorrect insertion or omission. Certain parts which could be assembled other way round were top housing of the paint spray can, hinge that assembles the lower portion with the upper portion, and the foot mount. However, some of these were due to the re-design of the assembly and these could not be eliminated. The only way to handle these was to instruct the assembly workers to help minimize the possibility of incorrect assembly and hence error proofing. We arrived at an error proofing metric of 0.73.

Through handling, we identified the sections which would tangle, nest or stick together and components which were fragile, sharp, slippery or required additional equipment for being picked for assembly. Hinge release pin and base part have chances of getting tangled or stuck. Also, it was difficult to get a hold of components like depressor and snap rings due to their size. We arrived at a metric of 0.67 for handling issues.

10.1.3 Insertion and Secondary operation:

Insertion issues and secondary operations like riveting, screwing, gluing etc. Take extra time, effort and money and hence manufacturers should take these into consideration to reduce the overall assembly time. Spray base, hinge release, tubes, are parts which need to be held down and these along with aluminum tubes face difficulty during insertion process as well. Base part is the only part in out assembly which has obstructed access. The metric achieved for insertion was 1.53 whereas the metric for secondary operations was 1.4

11. Economic Analysis

Extensive cost analysis was undertaken in order to ensure that the product could be manufactured at a low enough cost to be positioned as a competitor to standard surveyor's wheels available on Amazon. Simple (and therefore less accurate) Fermi estimates where conducted as a back-of-the-envelope calculation, to get an idea of the feasibility of our idea. These order of magnitude estimates where calculated for each part and then summed. They would not include assembly costs, but experience with surveyor's wheel had taught us that Fermi estimates in this field were generally high. Thus, we were not discouraged when the total Order of Magnitude Estimate returned $38, which was very close to our $40 goal.

Breakeven Price was calculated next and returned a much lower dollar value. Experience had shown us that breakeven price had typically come in low for the surveyor's wheel, so the $28 that it returned was the bottom bound on our per-piece cost. Armed with this information, it seemed reasonable to perform the full unit cost calculation for each piece and sum them to determine the cost of the complete Surveyor's Marking Wand.

11.1 Unit Cost Calculation

The most thorough cost calculation is explained here, with the simpler preliminary costs covered in the appendix. What follows are the substituent formulas used to find each component of each parts costs [2]; Breakeven Price and OME formulas and individual parts' results are all included but being less accurate they are left in 16. Appendix A: Complete Cost Analyses. Calculated values are discussed in the following section.

Material Cost:

$$C_M = \frac{mc_m}{1-f} \tag{6}$$

Where:
m = weight of material (lb)
c_m = cost of material ($/lb)
f = fraction of material that is scrap

Labor Cost:

$$C_L = \frac{C_w}{n'} \tag{7}$$

Where:
C_w = hourly cost of wages ($/hr)
n^0 = production rate (units/hr)

Tooling Cost:

$$C_T = \frac{C_t k}{n} \tag{8}$$

Where:
C_t = cost of tooling ($)
n = production run (# of parts)
k = tooling wear factor (n/life of tool)

Equipment Cost:

$$C_E = \frac{1}{n}\frac{c_e}{Lt_{wo}}q \qquad (9)$$

Where:
c_e = cost of capital equipment ($)
n^0 = production rate (units/hr)
L = load factor
t_{wo} = capital write off time
q = fraction of equipment sharing between products

Overhead Cost:

$$C_{OH} = \frac{c_{oh}}{n'} \qquad (10)$$

Where:
C_{OH} = overhead hourly rate ($/hr)
n^0 = production rate

Finally, all of the calculated C values are summed, resulting in the unit cost of an individual part. When repeated for every part in the complete Surveyor's Marking Wand, these return the most accurate cost of one assembled Surveyor's Marking Wand.

$$C_U = C_M + C_L + C_T + C_E + C_{OH} \qquad (11)$$

11.2 Part Cost Discussion

The three methods of cost calculation are compared in Table 8. Unit Cost is shown in orange, OME in green and Breakeven Price in yellow. Notably, certain individual parts account for large portions of the overall cost. These parts are either massive or metal. Most expensive is the wheel itself at $2.44, to which the product owes a large part of its functionality. To roll smoothly over uneven terrain or tall grass, this large-diameter wheel is required. Furthermore, its design is already minimal in terms of the volume of plastic used and the rigidity required. However, it was possible to change the type of plastic used. Providing similar rigidity, HDPE was selected, allowing a cost savings of $0.80 from the previous design, as shown in Table 9, Part #1210.

