Automated Grate Solutions: The Great Grate

These digital signatures ensure that every member of the team did his or her fair share to the satisfaction of the signatory:

Matt Devine ____________________________________

Zachary King ____________________________________

Katherine Konecny ____________________________________

Michael Kyei-Baffour ____________________________________

Scott Sterling ____________________________________

Neil Winston ____________________________________

Table of Contents

1 Executive Summary

Street flooding is a concern that expands across borders, affecting billions of people around the world. According to the Department of Homeland Security, in the last 5 years, all 50 states have experienced some degree of flooding or flash flooding ("Flood Facts"). While street flooding can happen for a number of reasons, each of the possible causes leads back to the inadequacy of storm drain grates. Due to heavy rainfall, street litter, leaves, and thick branches often get swept on top of storm grates, greatly hindering the flowrate of water through the drains. Ultimately, the problem must be addressed; grate cleaners must be implemented onto storm grates in order to maximize the flow of water into the drains without being hindered by the accumulation of debris.

After the problem and market was defined, the concept generation stage of the Product Design Process (PDP) began. The next step was to conduct research in order to find what kind of features customers were looking for in the product. After combing through government websites and other flood informational websites, a list of general customer needs or requirements was generated and consolidated in the Product Design Specifications.

Through this list, it was possible to translate the customer needs into Engineering Characteristics (ECs) for the customer groups. Group members Matt Devine, Zach King, Katherine Konecny, Michael Kyei-Baffour, Scott Sterling, and Neil Winston began looking into patents and generating different concepts that would work to clear the debris from atop the storm grates. Once all the concepts were consolidated, group members had debated which concepts were feasible and more effective based upon the current grate clearing methods.

Given the Customer Requirements (CRs) and the ECs, it was possible to begin selecting the top three feasible concepts. By using the House of Quality (HOQ) it was possible to identify the most important ECs and how they related to the needs of the customer. This translated nicely into selection criteria for the Pugh Chart, which was used to rank the concepts against the current recommended solutions in the market. Given the flexibility of our concepts it was necessary to utilize more than one Pugh Chart: one for the concepts and one for the energy sources.

After agreeing upon a final concept, we could start the next phase of the PDP: subsystem and embodiment design. One of the largest challenges for our concept was figuring out the ideal speed (rotational and translational) and configuration of the brush rollers. An early prototype constructed of toilet brushes, plastic bins, electric drills, and wet leaves allowed us to find some preliminary targets for the unknown values.

From the subsystem prototype, we determined the final components, dimensions, and materials of the prototype for the entire system. We selected a specific storm drain grate to design to because it was representative of the average grate, and based on our preliminary results, only a battery would provide reliable power. We have constructed the final prototype and have run tests in order to make sure it conforms to the performance expectations we put into place during the early portion of the project. In order to do this the group will use the statistical hypothesis tests to make sure the results of testing are significant.

Now that the prototyping phase is over, the future works must be considered in order to complete the concept. As a team a reflection of the entire process is in order in order to determine what could have gone smoother during the duration of the project. This report will summarize the steps of the process, what was learned, and any feedback that the group has for the project and its structure.

2 Market Analysis Information

General Need for Product

The heavy rainfall and high speed wind that comes with inclement weather can cause a potential threat to the safety of people and their property. Not all of the threats that come from storms are avoidable; however preventative measures can and should be taken to mitigate the impact that storms have on communities.

During periods of rain accumulation, storm water flows into the streets. Storm drainage systems are intended to facilitate the flow of aboveground water into underground water ways. The aboveground water typically carries debris, which flows toward road-surface-level storm drain inlet covers. These existing storm drain covers can become clogged which prevents water from flowing through effectively. If rain continues to accumulate while the storm drain is clogged, there is an increased chance of a potentially dangerous flood occurring in the area.

Currently, most clogged storm drains will go untreated unless cleared off manually by a person willing to volunteer. This hypothetical volunteer will use a rake or their hands to move debris off of the storm drain grate. Most drain clogs occurring during the storm and thus, the aforementioned method proves to be highly inconvenient and dangerous. Our project is intended to prevent street flooding due to inadequate functionality of existing street storm drain systems and without the use of manual labor.

In addition to debris accumulation being a cause of dangerous flooding, debris has also proven to be dangerous for bicyclist and pedestrian traffic. Wet leaves on a wet metal grate can make for a potentially hazardous slippery condition. If the debris covers the grate, the view of the metal grate beneath could be obstructed and unsuspecting pedestrians or bicyclists could slip and injure themselves. There is a need to remove debris from the surface of the storm drain grate in order to reduce the risk of slip and fall injuries.

A potential customer for our product would be the Department of Public Works. They would purchase the product and install it in locations affected by flooding due to poor street drainage caused by the accumulation of flow-obstructing debris. The people actually living in the area or commuting through the area would be the end users who would benefit from the improved interaction with their environment.

Description and Estimation of Market Size

The storm drain market is large and continues to grow. Storm drains are essential in preventing street flooding due to rainfall or snow melt. They are particularly important in an urban environment, where flooding creates hazardous conditions for both pedestrian and vehicular traffic, in addition to damaging private property. As the urban population continues to grow, the market for storm drains will closely follow. Cities and municipalities must establish an effective storm water management system to ensure safety of the residents. The construction of new roads as a result of increased urbanization furthers the need for water management, including storm drain inlets.

Within the municipality market, the need for storm water management systems in the United States is expected to exceed $105 billion over the next 20 years (Hydraulic Design Manual, 2016). Storm water control is a standard requirement in building codes throughout the country.

The Washington DC and Baltimore area is a highly urbanized location, and continuously expanding. In a survey (results pictured in *Appendix B*) distributed to ultimate customers, we asked customers if they thought there would be a need for a product that removes debris from atop grates. Out of 42 responses, 86% of respondents claimed they have seen debris cover the top of storm grates. Out of those same 42 responses, 69% of respondents stated they had never seen anyone cleaning the top of the grates. If the DMV population is targeted in entirety, this would place the target market at few million people, approximately. If our product proves to improve the function of storm water management, its implementation could be seriously considered by municipalities and highway engineers.

This project focuses on the redesign of a critical component of a storm water management system; the storm drain inlet. Inlets come in four major classifications: curb opening inlets, grate inlets, linear drains, or a combination of inlet types (Hydraulic Design Manual, 2016). We seek to improve the functionality of grate inlets by developing a system to prevent the accumulation of debris on the grate surface. Grate inlets are the second most common type of storm drain inlets, before curb opening inlets (Hydraulic Design Manual, 2016). Most standalone grate inlets are implemented in locations where no curb or barrier to install a curbside inlet. These locations include driveways, street intersections, and medians. As they can easily accumulate debris that obstructs flow, the inlet requires continuous attention to prevent accumulation. Our proposed system seeks to actively prevent debris accumulation during rainfall, allowing water to enter unobstructed. While not all grated storm drains are of the same dimensions, our system will be designed to retrofit the majority existing storm drain enclosures.

Benchmarking on Competitive Products

In order to benchmark competing products, we must analyze the function and effectiveness of existing storm drain inlet designs. The four major types of storm drains provide us with a good starting point to begin the benchmarking process. They each have different advantages in terms of road placement, dimensions, maintenance, and effectiveness.

Curb Opening Inlet:

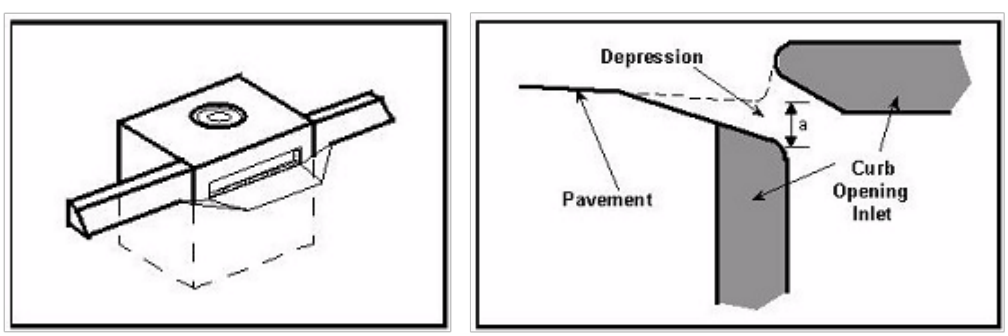


Figure 2 -1 A curb opening inlet ("Hydraulic Design Manual" 411-412).

On urban roadways, curb opening inlets can be found along the curb line. *Figure 2-1* shows an example of a curb opening inlet. The effectiveness of a curb opening inlet depends heavily on the size of the depression that feeds water into the inlet. A deeper depression with a larger area will allow water to more easily enter the drain. It is important to note that large depressions can be unsafe for vehicle and bicycle traffic, so the size of the depression is selected with consideration to its proximity to road traffic. Curb openings are effective along continuous grades, and at low points (sumps).

Due to the location of curb opening inlets, they are typically favored over grate inlets because they interfere less with bicycle and automobile traffic. However, they do not typically have the ability to prevent debris from entering the drain. The open design allows for litter and debris to fall into the storm sewer and introduce water pollution. The design also requires a curb to exist, so locations without roadside curbs can't utilize this type of inlet.

Grate Inlet:

In the grate inlet design, storm water falls through flat grates rather than a curb opening. Grate inlets vary widely in terms of size and grate structure between manufacturers. A typical grate inlet can be seen in *Figure 2-2*. Grates are typically placed in locations where a curb opening inlet cannot be utilized due to the location of such as near guard rails, traffic barriers, medians. They are very effective when placed at low points (sumps), where storm water is able to enter from all directions.

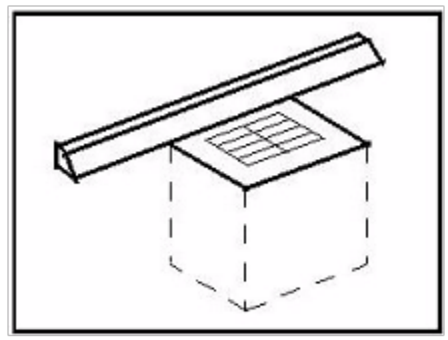


Figure 2-2 Grate Inlet ("Hydraulic Design Manual" 412).

The greatest advantage of a grated storm drain is that it provides easy access to the storm drain system. This is due to the fact that the majority of the grates are removable. However, the maintenance required for grated drains proved to be a continuous problem. Grated inlets suffer from debris accumulation which can severely impede flow into the drains, causing flooding or standing water on streets. In order to prevent debris accumulation on grated storm drains, they need to be regularly monitored to ensure they are clear.

Due to the location of grated storm drains, they must be designed with consideration for bicycle, vehicle, and pedestrian traffic. Because they must withstand the forces of vehicles, grated storm drains are typically constructed from steel or concrete. The spacing of the grates is particularly important to ensure safe crossing for bicycles, wheelchairs, and other transportation with thin wheels. Grate spacing that is too wide will interfere with such vehicles, so drains are either constructed with this consideration or placed in locations where interference is unlikely.

Linear Drains:

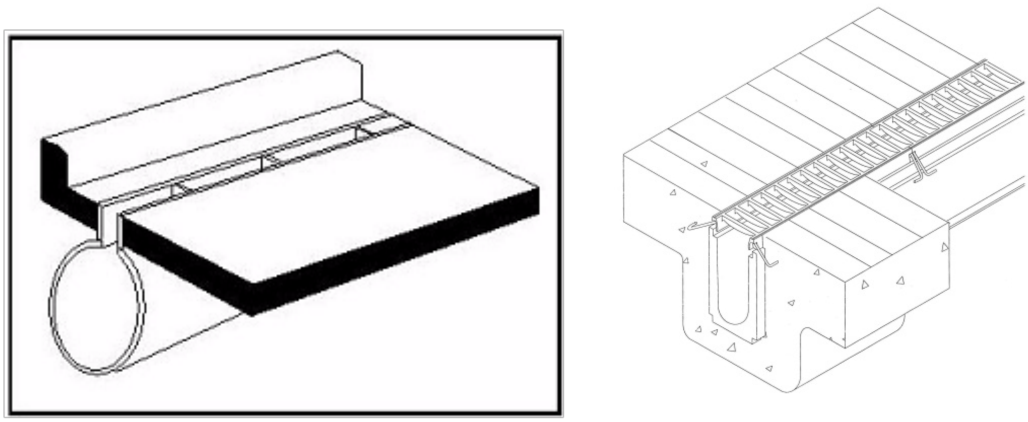


Figure 2 -3 Linear Drains: slotted drain (left) and trench drain (right) ("Hydraulic Design Manual" 413-414).

Linear drains are significantly longer than wide, and are designed to collect and channel water off roadways into ditches or storm drain systems. They are particularly useful for intercepting storm water that has a low flow and is spread over a wide area. In this case a grated or curb inlet is not desirable, as they provide only a single collection point for storm water. Linear drains also do not require any type of depression to collect water effectively, making them less prone to interfere with traffic. This makes them a suitable choice for placement transverse to a roadway, and is effective on long bridges with steep slope.

Linear drains can be found in two different design configurations. *Figure 2-3* shows a slotted drain, and a trench drain. A slotted drain inlet is called such as it is typically a corrugated piper with a slot that extends at the top. The thin slot reduces the need for grating, and can be laid under asphalt or concrete. The slope of the slotted drain must be enough that it can be self-cleaning, as water must be moving with a velocity that is high enough to clear debris from the corrugations. Many slotted drains have an access box at the low end of the slotted drain for maintenance and cleaning.

Trench drains are another type of linear drain. Their function is effectively the same as a slotted drain, however they differ in construction. Trench drains are typically precast, as seen in *Figure 2-3*, however they can also be cast into place with the roadway. Their main advantage over slotted drains is that they can have a shallower depth, although this does limit the volume of water they can carry. Trench drains are grated, but the grates are typically non removable. This is to prevent the grates from becoming loose and creating a dangerous situation for traffic.

The major disadvantage of linear drains is their tendency to collect debris is certain configurations. Due to this, they require regular maintenance to clear debris. For trench drains, they are usually constructed with enough open space to allow cleaning with a water or vacuum truck since their grates cannot be removed. Linear drains can also be difficult to install. Because they do not require any depression to allow the flow of water into the drain, the placement of inlet is critical to allowing water to enter.

Combination Drain Inlets:

Combination inlets can be useful in many situations. Most combination inlets are a mixture of the curb and grate design, as seen in *Figure 2-4*. This configuration combines the advantages provided by both designs. A curb and grate inlet has the advantage of being a discreet drainage point due to its location along the curb. It has the added advantage of easy access to the storm drain system, due to the removable grate. They are also more effective at managing debris clogging than standalone grated drains. If a significant amount of debris collects on the grate, the curbside inlet provides a path for overflow. Due to the more complex design, they are more expensive to manufacture and construct.

Figure 2-4 Combination Drain Inlet ("Drainage Design" 16).

In summary, each drain inlet provides certain advantages and disadvantages. These need to be considered when designing a storm water management system. Proper arrangement and selection of drain design is critical to prevent street flooding and damage to private property.