The second most expensive part is a new part, the Spray Base, which is a machined aluminum part that has a unit cost of $1.98. This cost calculation was detailed as a process selection example in Table 6: Unit Cost of the Spray Base in the Product Manufacturing Section. Other expensive parts include the three extruded aluminum tubes that make up the product's handle. Altogether, the overall reduction in the number of parts combined with a switch to lower cost materials for some parts allows the Surveyor's Marking Wand to come in just $1.17 more expensive than the Surveyor's Wheel. The initial target cost, $35, was therefore achieved, and this will allow us to price this product competitively; average surveyor's wheel cost is $50, but our product competes in the low-cost end of the spectrum.

Summing up, this product will sell for $40 on Amazon, providing a 15% profit.

Table 8: Comparison of Unit Cost, OME and Breakeven Price for the Surveyor's Marking Wand.

		Total Unit Cost	Order of Magnitude Estimate	Breakeven Price
	Equation	*C_U=C_M+C_L+C_T+C_E+C_OH*	*C_M*9*	*Q_B = C_F/(P-C_F)*
	Variable	C_U	OME Price	Q_B
Part Number & Name		$	$	$
1101	Base Part	$1.13	$1.53	$0.94
1100	Handle Left	$1.04	$0.81	$0.86
1110	Handle Right	$1.03	$0.72	$0.85
1301	Top Tube	$1.54	$1.56	$1.21
1302	Middle Tube	$1.59	$2.01	$1.26
1303	Bottom Tube	$1.53	$1.52	$1.21
1205	Hinge	$0.99	$0.55	$0.71
1307	Hing Release	$0.94	$0.09	$0.66
1401	Hinge Spring	$0.93	$0.02	$0.66
1105	Foot (Kick Stand)	$0.69	$1.22	$0.69
1150	Foot Mount	$0.99	$0.34	$0.81
1207	Position Arrow	$0.99	$0.34	$0.81
1210	Wheel	$2.44	$13.37	$3.02
1408	Spray Base	$1.98	$6.72	$1.81
1207	Top Housing	$1.10	$1.30	$0.91
1210	Depressor	$0.97	$0.18	$0.79
2000	**Counter Subassembly**			
2200	Gear Mount	$1.07	$1.08	$0.89
2100	Cover	$1.08	$1.10	$0.89
2404	Gear holder	$0.98	$0.24	$0.80
2320	Counter Gears	$0.94	$0.04	$0.61
2403	Driving shaft	$1.00	$0.01	$0.83
2402	Counter shaft	$1.00	$0.01	$0.81
2407	Stopper shaft	$1.17	$1.54	$0.98
2211	Counter Spring	$1.03	$0.28	$0.84
2406	Reset Spring	$1.03	$0.28	$0.84
2330	Reset lever	$1.09	$1.21	$0.90
2405	Gear enforcer	$0.96	$0.04	$0.77
2203	Counter driving gears	$0.96	$0.05	$0.77
2340	Wheel coupler	$0.96	$0.04	$0.77
		$34.12	**$38.21**	**$27.90**

Table 9: Comparison of Unit Cost, OME and Breakeven Price for the Surveyor's Wheel