Inlet Type	Applicable Setting	Advantages	Disadvantages
Grate	Sumps and continuous grades (should be made bicycle safe)	Perform well over wide range of grades	Can become clogged Lose some capacity with increasing grade
Curb-opening	Sumps and continuous grades (but not steep grades)	Do not clog easily Bicycle safe	Lose capacity with increasing grade
Combination	Sumps and continuous grades (should be made bicycle safe)	High capacity Do not clog easily	More expensive than grate of curb-opening acting alone
Slotted	Locations where sheet flow must be intercepted	Intercept flow over wide section	Susceptible to clogging

Table 2-1 Considerations for Drain Inlet Selection ("Drainage Design" 15).

Table 2-1 provides a list of considerations for each inlet type, and their applicable settings. The goal of our project is to improve upon the grate inlet design. Grate inlets are very effective at draining large volumes of water, especially at sump locations. However, they can be clogged easily by debris, drastically reducing their effectiveness. If we can safely and efficiently provide a solution to the debris accumulation issue, our redesigned drain inlet will effectively reduce maintenance and preventing street flooding.

Patent Study

While engaging in the search process for patents relevant to our project, we used Google Patents. In order to find relevant patents, we first began by searching keywords related to our problem. Some keywords which we searched include “storm drain”, “grate”, “prevent clogging”, “storm drain clog prevention”, and “storm drain flow.” There are numerous patents related to storm drains, so one approach we took was to focus on the ones that seek to address debris issues. During this process, we discovered the patent classification “E03F1/00.” This classification is for “Methods, systems, or installations for draining-off sewage or storm water.” Searching within this classification, we discovered Patent US6972088B2. We also discovered the patent classification “E04D13/0409.” This classification is for “Drainage outlets, e.g. gullies.” We discovered Patent US4525273A within this classification. During our patent search process, we utilized both patent classifications and keyword searches to uncover the patents described in detail later in this section.

From this search process, we learned that there is a wealth of useful documentation available readily online and at no cost. We also learned that there are many patents granted for designs which are similar yet unique in their own regards. Viewing the various patent documents exposed us to the current state of the art in storm drain systems. Understanding what technologies are currently at the highest level of development in the field of our project is valuable to our design team. This search could influence our design process to go in a more constructive direction by making us aware of what currently exists and by inspiring us to design a more highly developed product.

Patent No: US7160048B1 - Flow Restricting Member

Publication date: 2007-01-09

Inventor: James G. Fattori, Kenneth E. Brown, George Lesenskyj, Christopher M. Budzinski

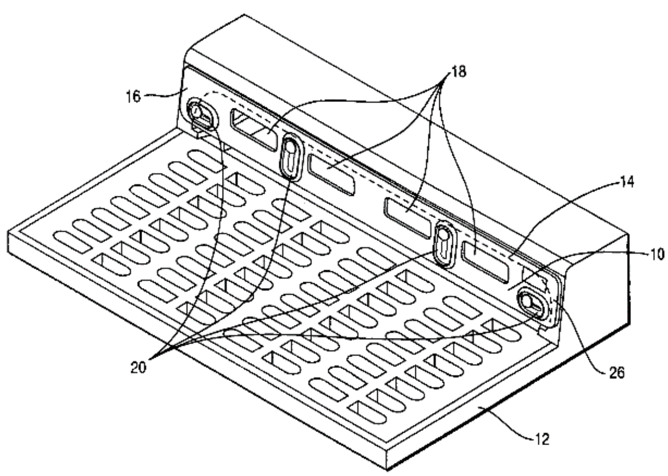


Figure 2-5 Patent US7160048B1.

Fattori’s US7160048B1 patent is for a flow restricting member to be used with a storm drain opening positioned at a curb inlet. *Figure 2-5* shows a faceplate (16) featuring four flow apertures (18) of limited size are able to be secured to the existing storm drain (12) by means of a mounting apparatus. The mounting apparatus consists of one or more mounting brackets (20) and an engagement device (14) which secures the mounting brackets with respect to the drain and faceplate. When the member is secured to the storm drain, the flow apertures allow for a regulated flow rate of water to pass through the drain.

Patent US7160048B1 is an existing device which is used to restrict flow of water through a curb inlet opening of a street storm drain. This patent is relevant to our project because we may choose to employ a device in our final design with the intended purpose of regulating the flow rate of water. The search terms we used to find this patent were based on the need of our final project to handle a flow of water.

Patent No: EP1700800A1 - Device for Transporting Sticky and/or Wet Material

Publication Date: 2006-09-13

Inventor: Voorthuysen Gerrit Van and Raymond Newman

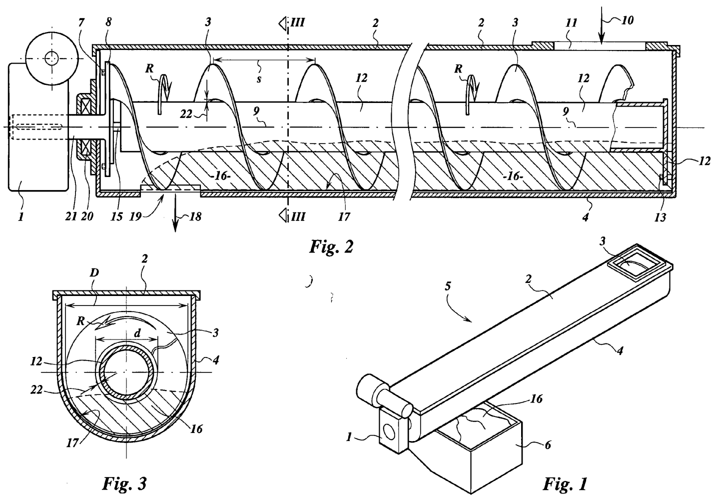


Figure 2-6 Patent EP1700800A1.

Gerrit Van and Newman's EP1700800A1 patent, shown in *Figure 2-6*, is for a shaft conveyor that is used for transporting wet and/or sticky material. The design of the patent resembles an auger driven by a motor, which has a large inlet and a small outlet. The housing for the device is made of thin faces of metal that enclose the spiral (4) with additional clearance at the top converging to a flat surface (2). The spiral consists of a shaft (12) freely supported by bearings (20), with a screw (3) spiraling around it. The radius of the shaft and screw combination is equal to the inside radius of the rounded portion of the housing. This allows the spiral to coincidentally fit in the tubular housing, which is a key concept to the device. A drive (1) is located at one end of the shaft that rotates the spiral inside the tubular housing. The orientation that the drive rotates the shaft is counter-clockwise, with the viewer's orientation facing the drive side looking down at the device. As the motor drives the shaft and screw, the screw acts as a continuous wall that forces and wet material within the tubular housing towards the drive side.

There are two ports in the housing. The first port is located on the top of the back end of the housing that acts as an inlet. The second port is located on the bottom of the drive end of the housing that acts as an outlet. Material enters the inlet and is forced to exit the outlet.

Patent No: US4525273A - Drain Grate with Adjustable Weirs

Publication Date: 1985-6-25

Inventor: Duane D. Logsdon

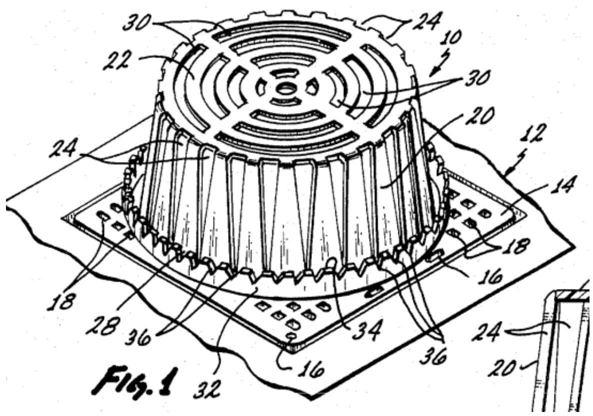


Figure 2-7 Patent US4525273A.

Duane D. Logsdon’s US4525273A, which is currently expired, is for a drain grate (*Figure 2-7*) with vertical weirs (24) whose openings increase in size toward the top of the grate (10). A regular grate has a constant opening area for water to travel through; this means that only a constant volume of water can flow through at all times. Unlike a regular grate, as the water level rises along this grate the weirs open up more and allow a larger volume flow; the lip (32) at the bottom helps prevent debris from clogging the weirs. This applies to our project because this grate aims to prevent flooding that occurs with increase fluid flow and debris blockage.

Patent No: US6972088B2 - Pivotal gate for a catch basin of a storm drain system

Publication Date: 2005-12-6

Inventor: Leon H. Yehuda

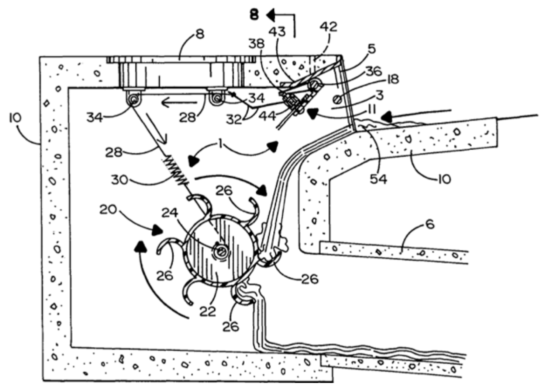


Figure 2-8 Patent US6972088B2,

This patent, *Figure 2-8*, is for a system that is located within the catch basin of a storm drain, as seen in Figure 1. The system is comprised of three major components: the blocking gate (11), waterwheel (20), and pulling cable/rod system (28/32). During dry periods or light rainfall, the gate (11) is in a closed position. This is to prevent leaves, litter, and other debris from entering the drain, and makes it easy for the debris to be cleared by a street sweeper or the like. As rainfall increases, more water will begin entering the drain. Water falls from underneath the gate, and strikes the scoops (26) attached to the water wheel (20). The wheel turns in response to the impact force of the water, and this generates a pulling force in the cable (28). When water entering the drain reaches a critical flow rate, the force on the pulling cable opens the gate. This allows water to freely flow into the drain during heavy rainfall. The critical flow rate is determined by the stiffness of torsional springs (38) between the rod and gate, and a tension spring along the pulling cable (30). This patent is relevant to our design, as it seeks to prevent street flooding during heavy rainfall.

Patent No: US10025644 - Rotisserie Cooker: Passive Skewer Rotation Subsystem

Publication Date: 2005-04-05

Inventor: Alan L. Backus, Ron Popeil

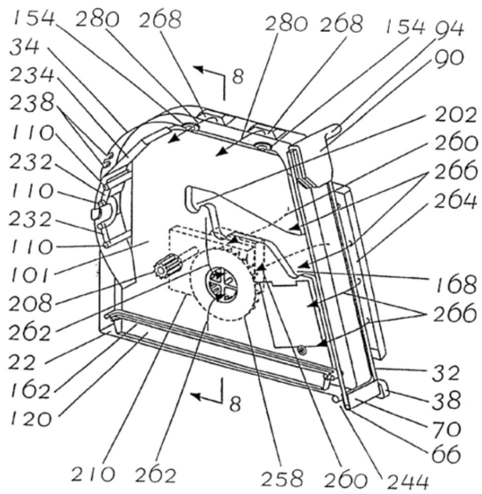


Figure 2-9 Patent US10025644.

Figure 2-9 shows an image of the passive skewer rotation subsystem which is part of the Rotisserie Cooker. This is something we could implement on our gates in order to create bars that automatically rotate. Judging by the patent description this is a very simplistic mechanical subsystem. This seems to be a gear reduction system that is working with a miniature motor within the mechanism. Through power applied to the apparatus through an electrical plug (an alternate power source will likely be used in our project) the gears are able to turn the skewers at a slow rate to allow even cooking. For the skewer system that we would implement on the drain system, it would be necessary to prevent debris from falling into the sewer. Therefore, on these bars we would have to implement a system that is only permeable by water or other liquids.

Patent No: US6733665B1 - Storm drain system for preventing and filtering debris, trash and hydrocarbons with removable inserts

Publication Date: 2004-05-11

Inventor: Khalil, Saleh S.

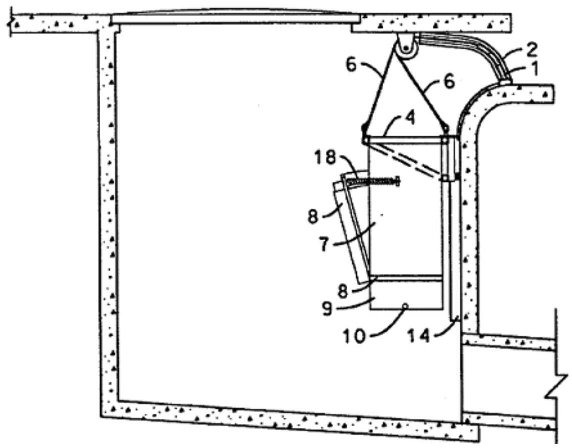


Figure 2-10 Patent US6733665B1.

Khalil's US6733665B1 patent is a mechanism that is assembled and inserted into storm drains right behind the inlet from the street curb which would be located at the opening by the part labeled (1) in *Figure 2-10*. This system can either be open or closed, which depends on if it is the dry season in that area or not which means it would be getting little to no rain. When the system is closed, it means that the horizontal rails (1) in *Figure 2-10* are moved to a position to block the storm drain inlet. These horizontal rails move along tracks (2) and are moved by two attached cables (6) on pulleys. When the opening is closed, debris is blocked from getting into the storm drain.

However, when there is rain this opening needs to be open so that the roads will drain quicker. As water passes in between the horizontal rails, it then fall down into the catch basin (7) where there are removable mesh bags that are water-permeable. This is where the filtering process happens because water can pass through but debris cannot. Water passes through an oil filter (8) and then into a canister (9) with small orifices for the water to drain out slowly. This canister is responsible for the opening and closing of the rails at the storm drain inlet depending on flow interception. The canister is connected to the two cables (6) and when there is high flow the canister is pushed downward which pulls the rails up and opens the inlet. If there is no water in the catch basin, tension will be released from the cables and the rails will be able to return to the closed position. After the water passes through the catch basin, it has been filtered and flows into the main storm drains with the rest of the rain water. The mesh bags in the catch basins are very easily removed and replaced when full to ensure that flow of water and filtering is optimal.

Opportunities for Competitive Advantage

Our design will provide a competitive advantage over existing products by adding functionality that does not exist within any current storm drain inlets. We seek to improve the design of the grated storm drain inlet by creating a system that actively clears debris to prevent accumulation and ultimately flooding. Currently, there is no product on the market that actively clears and prevents debris accumulation from occurring on grated storm drains.

Many of the patents we studied seek to improve the effectiveness of storm drains; however nothing found actively removes debris during rainfall. This active cleaning process is what will give our design a competitive advantage over all existing products. While some of the patents studied attempt to address the problem of debris, they only passively remove debris by means of filters or altered drain configuration. Our goal is to outright prevent debris from entering the drain by continuously removing any accumulation on the surface of the inlet. Through this, filtering storm water for debris removal is not necessary. This reduces the maintenance required to clean and replace filters, and leave us with a standalone, self-cleaning system.

3 Problem Identification

Problem Statement

Many neighborhood streets have simple storm drain grates; these grates easily clog with debris, especially in the fall or during a severe storm, and have no form of active cleaning. When the grate gets clogged, the street can quickly flood; *Figure 3-1* shows a street in Lusby, MD that flooded during a storm when the drain grate got clogged by leaves. The water was nearly 3.5 ft. deep at the lowest point of the street; cars could not pass through for several days. The county neglected to properly clear the storm drain, and the neighbors did not want to venture out in the storm to clear it themselves.