		Total Unit Cost	Order of Magnitude Estimate	Breakeven Price
Equation		C_U=C_M+C_L+C_T+C_E+C_OH	C_M*9	Q_B = C_F/(P-C_F)
Part Number & Name	Variable	C_U $	OME Price $	Q_B $
1101	Base Part	$1.13	$1.49	$0.94
1100	Handle Left	$1.09	$1.21	$0.90
1110	Handle Right	$1.09	$1.21	$0.90
1208	Handle Shim	$0.93	$0.05	$0.66
1301	Top Tube	$1.54	$1.56	$1.21
1302	Middle Tube	$1.59	$2.01	$1.26
1303	Bottom Tube	$1.53	$1.52	$1.21
1205	Hinge Male Side	$1.06	$1.20	$0.79
1304	Hinge Female Side	$1.07	$1.27	$0.79
1307	Hing Release	$0.94	$0.13	$0.67
1401	Hinge Spring	$0.93	$0.02	$0.66
1105	Foot (Kick Stand)	$0.69	$1.22	$0.69
1150	Foot Mount	$0.99	$0.34	$0.81
1207	Position Arrow	$0.99	$0.34	$0.81
1210	Wheel	$3.21	$20.29	$3.02
2000	**Counter Subassembly**			
2200	Gear Mount	$1.07	$1.08	$0.89
2100	Cover	$1.08	$1.10	$0.89
2404	Gear holder	$0.98	$0.24	$0.80
2320	Counter Gears	$0.94	$0.04	$0.61
2403	Driving shaft	$1.34	$0.26	$1.04
2402	Counter shaft	$1.34	$0.25	$1.02
2407	Stopper shaft	$1.52	$1.85	$1.19
2211	Counter Spring	$1.03	$0.28	$0.84
2406	Reset Spring	$1.03	$0.28	$0.84
2330	Reset lever	$0.96	$0.01	$0.77
2405	Gear enforcer	$0.96	$0.04	$0.77
2203	Counter driving gears	$0.96	$0.05	$0.77
2340	Wheel coupler	$0.96	$0.04	$0.77
		$32.95	$39.39	$26.52

12. Comparison to Surveyor's Wheel

Now that the DFX analysis of the surveyor's marking wand is complete, the next step is to compare it to the original surveyor's wheel which was analyzed in the Reverse Engineering project. This report already discussed the added functionality of this product compared to the original surveyor's wheel.

In summary, the surveyor's marking wand allows the user to measure long distances along the ground. It also can be used to make marks on the ground with paint wherever the user needs. The original product, in comparison, can only accomplish the former task.

The DFA metrics of both devices can also be compared. Since the team decided to make some changes to the design to mitigate any negative impacts that the adaptive redesign might have had on its DFA metrics, these values are analyzed in order to show that the new design is not significantly worse in its DFA. Table 10 below shows the DFA metrics of both the original design and the redesigned product side by side for easy comparison.

Table 10: Comparison of DFA metrics

	Metric	**Total Original**	**Total Redesign**	**DFA Metrics Original**	**DFA Metrics Redesign**
DFA Complexity	Number of Parts (Np)	43	33	52	48
	Number of Interfaces (Ni)	63	71		
Functional analysis/ redesign opportunity	Theoretical Minimum Part	20	15	46.50%	45.00%
	Parts can be standardized	13	12		
	Cost	13	12		
	Practical Minimum Part	19	19	44.20%	57.60%
Error Proofing	Assemble Wrong Part/Omit Part	10	8	0.65	0.73
	Assemble Part Wrong Way Around	3	3		
Handling	Tangle, Nest, or Stick Together	4	4	0.45	0.67
	Flexible, Fragile, Sharp, Slippery	4	4		
	Need Pliers, Tweezers, or Mag. glass	1	2		
Insertion	Difficult to Align or Locate	2	3	0.8	1.53
	Holding down required	4	9		
	Resistance to insertion	10	10		
	Obstructed access or visibility	0	1		
Secondary Operations	Reorient Workpiece	9	11	0.75	1.4
	Screw, drill, twist, rivet, bend, crimp	6	8		
	Weld, solder, or glue	0	0		
	Paint, lube, heat, apply liquid or gas	0	0		
	Test, measure, or adjust	0	2		

From this comparison, the most notable takeaway is that the overall part count (This is excluding parts from the counter subassembly. However, in both designs, that subassembly remains unchanged) is reduced with the new design. Although new functionality and, thus, new parts are added to the design, the team's efforts to make design changes to improve DFA outweigh the added marking wand parts. However, the assembly complexity in terms of handling, insertion, and secondary operations did increase compared to the original design. Additionally, the redesign is slightly more prone to assembly mistakes.