Figure 3-1 A street that flooded and overflowed into yards due to clogged drains (Pritchard 2010).

In 2015, flash flooding accounted for the most amount of weather-related deaths and damage; there were 129 deaths and 42 people injured, and the cost of damage to property and crops added up to about $2,124,410,000 (Summary of Natural 1). Many of the people that die as a result of poor weather are males that hold outdoor jobs; this justifies the need to keep roadways clear and empty not only to prevent homes from flooding but also for people that have to remain outside in dangerous conditions.

Currently, the only solution for cleaning out a clogged grate is for either a highway maintenance employee or homeowner to manually clean it. It can be quite time consuming to clear out every grate in a large neighborhood or town. It's also dangerous to be outside clearing drains during a severe thunderstorm or hurricane. The flooded streets that result can prevent people from travelling, prevent emergency services from reaching homes, and flood homes and buildings. Finally, this solution is potentially ineffective if the cleaner is lazy and decides to push the debris into the drain (defeating the purpose of the grate) or back on the road; many homeowners simply do not clean out the grates at all.

An automatic cleaning solution for storm drain grates would eliminate the need for a person to clean the grates during a storm, prevent extra debris from entering into the drain, and keep the drainage of rain water and runoff constant. There is currently no product available that is usable in a street storm drain, so it would not be replacing an existing product. This type of product would need regular servicing to ensure that it can safely operate at its best potential. The following Fishbone Diagram (*Diagram 3-1*) details the issues with the current method of clearing grates that a new product should solve. Appendix B Fishbone Diagram contains an enlarged version.

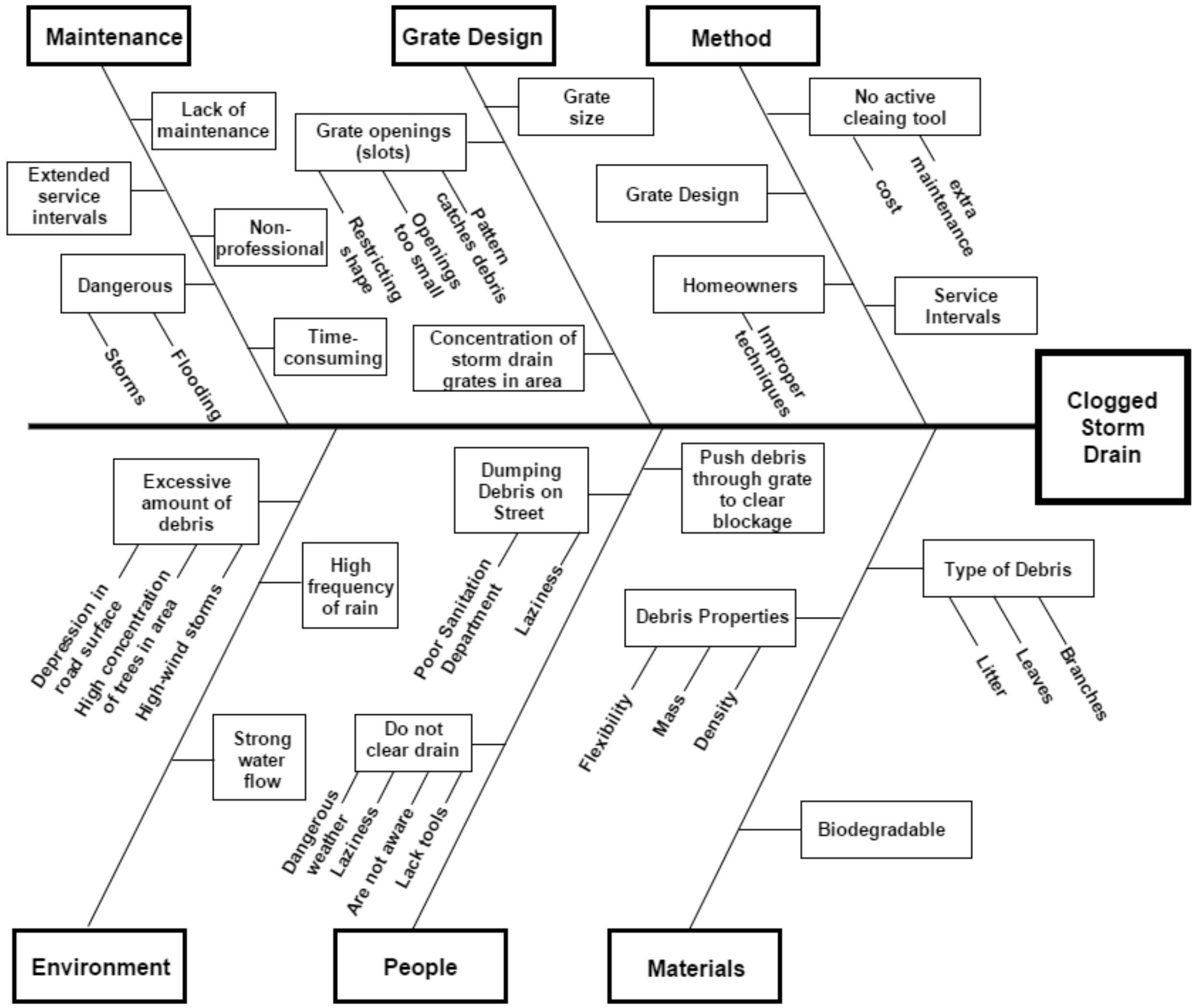


Diagram 3-1 A Fishbone Diagram detailing the causes of a clogged storm drain.

Physics of the System

First and foremost, our product or grate redesign needs to be able to withstand the forces of vehicles, debris, and water on top of it. Compared to the weight of a vehicle or large truck, the debris weight should be nearly negligible, but if the grate becomes clogged, it should not fail with water standing above it. *Figure 3-1* demonstrates the forces that the grate will need to withstand; it is assumed that the grate's mass is uniformly distributed. The weight of the vehicle and water can also be assumed to be evenly distributed; the weight of the vehicle will be distributed across the area of the contact surface between the tire and grate. It is unreasonable to assume that the weight of debris is evenly distributed, though, so its center of mass location will vary. The normal reaction force occurs around the edges of the grate where it contacts the road surface.

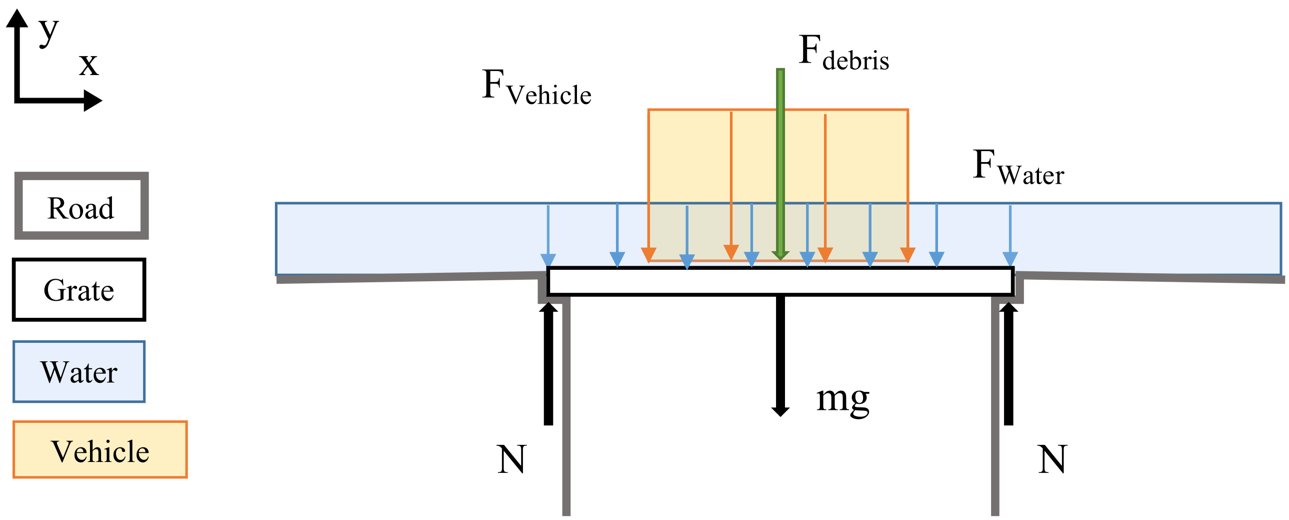


Figure 3-1 A free body diagram of the grate when it's in its use environment.

The following free body diagrams represent three different mechanisms that were considered at the beginning of our concept generation. The job of these mechanisms was to store energy and power the movement of a component. The first three mechanisms depend on the flow of rainwater through the grate to generate energy, so they were determined to be non-feasible concepts and eliminated from contention. The final mechanism is a motor, powered by a battery pack; this is the was the most reliable option and provided the best torque output out of all the options. It provides the most flexibility in design options.

One of the most intuitive mechanisms to use with rainwater was a waterwheel that is powered by water falling through the drain grate. A funnel may be used to direct the water flow into a concentrated area to maximize the moment it applies to the waterwheel. *Figure 3-2* demonstrates the forces and moments around the pivot point O of a waterwheel. The resistance moment is a combination of frictional forces acting within all the components that will prevent or hinder rotation. The torque output of the waterwheel is the difference between the water-produced and resistance moment.

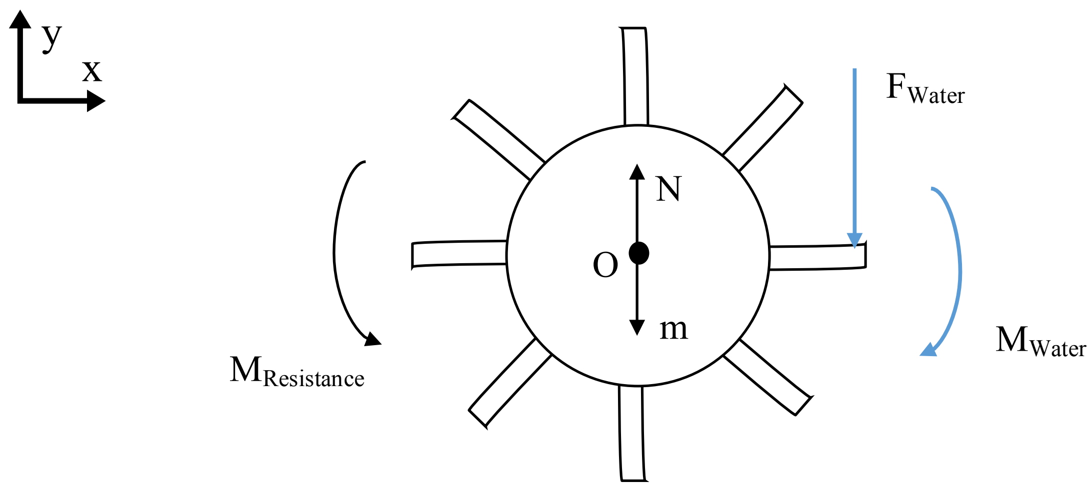


Figure 3-2 A free body diagram of a waterwheel.

Springs were another likely option, as a torsional spring could potentially accompany a waterwheel, or a linear spring could push or pull a component through debris. *Figure 3-3* demonstrate the forces present for a torsional and linear spring. The torsional spring would undergo an applied torsion from a component like a waterwheel or motor; it's unlikely that this would interact with debris directly. Like its counterpart, the linear spring would not be used to contact debris directly. The only forces acting on the spring are the ones applied by other components.

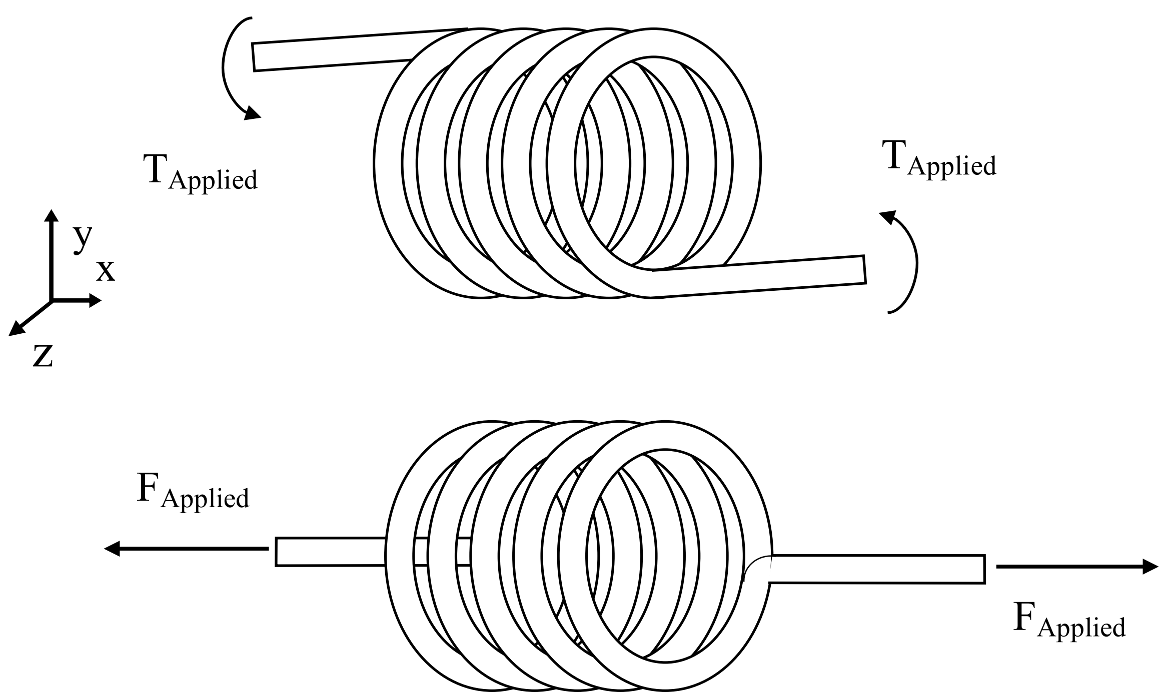


Figure 3-3 A free body diagram of a torsional spring (top) and linear spring (bottom).

For components that need to be pushed through the grate or pulled downward, a rain water catch basin attached to springs is a viable but tricky option. The basin would fill up with rain water and slowly lower due to resistance from the springs. There are small holes in the bottom of the basin so that when the water stops flowing through the grate (due to blockage), the basin will empty out and rise quickly. The problem with this mechanism is if the initial push through doesn't move debris out of the way, the basin may never refill; essentially, the product would then become useless. *Figure 3-4a* shows the basin filled, and *Figure 3-4b* shows the basin as it springs up; the vertical rectangle is an arbitrary depiction of the debris-pushing component.

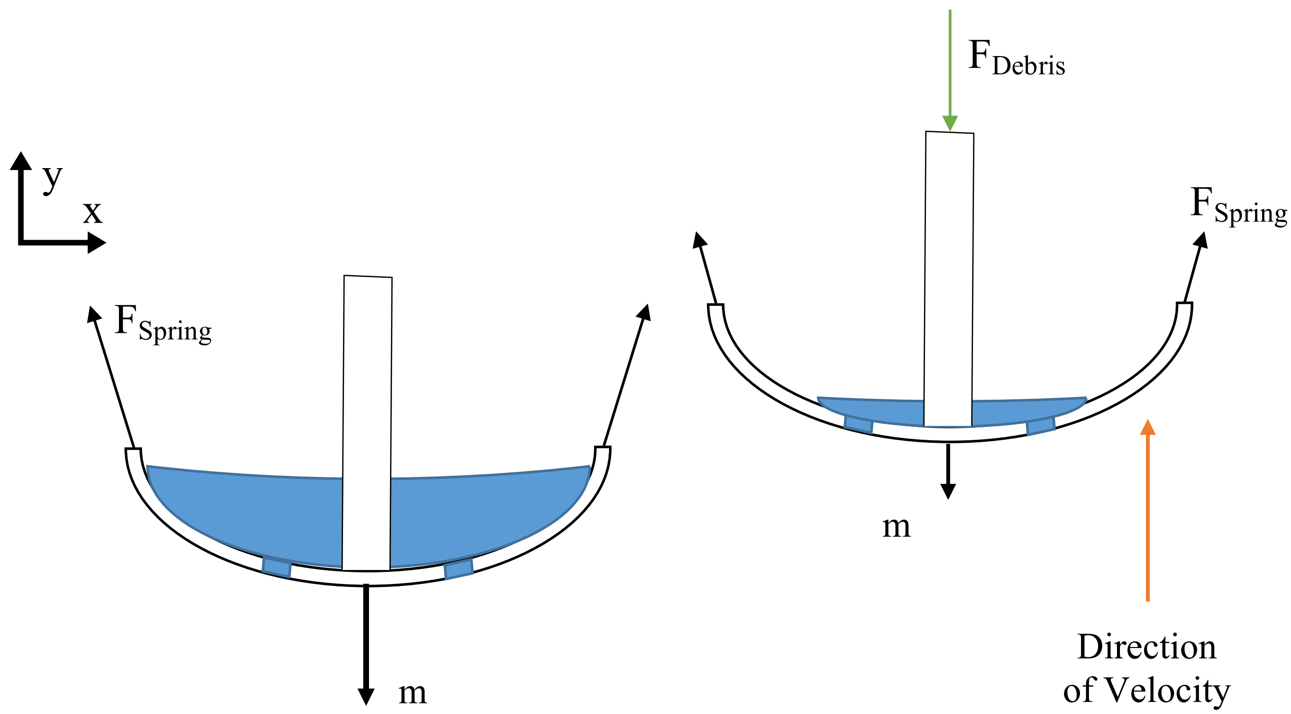


Figure 3-4a &b Part a is on the left; part b is on the right.

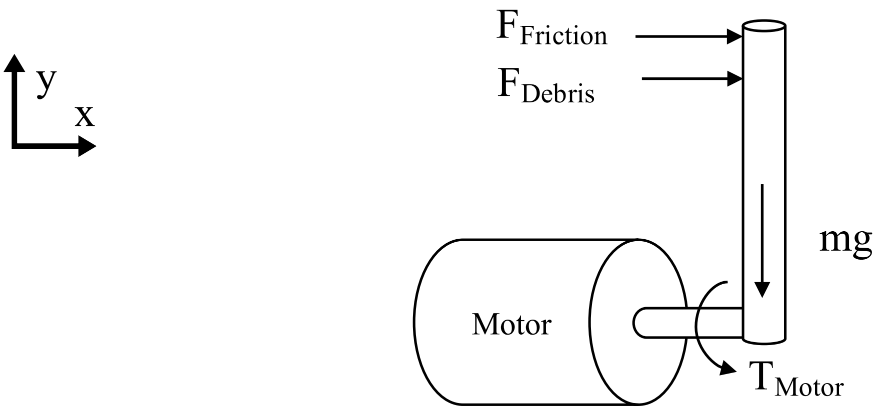


Figure 3-5 A free body diagram of an arm attached to a motor shaft.

Finally, *Figure 3*-5 demonstrates the rotational forces acting upon an arbitrary "arm" that is attached to the motor shaft. The arm will encounter various resistive forces from contacting debris and the grate. As the arm rotates, the total resistive moment will change due to the varying angle of the arm's weight. This is arguably the best method for maintaining constant and reliable control.

Human Factors Considerations

This product would be operating autonomously; no one would be interacting with it to complete its job other than to service it when a part fails. There is no manual operation required, it is not powered by people, it is not wearable, and it is not a tool to be used to reduce human effort. There are safety and serviceability concerns, though.

People need to be able to safely walk, drive, and bike over the new product as they can with a current grate inlet. The new product will most likely have moving parts, so they need to be able to clear debris without posing a safety hazard. Any moving parts will be placed below the grate to prevent injuries above the surface. Electrical components or batteries need to be water resistant and properly protected to prevent exposure or electrocution. The product must also be strong enough to withstand the forces that cars will repetitively put on it. It must exclude any sharp surfaces or points that could puncture tires or shoes; if a component reaches above the top of the grate, it needs to be flexible or wide to minimize the pressure applied to a tire.

During installation and service maintenance of the product, it will need to be lifted out of and lowered into the drain opening. The new product needs to be light enough to be lifted safely by an adult; a majority of highway maintenance workers are males in their 20s-60s ("Highway maintenance workers"). The Liberty Mutual lifting hazard tables provide the percentage of the male or female population that would be able to safely conduct a specific lift (Liberty Mutual Manual). Ideally, the worker should only need to lift the grate and product once during service, then replace it. The grate and product need to be easy to grip to avoid making lifting more difficult or uncomfortable. *Table 3-1* shows some percentages for several preliminary weights; for this table, it's assumed that the product is being lifted from the ground to 28 or 30 (for female and male, respectively) inches, the product is being lifted once every five minutes, and the lifter's hands are about 10 inches from their body. This seems like a safe and reasonable workload considering how infrequently the grate/product will need to be lifted.

Weight	Percentage of Males	Percentage of Females
5 lbs	> 90%	> 90%
10lbs	> 90%	> 90%
15 lbs	> 90%	89%
20 lbs	> 90%	80%
25 lbs	> 90%	63%

Table 3-1 The percentage of the general female and male populations that could lift various weights from the ground once every five minutes.

4 House of Quality

Customer Requirements

Customer requirements are the needs and wants the consumers desire in a product when visualizing the qualities of a storm drain. Our team discussed what we believe are important specifications that should be included in the design of a storm drain. Every member of our team has experience with storm drains. We all live in residential areas with storm drain on the streets. This makes our group qualified for determining an effective list of customer requirements. The customer requirements are ranked in order of importance. The ranking was also completed by our team on a scale 1 to 5, where 5 is the most important. The rankings are displayed next to the customer requirements.

1. **Will not Clog with Debris** (**5**) - As water flows towards the grate, it can carry debris that has gathered on the streets. This debris can clog the grate and stop the flow of water. The water then builds up and causes flooding in the streets. Traffic on the streets are then slowed or even halted at certain extremes.
2. **Handle Heavy Rain** (**5**) - Disregarding any debris within the water, if water accumulates in the street at a high enough rate then the water would build up in the street. Even as the water flows through the storm drain, the water level rises on the surface of the road. The flooding then negatively affects traffic on the street.
3. **Durable** (**5**) - The storm drain will be located outside in the open environment. External factors like extreme weather, heavy traffic and varying temperatures will all affect the structural and mechanical integrity of the storm drain. In order for the device to stay fully functional, the durability of the storm drain must be high.
4. **Safe** (**4**) - Safety is always a concern with any product that is open to the public. Underneath storm grates and curb drains are large vacant cavities that could harm any person or animal that falls into them. If the structural, mechanical and electrical integrity of the storm drain is compromised, safety concerns will certainly arise.
5. **Inexpensive** (**3**) - The consumers will not be interested in a highly efficient storm drain if it or its maintenance is significantly more expensive that a current drain grate.
6. **Retrofittable** (**3**) - If the existing standard for the storm drains could be integrated into a new product design that more efficient, that save the consumer money. They wouldn't have to get rid of the older product, while only purchasing a portion of a new product. Reusing existing components of older products also makes it easier to design with restrictions.
7. **Energy Efficient** (**3**) - The energy efficiency of the drainage system should be monitored since most standard units are static with no powered mechanisms. If a self-sustaining product can be designed, the product will not need to outsource any power. If the product needs outsource power, the consumer will have to pay for the energy to be applied to the device.
8. **Waterproof** (**3**) - Any material that is used in a drain product that allows water to pass through it, should be able to resist water to a certain degree. The structural, mechanical and electrical integrity of the storm drain system could be compromised if water constantly erodes the material of the product. This will cause performance and safety concerns to arise.

9. **Discrete Appearance/Hidden (2)** - Drain systems of any kind are eyesores and not cosmetically pleasing. Residential homes lining the streets that contain storm drains should operate without the homeowners knowing of their presence.
10. **Environmentally Friendly (2)** - Most products have a carbon footprint of some sort, while others pollute the air using diesel engines. A storm drain should be environmentally friendly and not contaminate the water that passes through it. That water may go to a larger, natural body of water without being filter along the way. The polluted water from a single toxic storm drain could then contaminate an entire water ecosystem.

Critical to Quality

The critical to quality requirements are high priority customer requirements. Our team selected all three of the 5 out of 5 ranked customer requirements as our critical to quality requirements. The three critical to quality requirements are:

- Will not Clog with Debris
- Handle Heavy Rain
- Durable

Engineering Characteristics

Physical features, variables and performance metrics that describe an effective storm drain our team is designing. They are not listed in any particular order.

1. **Flow Rate** - The rate at which water can pass through the storm drain. The main function of a storm drain is to allow water to pass through it and flow into a larger drainage system. If a storm drain has a flow rate that cannot match or exceed the amount of water approaching the drain, then the water remains in the street where it is a nuisance to the nearby residents.
2. **Size/Dimensions** - The physical measurements of the storm drain in 3 dimensions. The size of a storm drain can directly affect other performance metrics. A larger inlet area for water would increase the flow rate, while a larger grate would increase the storm drains mass.
3. **Material Strength** - The ability of the storm drain's material to withstand an applied load without plastically deforming or failing. Large loads passing over the storm drain will be applied a large force mostly downwards on the grate. In order for the grate to resist failing, it should have a higher material strength. A grate with a low material strength would fail and crack under the large forces applied by large vehicles.
4. **Debris Allowance** - The rate at which debris can either pass through the storm drain or be forced away from the water inlet. The design of storm drains today do not accommodate this critical quality. If the storm drains were to either stop amounts of the debris from gathering or allow portions of the debris to pass through the grate, the water would continuously drain.
5. **Material Rigidity** - The ability of the storm drain's material to resist deformation in response to an applied load. Large loads passing over the storm drain, such as cars and trucks, will be applied a large force mostly downwards on the grate. In order for the grate to resist deforming, it must have a higher material rigidity. If it had a low material rigidity, the storm drain would bend inwards and cave in from the force of the heavy loads.

6. **Power Consumption** - The amount of energy that the storm drain needs to operate for a given amount of time. The storm drain uses power in order to operate. The power it uses needs to be regulated in order to judge its effectiveness at completing its task. A self-sustaining device would be environmentally friendly, while operating on an outsourced power supply is less conservative.
7. **Service Intervals** - The amount of time an average storm drain can operate without needing a form of maintenance. This is preventative maintenance that will assist in elongating the lifespan of the device. The service completed is not to reconstruct a critically failed storm drain. This quality is important to those who install and work on the storm drains. Once they install the storm drain, the workers do not want to return to the street to fix operating issues frequently. The larger the service intervals, the more dependable the product.
8. **Noise Level** - The amount of sound that the storm drain produces. Surrounding residential do not want a loud mechanical device outside their doors. Noise pollution should be avoided when developing any product that will be used near residential areas. The current storm drains have little to no mechanisms, which means they operate quietly.
9. **Mass** - The physical property of the storm drain, relating to weight. Handling the storm drain during installation and maintenance brings about the physical quality mass. The larger the mass the more difficult handling becomes for the maintenance workers. Once the device is set in place in the road, the mass goes unnoticed by pedestrians.
10. **Liquids and Solids Resistivity** - The IP rating of the storm drain and all of its components. This rating classifies the amount of protection the materials provide for the intrusion of solid objects such as dust and small foreign bodies, as well as its resistivity to water. All devices are given IP ratings to inform the users of the suitable environments it can operate in.
11. **Reliability** - The amount of time passed before the average storm drain would critically fail. This implies that after this amount of time the storm drain is no longer operational. This quality is important to the customers that purchase the storm drains, and they will need to know, on average, how long the product will last after installation.
12. **Reflectivity** - All surfaces have an albedo or a reflection coefficient. This coefficient measures the "whiteness" of a surface. It is a non-dimensional parameter that will be used to measure the contrast of the storm drain to the surrounding pavement on the road's surface. Storm drains are installed on streets in residential areas, where people do not wish to notice the drainage systems. An object with a low reflection coefficient is not easily noticed when set near another object with a low reflective coefficient. There is no contrast between the items which makes it difficult to separate the two. When one item is a storm drain and the other is the road, the drainage system could go unnoticed.
13. **Hydrocarbon Tolerance** - The ratio of the amount of hydrocarbons that flow out of the storm drain, divided by the amount of hydrocarbons that flow into the storm drain. This ratio is multiplied by 100 to represent the value in a percent. The way that one measures the amount of hydrocarbons in each sample does not matter, as long as the units are the same. This quality represents the amount of pollutants that the storm drain releases into the drainage system.
14. **Operating Temperature** - The temperature at which the storm drain operates. Storm drains operate and are located outside in the elements. The climate changes with the

seasons, which alters the outside temperature. The range of the climate where storm drains are used and should operate is about 25 F to 100 F.

Constraints

Health and Safety Constraints

A storm drains main feature is to drain water off of the street. It accomplishes this by allowing water to pass through a grate on the surface of the street and flow into a basin which is connected to a larger drainage system. During heavy rains, the flow rate of water through a cleared storm drains can reach 0.002 m^3/s. At this high flow rate, water can cover the interior of the storm drain cavity. The cavity is also where the mechanical portion of our product design will be held. Any electronics that are used, if any, in the design of our storm drain need to be waterproof. A water resistant IP rating for any of the potential electronics should be 8, the highest rating. This will safely avoid any electrical failures.

Size Constraints

The location of storm drains has been predetermined to effectively collect water runoff. The top plane of the storm drain is coincident the surface of the pavement or concrete it is set in. Nothing extrudes above the surface of the road to avoid any disturbance of traffic. This allows any moving body to safety move over the storm drain without noticing a drastic alteration of altitude. If the planes of a storm drain and the surface of the road were not coincident by just a single inch, joggers, cyclists and drivers would all be negatively affected by the issue. Street walkers and joggers could trip on the uneven surface, cyclist could catch a tire and flip over their handlebars, while the suspension in cars would have to work harder in order to accommodate the disturbance in the road. For these reasons, nothing should obstruct the moving bodies on the road for safety concerns.

The cavity below the street's surface usually resembles a rectangular prism shape in the United States. The top and bottom surface areas of the chamber are larger than the surface area of the grate, while the depth is about twice as long as the grate's sides. This space will be utilized to design the mechanical aspect of our product, since we cannot design above the surface of the road as previously discussed.