Finally, it is useful to compare the costs and prices for each of the devices. Part of the goal of this project was to add functionality to the surveyor's wheel without significantly increasing its cost. Some of the economic parameters are shown in Table 11 for both devices. The values in this table show that the team was successful in their attempts to keep the price low enough to still be competitive in the same market with similar products.

Table 11: Cost Comparison

	Surveyor's Wheel	Surveyor's Marking wand
Main Assembly Part Count	43	33
Cost to Manufacture	$32.95	$34.12
Estimated Sale Price	$34.99	$40

13. Safety and Environmental Factors

13.1 Safety Factors

The spray-painting surveyor's wheel has no major concerns when it comes to safety for the user. However, a few minor factors could be considered. First off, this product has a lot of small parts which could be a choking hazard if left out in a home. However, most if not all of the small parts are contained within the counter cover, virtually eliminating this risk. The paint in the spray paint cans usually contains volatile compounds, potentially posing a health risk for users. However, if the sprayer is used in the intended environment — outside — then, the risks associated with breathing in the paint fumes is minimal.

13.2 Environmental Factors

Similar to the analysis of safety for this product, the environmental concerns for the paint-spraying surveyor's wheel are relatively small. In the operation of this product, the only notable environmental factor to consider would be the aerosol released when using the spray paint. However, there is a relatively small quantity of paint that would be used. In the product's post-life, the disposal of the materials from the product would have a small environmental impact as well. The surveyor's wheel has multiple materials that would not be easily disassembled and sorted for recycling by either the consumer or a recycling facility. Therefore, the team predicts that this product would end up in a landfill at the end of its functional life.

14. Conclusion

After reverse engineering and analyzing the surveyor's wheel, the team decided to modify the design to increase its functionality. In order to do this, the team redesigned the product to include the ability to mark the ground with spray paint at the same time as it measures distance. This was achieved by modifying the original base part to include a feature to hold a marking spray paint can upside down. A new subsystem was also added to the product which depressed the spray paint can's valve when the user pulls on a trigger.

In order to mitigate any reduction in DFA efficiency or increase in complexity or part count, the team also decided to redesign two parts of the surveyor's wheel to reduce the number of parts needed and, therefore, improve the DFA. This was also done in efforts to keep the surveyor's marking wand as close to the original cost of the surveyor's wheel as possible so that it could remain competitive in the same market. Initially, the team replaced the handle screws with integrated snap hooks in the design.

Additionally, the team redesigned the handle hinges to be molded as a single piece, rather than two pieces, and to remove the need for rivets to connect it to the handle column. Overall, these two changes reduced the overall part count on these subsystems by 20 total parts. Overall, the number of parts of the newly designed surveyor's marking wand is less than the number of parts contained in the original surveyor's wheel by 10 parts. This allowed the cost to manufacture the surveyor's marking wand to only increase by $1.17 per unit. Thus, the selling price is able to be kept in a competitive range of similar products, but with a feature that differentiates the product from similar ones.

Through the reverse engineering project, the team was able to use DFM principles to analyze a consumer product in significant depth. Through this project, however, the team learned to apply DFM principles to original design work, further solidifying their grasp on the concepts. In general, these principles can now be successfully applied by each team member in future mechanical design work.

15. References

[1] B. Innovations, "Surveyor Instrument Business Plan," [Online]. Available: https://www.bplans.com/surveyor_instrument_business_plan/market_analysis_summary_fc.php. [Accessed 22 10 2019].

[2] T. Brunsgaard, S. Maierhofer, C. Marvin and J. Montoya, "All-In-One French Press," Boulder, 2015.