Sustainability Constraints

Larger masses that travel on the street depend on more than just a flat driving surface for a safe ride. Cars and trucks have masses that require a strong base to hold the vehicle's weight. Roads are paved with multiple layers of pavement to create a compact base that can distribute heavy loads across their surfaces. The physical properties of large areas of compact pavement and the storm drains are different. The size of the surface area of a storm drain relative to the large area of road is extremely small. For this reason, storm drains cannot distribute heavy loads across their surface area. Storm drains instead rely on supporting heavy loads with stronger material.

Packed pavement is a strong compressive material in a large quantity, such as a road. The surface area of an average storm drain is only 1 meter by 0.75 meters. Pavement does not act as a good drain material because of its lack of tensile strength and non-porous qualities. Cast Iron is a common material used for storm drains because of its higher tensile strength and low cost. A trade off with a higher strength material, such as cast iron, is higher density. A material with a higher density also has a higher mass, given the same volume. This means that the grate portion of our storm drain will be quite heavy, in order to safely support heavy loads on the road.

Environmental Constraints

Any materials used with our design should not be toxic. The water that passes through the storm drain would get contaminated and flow through the larger drainage system. The storm runoff water sometimes ends up in a natural body of water, such as a reservoir, lake, river or sea. If the contaminated water were to get into the bodies of water, the effects could be detrimental to the environment.

Any large holes or openings should be blocked off to prevent people and wildlife from injuring themselves. People walking or cycling on the street could trip on the uneven surface and harm themselves. The same goes for the wildlife, except the smaller animals could potentially fall into the storm drain cavity.

Economic Constraints

Standard storm drains are moderately expensive. Installation and paying the maintenance workers for man hours is where the true expense comes from. This is because the products are static with no movement. No moving parts or mechanisms allows the life cycle of the existing storm drains to increase. Our product will have a mechanism to block debris from entering the grate. This means that the life cycle will be shorter than that of the existing products. The difference in the life cycles will increase the price of our design, along with the added debris blocking features. This product needs to cost as little as possible in order to attract consumers. We could research the most efficient manufacturing methods for our product's components.

Build and Interpret House of Quality

Quality Characteristics (a.k.a. "Functional Requirements" or "Hows") / Demanded Quality (a.k.a. "Customer Requirements" or "Whats")	Flow Rate (m^3/s)	Size/Dimensions (m, m^2, m^3)	Material Strength (MPa)	Debris Allowance (cm^3/s)	Material Rigidity (GPa)	Power Consumption (Whr)	Service Intervals (yr)	Noise Level (dB)	Mass (kg)	Liquids and Solids Resistivity (IP Rating)	Reliability (yrs to failure)	Reflectivity (Reflection Coefficient)	Hydrocarbon Tolerance (%)	Operating Temperature (°C)
Durable		O	Θ	▲	Θ	▲	Θ		O	O	Θ			O
Safe	O	▲	Θ	O	Θ	▲	O	▲		O	O	O	▲	▲
Handle Heavy Rain	Θ		▲	Θ	▲	O	▲	▲		Θ	Θ		▲	
Discrete Appearance/Hidden	▲	Θ		▲				Θ				Θ		
Inexpensive		O	O	▲	O	O	Θ		O		O		▲	▲
Energy Efficient				O		Θ		O					O	▲
Retrofittable		O				▲	▲		▲					
Environmentally Friendly				O		O		O					Θ	
Waterproof	O						O			Θ	▲			
Will not Clog with Debris	Θ			Θ		O	▲				O			

Figure 4-1 Engineering characteristics compared to customer requirements.

Our team determined 10 customer requirements and 14 engineering characteristics corresponding to the functionality of a storm drain. We entered these qualities into room 1 and room 2 respectively of the house of quality. Each of our customer requirements is directly related to at least one engineering characteristic. Some engineering characteristics represent more than one customer requirement. After inputting the customer requirements into room 1 and the engineering characteristics into room 2, our team compared them in room 4. *Figure 4-1* shows the body of our house of quality that compares the customer requirements directly with the engineering characteristics. The symbols represented for the relationship are as follows: no symbol means no relationship, a triangle means a weak relationship, a circle means a moderate relationship and a circle with a line in it means a strong relationship. Our team believes that the inputs to our house of quality are more than adequate for an accurate representation of the customer needs compared to the functional requirements of a storm drain.

Looking at the matrix above, the relationships are all reasonable. The size/dimensions share a strong relationship with discrete appearance/hidden. If an object is larger, it will be more noticeable. The operating temperature has no relationship with whether the product is retrofittable or not. If the operating temperature range goes up, the device does not become retrofittable if it was not previously beforehand. The last thing we did in the body of the house of quality was determined the direction of improvement of the engineering characteristics. The meaning to each symbol are as follows: an up arrow means to maximize the quantity, an “x” means to target the quantity and a down arrow means to minimize the quantity. Using this method came up with the results as seen in *Figure 4-2.* Some engineering characteristics we would like to maximize would be the flow rate, service interval and material strength. On the other hand we would like to minimize the noise level and power consumption, while target a specific value for the operating temperature.

1	2	3	4	5	6	7	8	9	10	11	12	13	14
▲	x	▲	▼	▲	▼	▲	▼	x	▲	▲	x	▲	x
Flow Rate (m^3/s)	Size/Dimensions (m, m^2, m^3)	Material Strength (MPa)	Debris Allowance (cm^3/s)	Material Rigidity (GPa)	Power Consumption (Whr)	Service Intervals (yr)	Noise Level (dB)	Mass (kg)	Liquids and Solids Resistivity (IP Rating)	Reliability (yrs to failure)	Reflectivity (Reflection Coefficient)	Hydrocarbon Tolerance (%)	Operating Temperature (°C)

Figure 4-2 Direction of improvement for the engineering characteristics.

Our team then moved on to room 3 of the house of quality, which is the triangle matrix on the top of body. This matrix relates the engineering characteristics to each other. This is where we can determine how each engineering characteristic affects one another. Room 3 can be seen in *Figure 4-3*. The meaning to each symbol are as follows: a double plus means a strong positive correlation, a plus means a positive correlation, a minus means a negative correlation and a down arrow means a strong negative correlation.

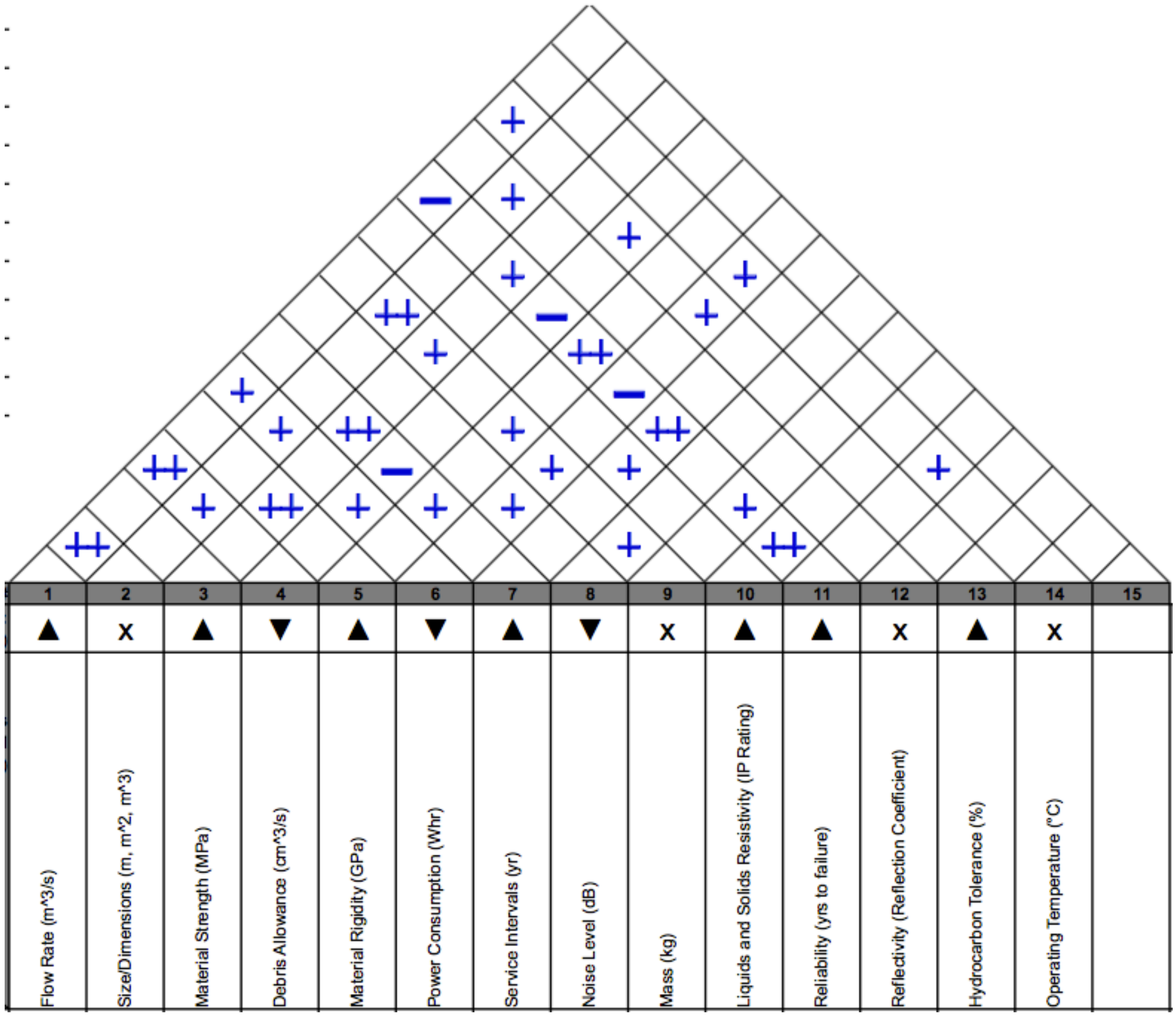


Figure 4-3 Engineering Characteristics Correlations.

The correlations between the engineering characteristics are more difficult to comprehend than when relating engineering characteristics to customer requirements. This is because there is also a negative option as a correlation between engineering characteristics. Looking at the correlation between the flow rate and reliability, it's negative. This means if we were to increase the flow rate of our product, the reliability would decrease. The higher volume of water that the device drains for a given time, the more strain that is applied to the mechanisms. The storm drain has to work harder in order to keep up with the higher flow rate. On the other hand, if the flow rate were to decrease then the reliability of the storm drain would increase. The device is easily accomplishing its task to drain water, the moving parts aren't put under high strain.

In room 6 of the house of quality, our team compared four existing products in the storm drain market. The existing products are all seen today on residential streets and parking lots. The competitive products we researched were the curb opening inlet, grate inlet, linear drain and combined drain inlet. The competitive analysis can be seen in *Figure 4-4*. The matrix on the left hand side is composed of the products across the top and the customer requirements down the side in the order previously displayed. The values in the matrix is a scale that compares the products together based on the customer requirements. All of the products vary when compared to each other, but they do share some similarities. For instance, none of the products are retrofittable. This results in the ranking of a 0 for the entire 7th row down. Each product has its own strong quality though. The grate inlet is the most durable, the linear drain is the safest, the combination drain inlet can handle the most rain water and the curb opening inlet is the best at not clogging with debris. Room 6 of the house of quality is a great way to compare the competitive products to one another and find beneficial qualities to replicate.

Competitive Analysis
(0=Worst, 5=Best)

Curb Opening Inlet	Grate Inlet	Linear Drain	Combination Drain Inlet		
4	5	3	4		
4	3	5	3		
4	4	3	5		
3	2	4	2		
2	3	4	1		
5	5	5	5		
0	0	0	0		
3	3	4	3		
5	5	5	5		
5	3	2	4		

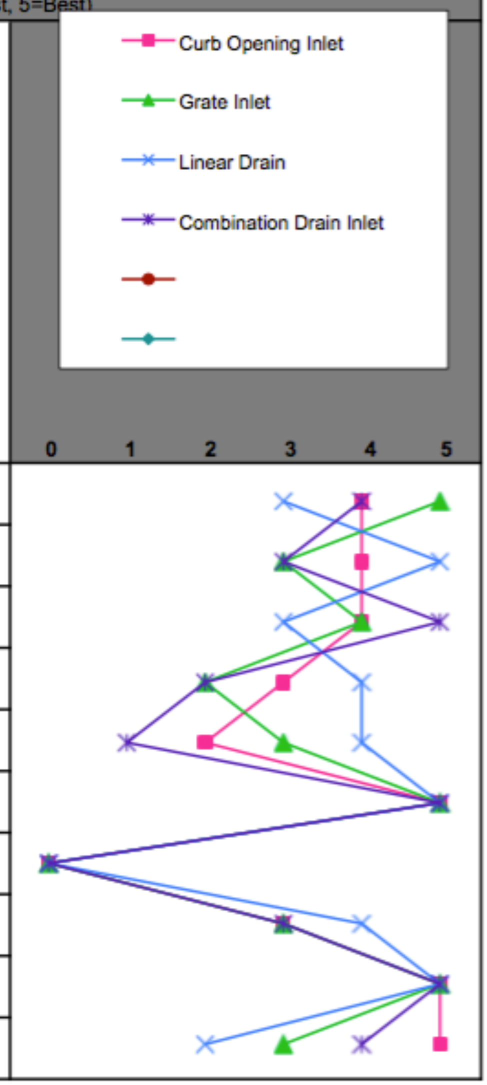


Figure 4-4 Competitive analysis matrix and plot.

After researching competitive products, our team determined some target and limit values that we will be designing our product around. Some of the values may be changed or altered later on in the product development process, since we will continue to research and discover new information. The target values can be seen in *Figure 4-5.* The corresponding engineering characteristics to the values are in the same orientation as the above figures. Our team also discussed the difficulty it would be in order to achieve those target and limit values. We found that some would be easy to do that others. Obtaining a material that has the strength to withstand any plastic deformation when 275 MPa of pressure is applied to it should be easy. We can purchase many types of metals that are that strong. Having the product to be reliable for at least 20 years is much more difficult.

Target or Limit Value	0.002 m^3/s	1m x 0.75m x 1.5m	275 MPa	5 cm^3/s	41 GPa	400 Whr	5 yrs	60 dB	70 kg	IP Rating: IP58	20 yrs	Albedo Coefficient: 0.10	Hydrocarbons out/in: 50%	20°C
Difficulty (0=Easy to Accomplish, 10=Extremely Difficult)	8	4	3	8	3	7	7	3	4	3	9	5	6	2
Max Relationship Value in Column	9	9	9	9	9	9	9	9	3	9	9	9	9	3
Weight / Importance	322.9	157.1	271.4	362.9	271.4	240.0	302.9	120.0	77.1	282.9	368.6	85.7	111.4	71.4
Relative Weight	10.6	5.2	8.9	11.9	8.9	7.9	9.9	3.9	2.5	9.3	12.1	2.8	3.7	2.3

Figure 4-5 Engineering characteristics target/limit values and importance.

Rating of Engineering Characteristics

The last thing that our team noted on our house of quality was look up the relative weight of each of the engineering characteristics. The relative weight uses the relationships between the customer requirements and the engineering characteristics to ranking the importance of the engineering characteristics. The very last line in *Figure 4-5* contains the values. We ordered the engineering characteristics from most important to least important according to the house of quality. The relative ranking is displayed in bold next to the ranked engineering characteristics. The sum of the relative ranking is 100, so it could be thought of as a percentage of importance.

1. Reliability (**12.1**)
2. Debris Allowance (**11.9**)
3. Flow Rate (**10.6**)
4. Service Intervals (**9.9**)
5. Liquids and Solids Resistivity (**9.3**)
6. Material Strength (**8.9**)
7. Material Rigidity (**8.9**)
8. Power Consumption (**7.9**)
9. Size/Dimensions (**5.2**)
10. Noise Level (**3.9**)
11. Hydrocarbon Tolerance (**3.7**)
12. Reflectivity (**2.8**)
13. Mass (**2.5**)
14. Operating Temperature (**2.3**)

Key Engineering Characteristics

In order to determine the key engineering characteristics, our team looked at the engineering characteristics that held a strong relationship with the critical to quality requirements. The critical to quality requirements are shown below with the engineering characteristics that the held a strong relationship with.

- **Will not Clog with Debris** - Flow Rate, Debris Allowance
- **Handle Heavy Rain** - Flow Rate, Debris Allowance, Liquids and Solids Resistivity, Reliability
- **Durable** - Material Strength, Material Rigidity, Service Intervals, Reliability

Some engineering characteristics are noted twice, which means that they are critical to responding to more than just one critical to quality requirement.

Taking note of these relationships, we determined the key engineering qualities as shown below in order of priority.

1. Reliability
2. Debris Allowance
3. Flow Rate
4. Service Intervals
5. Liquids and Solids Resistivity
6. Material Strength
7. Material Rigidity

This list of key engineering characteristics makes sense for the given critical to quality requirements. In order for a storm drain not to clog with debris it needs to be able to allow a large amount of debris to either pass through it or be blocked off from the drain altogether. If a storm drain is going to handle heavy rain, it should have a high flow rate. The higher the flow rate, the larger volume of water the storm drain can allow to pass through it in a given amount of time. When an object is durable, it could also be said that it is reliable. Once the storm drain is installed in the street, the customers do not want to worry about it failing. In order to prevent the storm drain from failing, the workers could do some preventative maintenance on it in the form of service intervals. The more durable and object is, the higher the material strength and rigidity. That same object's ability to resist water and dust will also determine its durability. These key engineering characteristics logically make sense.

Determine your Decision Characteristics Set

Our team's full house of quality can be seen in Appendix D. We determined that our engineering characteristics adequately represent the customer requirements and no engineering characteristics will be added or removed. The house of quality has its flaws and biases in some cases, but our team's discussions eliminated the noticeable ones.

Group Sign Off

All members of Team 32 participated in the selection of customer requirements, engineering characteristics, constraints for our project. Each member had a voice when building and interpreting the house of quality. By digitally signing your name, you as a team member approve of this portion of the report.

Matt Devine
Zachery King
Katherine Konecny
Michael Kyei-Baffour
Scott Sterling
Neil Winston

5 Conceptual Design Process

Five Feasible Concepts

Function Structure Diagram

Our function structure, *Figure 5-1*, is designed to show the flow of material, energy, and signal throughout our proposed design. To create our function structure, we first defined a black box diagram. The purpose of the black box diagram is to reflect the ultimate goal of our design, to remove and prevent debris from entering the storm drain.

The completed function structure has 3 inputs: storm water, debris, and the kinetic energy associated with flowing water. First, the inputs enter the inlet, where the debris is removed. The water and its associated kinetic energy pass through the drain and is accelerated by converting gravitational potential energy to kinetic energy. The energy of the flowing water is captured by a device, as it is needed to provide power to clear the drain inlet. When enough energy is stored, it is released in order to remove debris from the grate inlet. After being filtered for hydrocarbons, the water is allowed to exit the system and enter the storm sewer network.

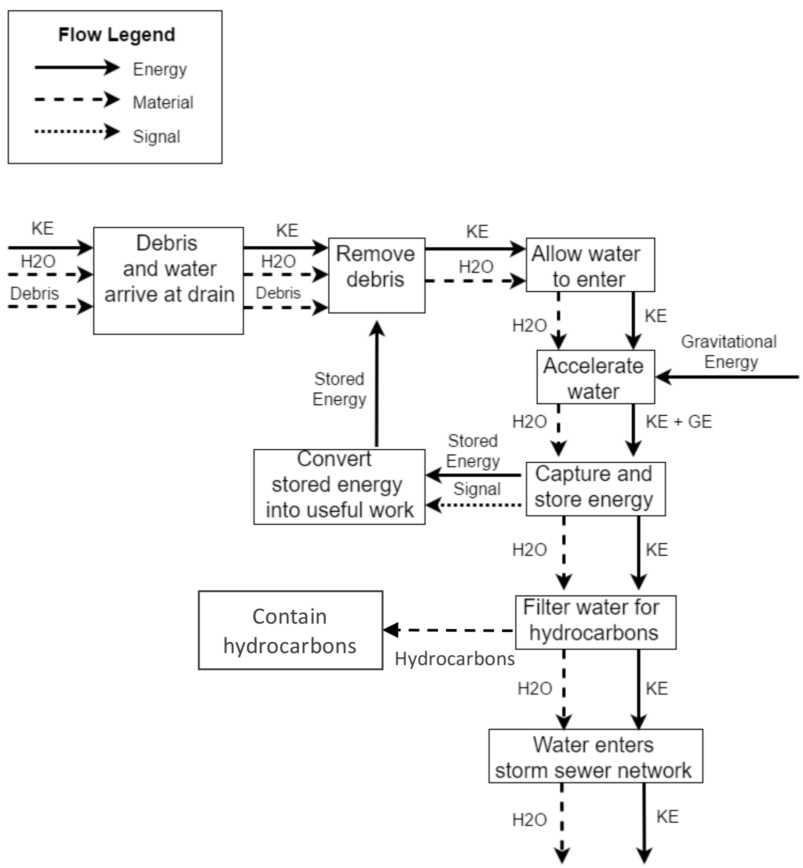


Figure 5-1 Function structure chart for a storm drain debris clearing system.

Morphological Chart

To create our morphological chart, our team first identified the sub problems within our design that must be addressed. We identified these sub problems based on our customer requirements and engineering characteristics to ensure they encapsulate our entire system. These sub problems are found along the top row of the morphological diagram. Upon identifying five sub problems, we began to compile solution concepts associated with each one of the sub problems. While it may be easy to identify one or two solutions to each concept, creating a list of 4 or 5 solutions can prove to be more difficult. It was important for us as a team to analyze and discuss the solutions as a team due to us conducting research in specific areas.

Morphological Chart for Grate-Style Road Surface Level Storm Drain Inlet Cover

	Subproblem Solution Concepts				
Row Number	**Convert Kinetic Energy into Useful Work**	**Clear Debris Off Grate Surface**	**Accelerate and Direct Water Flow**	**Allows Sufficient Flow Rate**	**Safe For Vehicle, Bicycle, and Pedestrian Traffic**
1	Linear spring	Conveyor w/ Pushers	Flow apertures	Open grate surface area	Small grate openings
2	Torsional spring	Slot Pushers	Funnel	Placement on road	Minimal Prominence
3	Water wheel	Sweeping Bristle Roller	Water ramp	Road surface depression	Smooth, flat surface
4	Generator	Swing Arm Brush	Hoses or pipes	Angle of water interception	High Strength Material
5	Catch basin	Shaft Conveyor	Pump		Flat Surface

Table 5-1 The morphological chart showing possible solutions for the sub problems associated with storm drain inlets.

Five Feasible Concepts

Concept 1: Permeable Rolling Grate with Rubber Pushers

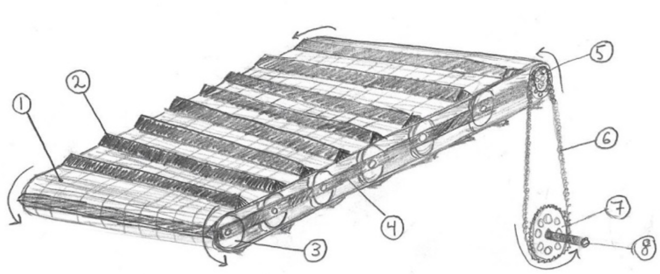


Figure 5-2 Sketch of Permeable Rolling Grate and Parts List.

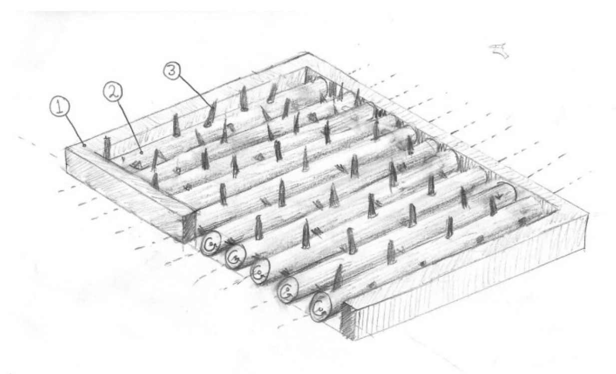
Parts List

1) Mesh grate surface
2) Rubber debris pushers
3) Cylindrical rollers
4) Internal support grate
5) Small gear
6) Chain
7) Large Gear

This concept uses a conveyor belt system to actively clear debris away from the storm drain inlet so that stagnant debris does not obstruct the flow of water. A permeable mesh grate surface (1) featuring triangular rubber debris pushers (2) moves parallel to the surface of the road and away from the curb, forcing debris away from the storm drain. The motion of this conveyor is continuous during rainfall. An internal grate (4) provides the entire system with structural support and multiple cylindrical rollers (3) facilitate the motion of the conveyor. A power source located beneath the road surface supplies power to the powered shaft (8), where a large driver gear (7) rotates and translates power through a chain (6) to a small driven gear (5). The small driven gear is fitted to a shaft located radially inward from the outside surface of one of the rollers.

This concept works continuously during rainfall to assure no debris can buildup on the surface of the drain grate. The design mimics a conveyor belt or a treadmill which are both used to transport something. This is why it was feasible to implement a similar concept to transport debris away from the surface of the storm drain. As already stated, the strength of this concept is that it will work continuously so ideally there should never be more than a miniscule amount of debris on top of the grate. This design will also help filter out more sediment from the water than other concepts because not all of the dirt, mud, grit, etc. will be able to pass through the permeable mesh conveyor as its moving. It will be powered by either a battery, the most reliable option, or by a waterwheel, which would be unreliable but cheaper. The weaknesses of this concept deal with both safety and durability. If there was a cyclist riding in the rain and happened to ride over this drain conveyor system while it is in motion, it could possibly cause the rider to lose control and injure him/herself. From a durability aspect, if vehicles are constantly riding over this system as it is moving it is subject to tearing as it is worn over time.

Concept 2: Shaft Conveyor



Parts List

1) Inlet frame
2) Heavy duty rods
3) Rubber fingers

Figure 5-3 Sketch of Shaft Conveyor and Parts List.

Rubber fingers (3) actively carry debris away from the storm drain inlet. These rubbers fingers are positioned on the surfaces of heavy duty rods (2) which are supported by the inlet frame (1). The rods are driven by a power source located beneath the grate which allows them each to rotate about their own axis. The fingers are positioned in a unique pattern along the rods so that the debris will be carried away from the curb by the fingers.

The Shaft Conveyor is a feasible concept because the design does not interfere with road surface while utilizing a simple concept in rubber protruding fingers to push debris away. Although the rubber fingers do protrude above the road surface slightly, they are very soft rubber and flexible so they will not affect vehicles or cyclists if they were to ride over them. A weakness of this concept is that it could possibly allow debris to fall into the drain as all the rods rotate on their own axis.

Concept 3: Slot Pusher

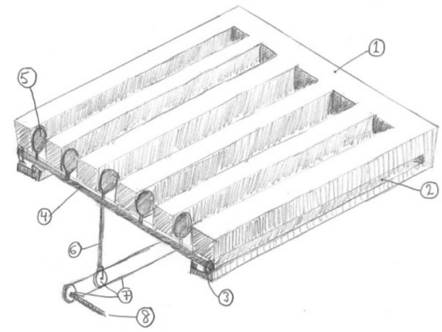


Figure 5-4 Sketch of Slot Pusher and Parts List.

Parts List

1) Steel grate
2) Slot
3) Roller
4) Support bar
5) Scoops
6) Shaft
7) Belt/pulley system
8) Powered Shaft

This concept uses moving scoops to actively clear debris out of the openings of a storm drain inlet cover so that stagnant debris does not obstruct the flow of water. A steel grate (1) whose top face is coincident to the surface of the road has openings running perpendicular to the curb face. A support bar (4) featuring five debris clearing scoops (5) is able to be secured to the steel grate by means of a roller-in-slot apparatus. One roller (3) on each end of the support bar is installed into a motion allowing slot (2) on each side of the steel grate. A shaft (6) provides the desired translational motion to the support bar by receiving power through a belt/pulley system (7) located below. A pulley system is driven by a powered shaft (8) which receives power from a power source beneath the ground. The resulting axial motion of the scoops forces debris out of the grate openings.

The "Slot Pusher" is a simple design to just push debris out of grate openings and would be completely retrofittable to a standard storm drain grate. This makes it a feasible concept when looking at the ease of implementation. The strengths of this concept are that the scoops just slightly protrude above the grate surface so there would be little to no interference with vehicles or pedestrians passing by. This is especially true when you consider the fact that this "pushing" process is periodic so the probability of a vehicle or pedestrian coming into contact with the scoops should be low. One weakness of the concept is that the scoops will not completely clear the grate off all debris because they only move on one axis so there will be debris that is smashed against the end of the grate slots. Another weakness is that this system could get clogged or jammed easily if something hard or rigid were to get lodged into one of the slots and blocked the scoops from pushing the debris out of the grate.

Concept 4: Sweeping Bristle Roller

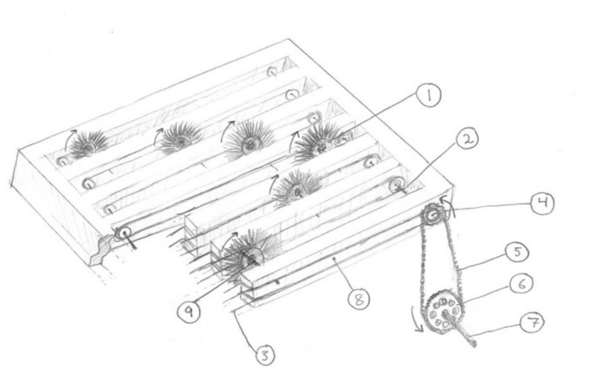


Figure 5-5 Sketch of Sweeping Bristle Roller and Parts List.

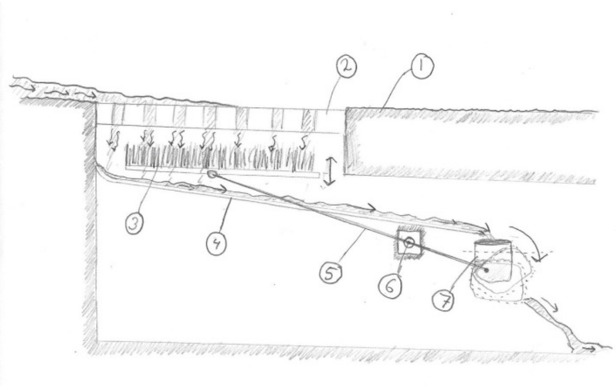
Parts List

1) Spinning Brush (qty. 6)
2) Large Driving Rod
3) Belt (qty. 12)
4) Small gear
5) Chain
6) Large gear
7) Powered shaft
8) Grate inlet

Debris is actively cleared from the storm drain openings by six spinning brushes (1). The brushes sweep debris out of the openings with bristles as they undergo both rotational and translational motion. Six small rods (9) pass through the radial centers of the brushes, allowing rotational motion. In addition to allowing rotational motion, they also guide the brushes as they translate along the slots in the drain grate due to the belts (3). These belts are driven by pulleys attached to the large driving rod (3). The driving rod is driven by a small gear (4) which receives power from a chain (5) being driven by the larger driver gear (6). The large gear is attached to the power shaft (7) which receives power from a source located beneath the grate.