16. Appendix A: Complete Cost Analyses

Table 12: Complete OME and Breakeven Price analysis with unit cost for reference

		Total Unit Cost	Order of Magnitude Estimate			Breakeven Price						
	Equation	C_U=C_M+C_L+C_T+C_E+C_OH	C_M	C_M*3	C_M*9	Q_B = C_F/(P-C_F)						
	Variable	C_U	Material Cost	Manufacture Cost	OME Price	G & A	Depreciation	Factory	S & O	Fix. Costs	Var. Costs	Output
						∑ = C_F				C_F	C_V	Q_B
Part Number & Name		$	$	$	$	$	$	$	$	$	$	$
1101	Base Part	$1.13	$0.17	$0.51	$1.53	15000	25000	50000	77,944	167,943.55	$0.61	$0.94
1100	Handle Left	$1.04	$0.09	$0.27	$0.81	15000	25000	50000	77,944	167,943.55	$0.52	$0.86
1110	Handle Right	$1.03	$0.08	$0.24	$0.72	15000	25000	50000	77,944	167,943.55	$0.51	$0.85
1301	Top Tube	$1.54	$0.17	$0.52	$1.56	15000	25000	50000	107,389	197,388.89	$0.82	$1.21
1302	Middle Tube	$1.59	$0.22	$0.67	$2.01	15000	25000	50000	107,389	197,388.89	$0.87	$1.26
1303	Bottom Tube	$1.53	$0.17	$0.51	$1.52	15000	25000	50000	107,389	197,388.89	$0.81	$1.21
1205	Hinge	$0.99	$0.06	$0.18	$0.55	15000	25000	50000	155,887	245,887.10	$0.47	$0.71
1307	Hing Release	$0.94	$0.01	$0.03	$0.09	15000	25000	50000	155,887	245,887.10	$0.42	$0.66
1401	Hinge Spring	$0.93	$0.00	$0.01	$0.02	15000	25000	50000	155,887	245,887.10	$0.41	$0.66
1105	Foot (Kick Stand)	$0.69	$0.14	$0.41	$1.22	15000	25000	50000	37,173	127,173.08	$0.44	$0.69
1150	Foot Mount	$0.99	$0.04	$0.11	$0.34	15000	25000	50000	77,944	167,943.55	$0.47	$0.81
1207	Position Arrow	$0.99	$0.04	$0.11	$0.34	15000	25000	50000	77,944	167,943.55	$0.47	$0.81
1210	Wheel	$2.44	$1.49	$4.46	$13.37	15000	25000	50000	77,944	167,943.55	$1.92	$2.25
1408	Spray Base	$3.64	$2.20	$6.59	$19.77	15000	25000	50000	120,813	210,812.50	$2.83	$3.26
1207	Top Housing	$1.10	$0.14	$0.43	$1.30	15000	25000	50000	77,944	167,943.55	$0.58	$0.91
1210	Depressor	$0.97	$0.02	$0.06	$0.18	15000	25000	50000	77,944	167,943.55	$0.45	$0.79
2000	**Counter Subassembly**											
2200	Gear Mount	$1.07	$0.12	$0.36	$1.08	15000	25000	50000	77,944	167,943.55	$0.55	$0.89
2100	Cover	$1.08	$0.12	$0.37	$1.10	15000	25000	50000	77,944	167,943.55	$0.55	$0.89
2404	Gear holder	$0.98	$0.03	$0.08	$0.24	15000	25000	50000	77,944	167,943.55	$0.46	$0.80
2320	Counter Gears	$0.94	$0.00	$0.01	$0.04	15000	25000	50000	389,718	479,717.74	$0.42	$0.61
2403	Driving shaft	$1.00	$0.00	$0.00	$0.01	15000	35000	50000	77,944	177,943.55	$0.47	$0.83
2402	Counter shaft	$1.00	$0.00	$0.00	$0.01	15000	25000	50000	77,944	167,943.55	$0.47	$0.81
2407	Stopper shaft	$1.17	$0.17	$0.51	$1.54	15000	25000	50000	77,944	167,943.55	$0.64	$0.98
2211	Counter Spring	$1.03	$0.03	$0.09	$0.28	15000	25000	50000	77,944	167,943.55	$0.50	$0.84
2406	Reset Spring	$1.03	$0.03	$0.09	$0.28	15000	25000	50000	77,944	167,943.55	$0.50	$0.84
2330	Reset lever	$1.09	$0.13	$0.40	$1.21	15000	25000	50000	77,944	167,943.55	$0.57	$0.90
2405	Gear enforcer	$0.96	$0.00	$0.01	$0.04	15000	25000	50000	77,944	167,943.55	$0.44	$0.77
2203	Counter driving gears	$0.96	$0.01	$0.02	$0.05	15000	25000	50000	77,944	167,943.55	$0.44	$0.77
2340	Wheel coupler	$0.96	$0.00	$0.01	$0.04	15000	25000	50000	77,944	167,943.55	$0.44	$0.77
		$34.81			$51.26							$28.58