This concept basically adds a rotating brush to the “Slot Pusher” concept previously discussed which improves on that design that was already declared a feasible concept for the problem statement. The strengths of this concept are that it will effectively clear the grate openings of debris and it will also not interfere with roadways. This is because the bristles of the rotating brushes are soft and flexible enough that they will compress if rode over by a car, motorcycle, bicycle, etc. This poses no threat to safety of those who travel roads with this system implemented. A weakness of this system is that the bristles of the brush could quickly wear because of the friction of contacting debris and other resisting material.

Concept 5: Swing Arm Brush



Parts List

1) Road surface
2) Grate inlet
3) Plate and bristles
4) Water chute
5) Long rod
6) Pivot
7) Bucket

Figure 5-6 Sketch of Swing Arm Brush and Parts List.

This concept uses a brush to periodically clear debris from a storm drain grate inlet with force delivered by a swinging motion. During periods of rainfall, water accumulates on above the road surface (1) and falls below ground through storm drain grate inlets (2). Water is guided down a water chute (4) and into a water collection bucket (7). Water accumulates in the collection bucket until the water level rises high enough to shift the center of gravity of the bucket, causing it to tip and quickly pour out the collected water. The bucket is pinned to a long rod (5) which pivots (6) as the bucket dumps. The pivoting motion of the long rod allows a plate and bristles (3) to deliver a sweeping motion to the storm grate which clears away debris.

The “Swing Arm Brush” presents itself as a feasible concept because it mimics a simple, yet effective tool in that of a broom. A broom is a proven tool to clear debris off of a surface so it is feasible to apply it to a concept to clear debris off of a storm drain grate. Another important aspect of this concept is the fact that this brush would not interfere with vehicles or pedestrians on the road surface. Even though the brush will protrude slightly above the road surface during its sweeping motion, its bristles are flexible enough that it would pose no threat to cars, motorcycles, pedestrians, etc. A weakness of this concept arises in the situation that some heavy object, like a car for example, was parked on the storm drain grate. As a result of only using the rainwater’s kinetic energy for power transmission the brush cannot push through a lot of resistance. If there was a car tire on the drain grate, the brush would not be able to clear debris from the surface for however long the vehicle is parked there. There is also the possibility that debris could get stuck in the bristles of the brush as it returns back under the road surface where it would most likely be passed into the water drain off.

Power Source Concept Discussion

To make our design a reasonable choice for grate inlet replacement, it will need to operate without the need for external power. Being a standalone system, it requires an independent source of energy. While we considered electric power in the form of batteries and motors, it is not ideal due to the maintenance in charging/replacing batteries in addition to the added cost. The only other significant source of energy available to a storm drain inlet in the inflow of water. We seek to harness the energy of the water entering our system, and convert it into useful work to clear debris. Effectively capturing the energy of flowing water will be crucial to our design functioning at maximum performance.

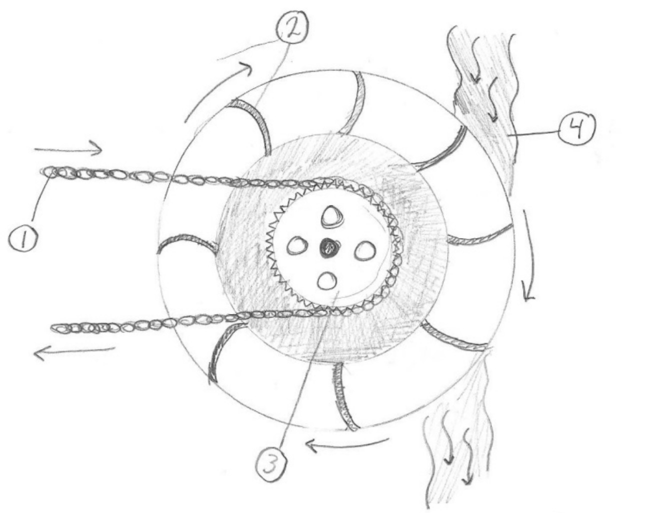


Figure 5-7 Sketch of Water Wheel concept.

We first consider the water wheel (*Figure 5-7*) as a means of capturing the energy in flowing water. Water wheels are simple devices with only a small number of components that have existed for thousands of years as a way to harness energy. A drawing of a simple water wheel can be seen. Flowing water (4) strikes the water wheel scoops (2), located around the hub and gear assembly (3). The torque provided by the impact is able to create motion, which can be used to operate a chain (1), belt, rod, or other device.

Using simply a water wheel as a source of power has its drawbacks; without significant flow rate, the water wheel will not be able to overcome and frictional or other resistive forces involved in the cleaning process. Therefore, the use of a single water wheel is not a feasible design solution. In order to overcome the (possibly large) resistive forces that debris accumulation may create, the system will require more instantaneous power.

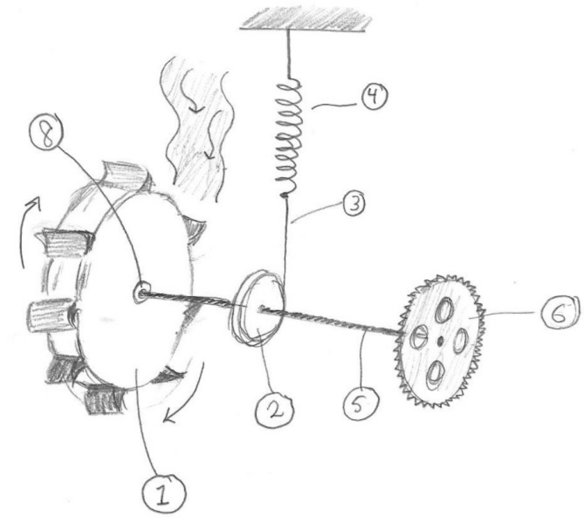


Figure 5-8 Sketch of Spring System concept.

This design (*Figure 5-8*) is an example of a technique for capturing, storing, and releasing the energy of flowing water. A cycle begins when flowing water strikes the scoops of the water wheel (1), causing a shaft to turn (5). Midway along the shaft sits a spool (2). As the shaft rotates, the spool winds up wire (3) attached to a fixed spring (4). As the shaft continues to make rotations, the spring and wire will impart larger torque on the shaft. When this torque exceeds that provided by water striking the wheel, the system will release energy. A clutch bearing (8) will engage, preventing the water wheel from turning. The spring will pull against the spool, creating a rapid rotation of the shaft. The shaft could either deliver the power directly, or be combined with a gear (6) and chain/belt system to deliver power.

The effectiveness of such a system to store energy depends significantly on the design. The size and weight of all rotating components are very important to prevent unnecessary rotational inertia and ensure the proper amount of torque delivered. In addition to this, the spring (or system of springs) will need to be carefully selected based upon its constant, k, and dimensions. Also, gearing ratios must be carefully selected based on the requirement of the cleaning mechanism selected. More important design considerations include the shape of the water wheel for maximum efficiency. Multiple water wheels may need to be used to ensure maximum energy capture.

Concept Selection Process

Given the nature of the storm grate product, it was necessary to create and assess concepts with two separate Pugh Charts. Although most of the concepts were created with an energy source in mind, some were not. After much deliberation, it became clear that a majority of the concepts could work with any of the common energy sources: electric power, torsional/linear springs, water wheels, or catch basins. It became apparent that the same concept could be received differently by the customer depending on the source of energy. Therefore, it was understandable why the energy sources would demand one set of selection criteria while the mechanical concepts would require another.

Mechanical System Selection Criteria

The first Pugh Chart was used to objectively consider the generated concepts against current methods of unblocking storm grates during a storm. As aforementioned, currently there is no clear way to assure storm grates remain unblocked or uncovered during rainfall. A majority of state governments recommend checking storm grates before rainfall and manually clearing debris during rainfall as the only solution. There is also the possibility of using street sweepers, but they are not used during inclement weather. Additionally, street sweepers are generally operational during late nights or early mornings, once a week or even less frequently. Understandably, it was decided that the only appropriate datum would be manually clearing the drains. In order to create a more balanced evaluation, the concepts would be assessed against manual labor that was consistent – as if someone had made it their job to clear storm grates during the storm. With human manual labor as the datum, it would be clear how the concepts related to current solutions as well as how they were related amongst themselves.

With the datum determined, the selection criteria had to be generated in a way that the datum would measure equally with each of the concepts. *Table 5-2*, has a list of the selection criteria used in the Pugh Chart, descriptions of each criterion, and the ECs they were derived from. The better a concept addresses these criteria, the more likely it would be the most effective final concept. Requirements such as durability, flowrate, and reliability were directly translatable. Other requirements had to be modified slightly, but they were ultimately represented in the selection criteria, in some form. ECs such as Hydrocarbon Tolerance, Mass, Material Rigidity, and Size could not be implemented into selection criteria because they either did not apply to the selected datum, could not effectively be measured, or had some sort of bias towards the datum or the generated concepts.

Selection Criteria	Description of Criteria	Engineering Characteristics
Water Flowrate	Amount of water that will be able to flow through the grates while cleaning debris from the grate.	Flowrate
Durability	Measure of the strength and resilience of cleaning mechanism parts (springs, human bones/muscles, bolts, etc.)	Material Strength & Rigidity
Safety	Measure of if any piece of the mechanism is dangerous - consider volunteers standing out in natural disasters, sharp objects protruding from the grates, and harmful substances exposed to the environment.	N/A
Debris Allowance	Amount of debris that may slip through the grate during cleaning.	Mass/Time
Energy Dissipation	Measure of how much effort/energy is required for the mechanism to effectively clean the surface of the grate.	Power Consumption
Reliability	Measure of the how often the system will be operating without jams, difficulties, or other impairments.	Reliability
Intrusiveness	Measure of the ability for cars or pedestrian to travel over the grate while cleaning processes are ongoing without being disturbed or damaged.	Visibility, Noise Level, Size & Dimensions

Table 5-2 List of Selection Criteria, Descriptions, and Related ECs for Mechanical Concepts.

Concept Pugh Chart Results

The results of the Pugh Chart (Figure 1, Appendix C) are not completely objective. While the Pugh Chart's job is to identify the most prominent concepts, there are exceptions to the selection process. Looking at the raw results of the Pugh chart, it would appear that concept 1, the Rolling Grate with Rubber Pushers, is the most suitable concept. Compared to human manual labor, it ranks either the same or better in each of the 8 selection criteria. Concepts 2 through 5 seem to be a tier below concept 1, which still puts them substantially above the datum. In last place, Concept 5, the Swing Arm Brush is the concept least suited to tackle the problem. This makes sense because the Swing Arm Brush is a concept that mimics the raking or broom sweeping movement that a human would make in attempt to clear the storm grate.

While in this instance, the selection criteria were unweighted, it is beneficial to look at how the concepts faired in some of the more significant categories. According to the House of Quality, the most significant engineering characteristics are reliability, debris allowance, and flowrate. Since flowrate is expected to be, on average, equal across all concepts, scoring can temporarily be overlooked. As for ratings in debris allowance and reliability, concept 1 was able to score better than manual labor in both categories. Although, concepts 2 and 4 were able to score at positive in at least one of the two categories, concept 1 has definitely distinguished itself as a frontrunner based upon the selection criteria.

Coincidentally, it would seem the top three most feasible concepts are the ones that scored the best in the Pugh Chart. Concepts 1, 2, and 4 all unique ideas that modify different parts of storm grates in order to accomplish the same function. Concept 1 was able to establish itself as the frontrunner amongst the concepts by show its well-roundedness. This concept is reliable, it is not intrusive, it prevents debris from sitting on top of grates while maximizing flowrate, and it is more effective than manually clearing the storm grates during rainfall. Concept

4 is definitely the second most feasible concept amongst the five. The only category it ranks worse than manual labor comes in durability.

Durability is an important criterion because these mechanical systems need to be able to hold up in harsh conditions in order to assure they are preventing the grates from being covered with debris. Customer will be relying on these grate systems to prevent street flooding and in worst case scenarios, property damage. While material strength and rigidity are not part of the top three important Engineering characteristics, according to the House of Quality they are ranked in the middle at rank 6 and 7, respectively.

Finally, the third most feasible concept is Concept 2. This concept ranked positive in every category except for one, reliability. Reliability is the most critical Engineering Characteristic to this system, so the fact that it was rated worse than manual labor is a huge downside. Similar to durability, reliability is very important because customers need to be able to trust the mechanism will be operating appropriately and efficiently. If customers have to invest additional resources to assure the system is preforming adequately, the product would have failed to fix the problem.

Energy Generation Selection Criteria

Considering the customer requirements and engineering characteristics were generated with the mechanical concept in mind instead of the energy generation concept, it was a little bit more difficult to follow the same process. First, it was necessary to determine what the datum for the energy source Pugh Chart would be. Originally, it was thought that physical exertion required to power the manual labor would be used as the datum for the second Pugh Chart because it was the only viable solution, currently. However, physical exertion is hard to measure objectively; one person could be lazier than another or even less suited to clear storm grates. It was decided that electrical power translated to mechanical energy by means of a motor would be the appropriate datum. Since energy loss due to conversion would be a factor in each concept, they seemed more evenly leveled than purely using electrical grid energy or physical exertion. Additionally, electrical power made sense because it is the most cost effective form of energy available in the United States.

Creating selection criteria once the datum had been determined became a bit easier. Some of the engineering characteristics generated for the House of Quality could definitely be applied to the whole system rather than just the mechanical system concepts. *Table 5-3* provides a list of each qualifying criteria along with descriptions and related ECs for each. ECs such as weather resistivity, cost, and service interval seemed to apply more specifically to the power sources than the actual concepts. Other ECs such as durability and reliability were universal ECs and could be applied to either category of concepts, so they were included on this Pugh chart as well. From there, it was necessary to brainstorm a list of benchmarks or measurable quantities that could be used to compare the effectiveness of the power sources. It was determined that Environmental Impact, Energy Storage Capacity, and Energy Required were all criteria that could be used to assess each concepts' capabilities.

Selection Criteria	Description of Criteria	Engineering Characteristics
Energy Required (Efficiency)	Measure of energy that will need to be built up and used to clean the grate during rainfall.	Flowrate
Durability	Measure of the resilience of the power source (lifetime of the springs, water wheel, and catch basin, and the amount of reuses on electrical power source).	Material Strength & Rigidity
Impact on Environment	Measure of how the power source can negatively impact the environment. Consider battery acid flowing into marine life, rust of metal spring components, or other effects of water wheels and catch basins.	Debris Allowance & Hydrocarbon Tolerance
Energy Storage Capacity	Measure of the amount of energy that can stored for system usage.	Power Consumption
Service Intervals	Measure of the amount of time that will pass before the power source will need to be changed, maintained, or compensated.	Service Intervals
Weather Resistance	Measure of weather effects such as rain, ice, snow, or extreme temperatures on the power source system.	Water Resistivity Standards
Reliability	Measure of the how often the system will be operating without jams, difficulties, or other impairments.	Reliability
Cost	Amount of money and time it would take to implement this solution to storm grates across the country.	N/A

Table 5-3 List of Selection Criteria, Descriptions, and Related ECs for Energy Generation.