Table 13: Complete unit cost breakdown

		Unit Cost of Material				Unit cost of labor			Unit cost of tooling					Unit cost of capital equipment						Unit cost of factory overhead			Total Unit Cost
	Equation	C_M = m*c_m/(1-f)				C_L = c_w/n_dot			C_T = c_t*k/n					C_E = c_e*q/(n_dot*L*t_wo)						C_OH = c_oh/n_dot			C_U=C_M+C_L+C_T+C_E+C_OH
	Variable	Mass	Cost	Scrap	Output	Cost	Prod. Rate	Output	Cost	Run	Life	Sets	Output	Cost	Write-Off		Load	Share	Output	Overhead	Production rate	Output	C_U
		m	c_m	f	C_M	c_w	n_dot	C_L	c_t	n	n_t	k	C_T	c_e	t_woy	t_wo	L	q	C_E	c_oh	n_dot	C_OH	
Part Number & Name		lb	$/lb	%	$	$/hr	Units/hr	$	$/set	Units	Units		$	$	years	hours	%	%	$	$/hr	Units/hr	$	$
1101	Base Part	.125	1.29	5	$0.17	35	124	$0.28	26,000	500,000	200,000	3	$0.16	4,000,000	5	43,800	68.49315068	3.571428571	$0.04	60	124	$0.48	$1.13
1100	Handle Left	.100	0.85	5	$0.09	35	124	$0.28	24,733	500,000	200,000	3	$0.15	4,000,000	5	43,800	68.49315068	3.571428571	$0.04	60	124	$0.48	$1.04
1110	Handle Right	.090	0.85	5	$0.08	35	124	$0.28	24,733	500,000	200,000	3	$0.15	4,000,000	5	43,800	68.49315068	3.571428571	$0.04	60	124	$0.48	$1.03
1301	Top Tube	.066	2.50	5	$0.17	40	90	$0.44	1,000	500,000	5,000	100	$0.20	4,000,000	5	43,800	68.49315068	3.571428571	$0.05	60	90	$0.67	$1.54
1302	Middle Tube	.085	2.50	5	$0.22	40	90	$0.44	1,000	500,000	5,000	100	$0.20	4,000,000	5	43,800	68.49315068	3.571428571	$0.05	60	90	$0.67	$1.59
1303	Bottom Tube	.064	2.50	5	$0.17	40	90	$0.44	1,000	500,000	5,000	100	$0.20	4,000,000	5	43,800	68.49315068	3.571428571	$0.05	60	90	$0.67	$1.53
1205	Hinge	.068	0.85	5	$0.06	35	124	$0.28	25,000	1,000,000	200,000	5	$0.13	4,000,000	5	43,800	68.49315068	3.571428571	$0.04	60	124	$0.48	$0.99
1307	Hing Release	.011	0.85	5	$0.01	35	124	$0.28	25,000	1,000,000	200,000	5	$0.13	4,000,000	5	43,800	68.49315068	3.571428571	$0.04	60	124	$0.48	$0.94
1401	Hinge Spring	.002	1.29	5	$0.00	35	124	$0.28	25,000	1,000,000	200,000	5	$0.13	4,000,000	5	43,800	68.49315068	3.571428571	$0.04	60	124	$0.48	$0.93
1105	Foot (Kick Stand)	.100	1.29	5	$0.14	40	260	$0.15	25,000	500,000	200,000	3	$0.15	4,000,000	5	43,800	68.49315068	3.571428571	$0.02	60	260	$0.23	$0.69
1150	Foot Mount	.028	1.29	5	$0.04	35	124	$0.28	25,000	500,000	200,000	3	$0.15	4,000,000	5	43,800	68.49315068	3.571428571	$0.04	60	124	$0.48	$0.99
1207	Position Arrow	.028	1.29	5	$0.04	35	124	$0.28	25,000	500,000	200,000	3	$0.15	4,000,000	5	43,800	68.49315068	3.571428571	$0.04	60	124	$0.48	$0.99
1210	Wheel	1.660	0.85	5	$1.49	35	124	$0.28	25,000	500,000	200,000	3	$0.15	4,000,000	5	43,800	68.49315068	3.571428571	$0.04	60	124	$0.48	$2.44
1408	Spray Base	.747	2.50	15	$2.20	35	80	$0.44	1,000	500,000	5,000	100	$0.20	4,000,000	5	43,800	68.49315068	3.571428571	$0.06	60	80	$0.75	$3.64
1207	Top Housing	.162	0.85	5	$0.14	35	124	$0.28	25,000	500,000	200,000	3	$0.15	4,000,000	5	43,800	68.49315068	3.571428571	$0.04	60	124	$0.48	$1.10
1210	Depressor	.022	0.85	5	$0.02	35	124	$0.28	25,000	500,000	200,000	3	$0.15	4,000,000	5	43,800	68.49315068	3.571428571	$0.04	60	124	$0.48	$0.97
2000	Counter Subassembly																						
2200	Gear Mount	.088	1.29	5	$0.12	35	124	$0.28	25,000	500,000	200,000	3	$0.15	4,000,000	5	43,800	68.49315068	3.571428571	$0.04	60	124	$0.48	$1.07
2100	Cover	.090	1.29	5	$0.12	35	124	$0.28	25,000	500,000	200,000	3	$0.15	4,000,000	5	43,800	68.49315068	3.571428571	$0.04	60	124	$0.48	$1.08
2404	Gear holder	.020	1.29	5	$0.03	35	124	$0.28	25,000	500,000	200,000	3	$0.15	4,000,000	5	43,800	68.49315068	3.571428571	$0.04	60	124	$0.48	$0.98
2320	Counter Gears	.003	1.29	5	$0.00	35	124	$0.28	25,000	2,500,000	200,000	13	$0.13	4,000,000	5	43,800	68.49315068	3.571428571	$0.04	60	124	$0.48	$0.94
2403	Driving shaft	.002	0.85	5	$0.00	40	124	$0.32	25,000	500,000	200,000	3	$0.15	4,000,000	5	43,800	68.49315068	3.571428571	$0.04	60	124	$0.48	$1.00
2402	Counter shaft	.002	0.85	5	$0.00	40	124	$0.32	25,000	500,000	200,000	3	$0.15	4,000,000	5	43,800	68.49315068	3.571428571	$0.04	60	124	$0.48	$1.00
2407	Stopper shaft	.126	1.29	5	$0.17	40	124	$0.32	25,000	500,000	200,000	3	$0.15	4,000,000	5	43,800	68.49315068	3.571428571	$0.04	60	124	$0.48	$1.17
2211	Counter Spring	.019	1.55	5	$0.03	40	124	$0.32	25,000	500,000	200,000	3	$0.15	4,000,000	5	43,800	68.49315068	3.571428571	$0.04	60	124	$0.48	$1.03
2406	Reset Spring	.019	1.55	5	$0.03	40	124	$0.32	25,000	500,000	200,000	3	$0.15	4,000,000	5	43,800	68.49315068	3.571428571	$0.04	60	124	$0.48	$1.03
2330	Reset lever	.099	1.29	5	$0.13	35	124	$0.28	25,000	500,000	200,000	3	$0.15	4,000,000	5	43,800	68.49315068	3.571428571	$0.04	60	124	$0.48	$1.09
2405	Gear enforcer	.004	1.00	5	$0.00	35	124	$0.28	25,000	500,000	200,000	3	$0.15	4,000,000	5	43,800	68.49315068	3.571428571	$0.04	60	124	$0.48	$0.96
2203	Counter driving gears	.004	1.29	5	$0.01	35	124	$0.28	25,000	500,000	200,000	3	$0.15	4,000,000	5	43,800	68.49315068	3.571428571	$0.04	60	124	$0.48	$0.96
2340	Wheel coupler	.003	1.29	5	$0.00	35	124	$0.28	25,000	500,000	200,000	3	$0.15	4,000,000	5	43,800	68.49315068	3.571428571	$0.04	60	124	$0.48	$0.96
		3.837			$5.70			$8.90	$629,466				$4.46						$1.16			$14.59	$34.81