Energy Generation Pugh Chart Results

The results of the second Pugh Chart (Figure 2, Appendix C) seemed to be more closely aligned than the results for the concept selection. Based purely off of raw date, Concept 3, the catch basin seems to be the best method of creating mechanical energy. Like other concepts, it suffers from energy loss due conversion. Additionally, it ranked worse than electric energy in the capacity and durability categories. In second place, Concept 4, which happens to be the water wheel. In addition to durability and energy storage capacity, the water wheel seems to be worse off in cost due to the amount of components necessary in order to make it work appropriately. Lastly, both the linear and torsional springs placed last. They sport the same issue that is found with the battery or electrically powered motor; springs will require frequent service due to weather fatigue.

While it is not possible to weigh all the criteria based upon the House of Quality, it is possible to see how the energy options rank in some of the critical, universal ECs. Of the top three critical ECs, reliability is the only selection criteria that translates to the energy source. In this category, both spring concepts fall short of the datum. Alternatively, the catch basin and the water wheel are more reliable than the other sources. This is due to the fact the water wheel and catch basin are not affected by inclement weather. In fact, these two concepts strive off of heavy waterfall while electric power and springs can be limited in heavy rainfall due to power outages or suffering from rust, respectively. Furthermore, ranked fourth and fifth in significance, are Service Intervals and Weather Resistance which cements the water wheel and catch basin as the front running concepts.

Factoring in the results of the Pugh Chart as well as the conditions the product is expected to operate make choosing the top three energy sources simple. The water wheel, catch basin, and electrically powered battery are the strongest concepts for energy generation. The springs fall short because of questionable reliability. While the water wheel and catch basin strive off of heavy downfall and increased flowrates, the springs suffer from the capability of rust and frequent service intervals. Alternatively, the system could abuse water resistant spring materials, but that would drive the cost of the system higher than the other options. While the electric power is also vulnerable to the weather conditions, affordable alternatives are available such as capacitors or plastic housing. Aside from efficiency ratings and storage capacity, where all concepts were ranked lower than the electrically powered motor, the catch basin and water wheel fall short in the durability criterion. While this is a significant blow to these concepts, there are also upsides. Many of the components of these concepts are easily replaceable and cheap which ramp down the severity of the low durability. Overall, it seems the burden associated with springs outweighs the benefit provided to them when compared to the other three options.

Group Sign Off

All members of Team 32 participated in the selection of the criteria, rating in the Pugh Chart, and the final concept selection for our project. By digitally signing, each member is agreeing they held an active role in selecting their concepts and approve of the steps taken to reach the final three concepts for energy source and mechanical concepts.

Matt Devine
Zachery King
Katherine Konecny
Michael Kyei-Baffour
Scott Sterling
Neil Winston

Final Concept Selection

After using the Pugh Chart to narrow the number of concepts from five to three, there was another design tool that was used in order to select the final concept. The Analytical Hierarchy Process uses proportional comparison in order to determine which concept demonstrate specifically weighted Engineering Characteristics. By choosing three of the most significant ECs, the AHP will compare the top three concepts amongst themselves. The result of the AHP will be the single concept that is, based upon proportional relationships, better than the other two. Reliability, Flow Rate, and Debris Allowance are the three ECs that will be used in the AHP spreadsheet because according to the House of Quality, they are the most significant in the design of the concept. These are the most significant because they are defining features of the concept's performance.

Criteria Comparison (Normalized)

	Reliability	Debris Allowance	Flow Rate	**Average**
Reliability	0.17	0.11	0.20	**0.16**
Debris Allowance	0.33	0.22	0.20	**0.25**
Flow Rate	0.50	0.67	0.60	**0.59**

Table 5-4 Normalized Criteria Comparison

In *Table 5-4* the Normalized Criteria Comparison shows how the three criteria weigh against each other. Weights and significances of the Engineering Characteristics are a little different than what it had appeared to be based upon the House of Quality. The most significant characteristic was the flowrate, which happened to the be the lowest among the three in the House of Quality. The concept's performance was based off its ability to keep the grate clear in order to maximize the flowrate, so in the scope of the performance, flowrate is the most critical characteristic. Debris Allowance was rated the second highest because the product becomes more complete if it is able to prevent debris from entering the sewage system. Reliability was weighted the least significantly. The idea behind the concept was to create a reliable alternative to having someone clear the grate during the storm. All of the final five concepts would have been reliable, so the significance of reliability was minimal in deciding upon the final concept.

Reliability	Conveyor w/ Rubber Pushers	Roller Brushes	Slot Pushers	***Average***
Conveyor w/ Rubber Pushers	0.55	0.57	0.50	***0.54***
Roller Brushes	0.27	0.29	0.33	***0.30***
Slot Pushers	0.18	0.14	0.17	***0.16***

Table 5-5 Reliability AHP (Normalized)

While all concepts were considered reliable, the number of mechanical parts differed between the concepts. *Table 5-5* shows the normalized results of the AHP in terms of reliability. The slot pushers rely heavily on dynamic movement in order to function properly. While the roller brushes required more mechanical parts than the slot pushers, this concept did not seem as susceptible to jamming. By rotating and translating the roller brushes had multiple conditions that had to be met in order for total failure to occur. This made it more reliable than the slot pushers. In certain situations, it was easy to see the conveyor belt becoming jammed as well;

however, these situations were less likely to occur than jamming in the other concepts, so it was deemed the most reliable concept among the three.

Debris Allowance	Conveyor w/ Rubber Pushers	Roller Brushes	Slot Pushers	***Average***
Conveyor w/ Rubber Pushers	0.59	0.50	0.71	***0.60***
Roller Brushes	0.29	0.25	0.14	***0.23***
Slot Pushers	0.12	0.25	0.14	***0.17***

Table 5-6 Debris Allowance AHP (Normalized)

In *Table 5-6*, the Debris Allowance portion of the AHP is depicted. Once again the conveyor concept trumps the other two concepts by a pretty significant margin. The conveyor concept was sketched to include a semi-permeable mesh that would keep litter and debris out but allow water and other fluids to pass through. The other two concepts did not come with such a design and because they functioned by translating debris and litter off the grates. Due to the translational motion within the slots of the grate it is easier to envision debris passing through the grate. The roller brushes were rated a tad bit more favorable than the slot pushers because the rotational motion helps to prevent debris from falling into the sewer channel.

Flow Rate	Conveyor w/ Rubber Pushers	Roller Brushes	Slot Pushers	***Average***
Conveyor w/ Rubber Pushers	0.11	0.14	0.14	***0.13***
Roller Brushes	0.56	0.43	0.43	***0.47***
Slot Pushers	0.56	0.43	0.43	***0.47***

Table 5-7 Flow Rate AHP (Normalized)

Finally, the flowrate (shown in *Table 5-7*), the most significant characteristic to determining the final concept design. The flowrate is the main variable that defines the performance of the concept. The concept aims to maximize the flowrate in order to prevent flooding on the street. Contrary to the first two characteristics, the conveyor concept ranked the lowest in flowrate. The conveyor concept was to come equipped with a semi-permeable mesh that would allow water to pass but none of the debris that laid atop the grate. Although the mesh would be permeable to water and other liquids, mechanism would greatly hinder the flow of water. The slot pushers and the roller brushes are evaluated as equals when in the realm of flowrate. The mechanisms are similar so it was assumed they would perform similarly.

	Aggregated
Conveyor w/ Rubber Pushers	**0.314522751**
Roller Brushes	**0.383438842**
Slot Pushers	**0.347500058**

Table 5-8 AHP Aggregated Totals

The final aggregated total (shown in *Table 5-8*) shows that the roller brush concept was slightly favored over the conveyor and slot pusher concepts. The result is not surprising because each of these concepts are fairly similar in the way they operate. The only thing that chances is the medium used to push the debris off of the grate. Throughout the AHP process, it seemed that the Conveyor concept was going to be heavily favored. However, the conveyor concept suffered the most in the most significant category – flow rate. This hindered the conveyor concept greatly because it fell behind the other two concepts significantly in the most critical category. The roller brush concept seemed to be middle of the pack until it outperformed both of the other concepts in the realm of flowrate. While it was really close, by means of the AHP, the final concept design will be modelled off of the roller brush concept.

Final Concept Sketch and Description

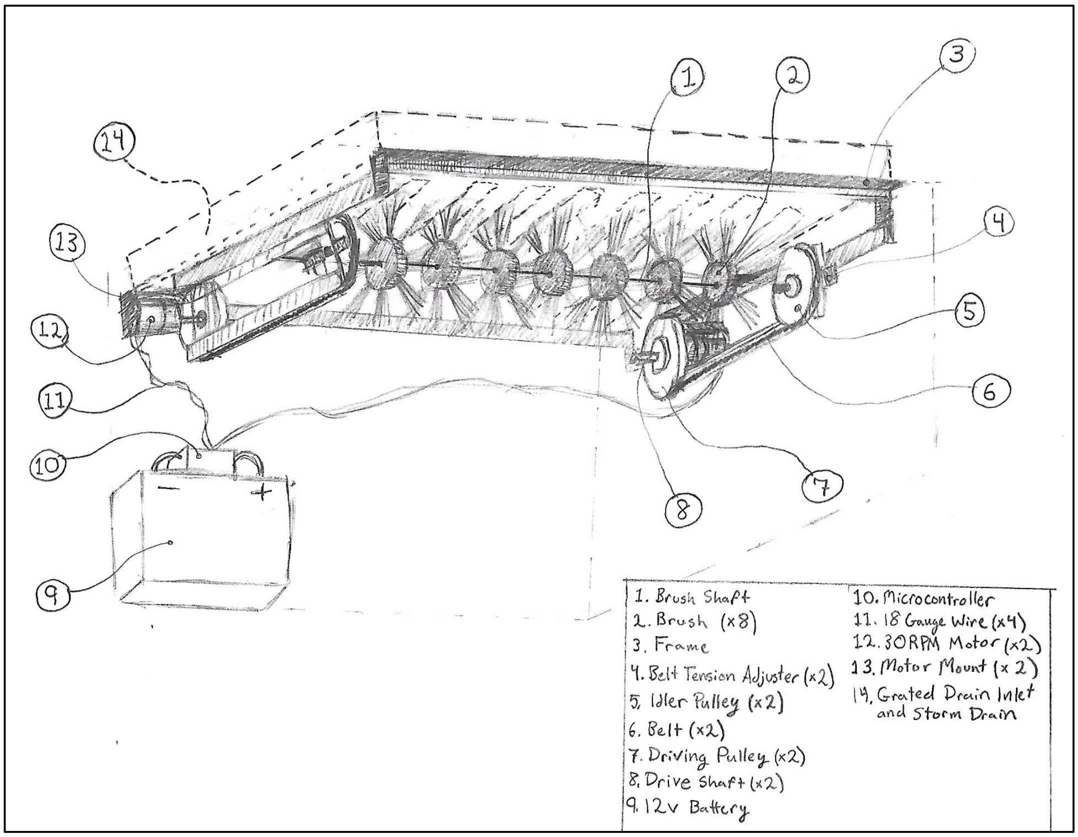


Figure 5-9 Final Concept Sketch

Our group maintained the basic concepts that our previous concept embodied, however we modified the design to better reflect our refined customer requirements. The major change to our design involves the position of the rotating and translating brushes. The original sketch depicts brushes translating through slots embedded in the storm drain. This is not a desirable solution, as it required a redesigned drain grate with slots to allow the brushes to translate. In our final prototype, the brushes are all located along a single shaft. The shaft rotates and translates between the frame and the two driving belts. The entire system is suspended below the storm drain, and the grate requires no modification. This adds significant advantage over the previous design, by allowing us to retrofit the system to existing drain inlets rather than needing to manufacture entirely new grates. For this concept, we modeled our retrofittable design off of a standard highway grate as seen in the engineering drawings.

In our original concept, we had planned to harness the kinetic energy of the water flowing into the drain to generate power. After testing with our prototype, we determined that the energy required in order to reach the desired rotation velocity was not feasible to obtain with water power. Our group realized that our product would not effectively be self- sustaining once installed. In order to accommodate our power generating issue, we concluded that a 12-Volt deep cycle battery (9) will best accommodate the low power draw of small DC electric motors over a long period of time. Although our concept no longer draws its power from the surrounding environment, it will be capable of functioning over long periods of time with no manual labor involved.

Figure 5-9 depicts the final concept sketch for the roller brush concept. Two high torque low RPM DC (12) motors are used to convert electrical energy into useful work. The motors sit on mounts (13) that are welded to the frame. The motors turn pulleys (7) on opposing sides of the frame. A belt (6) spans between each driving pulley and idling pulley (5). The ends of the brush shaft (1) sit between the belts and frame, and the motion of the belt combined with the friction between the belt and frame allow for rotation and translation. To most effectively provide rotation and translation, the position of the idling pulleys can be moved forward or backwards via a simple belt tension adjuster. The idling pulley sits on an axle attached to a small bar fitted in a channel in the frame. A small bolt (4) can be loosened, allowing the axle and bar to be slid forwards or backwards as necessary. Upon reaching the desired position and belt tension, the bolt is tightened to lock the pulley in place. As belts can stretch over time, the tension adjust can also accommodate for slight changes in belt length.

The frame, which provides structural support for everything except the battery and microcontroller (10), sits underneath the grated inlet (14). Steel angles span between the two sides of the frame, parallel to the brush shaft. The horizontal portion of the angles rest on the lip of the drain inlet, and the grate is placed on top of the flat angle section. For installation, the grate is lifted from the storm drain, and the entire assembly is placed to rest on the inlet lip. Finally, the grate can be returned to the rectangular inlet, completing the retrofit.

6 Embodiment Design Process

Determine Product Architecture

Product architecture is the arrangement of the physical elements of a product to carry out its required function. The intended function of our product is to effectively prevent street flooding caused by debris accumulation on storm drains by clearing the debris away from the grate inlets, allowing water to pass through. We have selected the product architecture for our product that we believe will provide a way to establish the best system for functional success.

Our product is organized into a number of subsystems that act as the physical building blocks of the entire system. The key subsystems include Structural, Power Transmission, and Electrical and Control. Each one of the aforementioned subsystems is made up of a collection of components that carry out functions.

The Structural subsystem will include four triangular truss pulley support frames, eight lubricated roller tracks (a backup solution if the belts slip sideways), eight mounting brackets, two motor mounting brackets, fasteners, and additional metal for support structures and welding material as needed. The Power Transmission subsystem includes four drive pulleys, four idler pulleys, four flat belts, eight nylon wheel brushes, two driving shafts, two brush shafts, four brush shaft rollers, and eight bearings. The Electrical subsystem includes one 12V DC battery, one waterproof battery case, one humidity sensor, two DC motors, one 12V PWM controller, one switch, one microcontroller, fuses, fuse holders, crimping connectors, solder, and wires as needed.

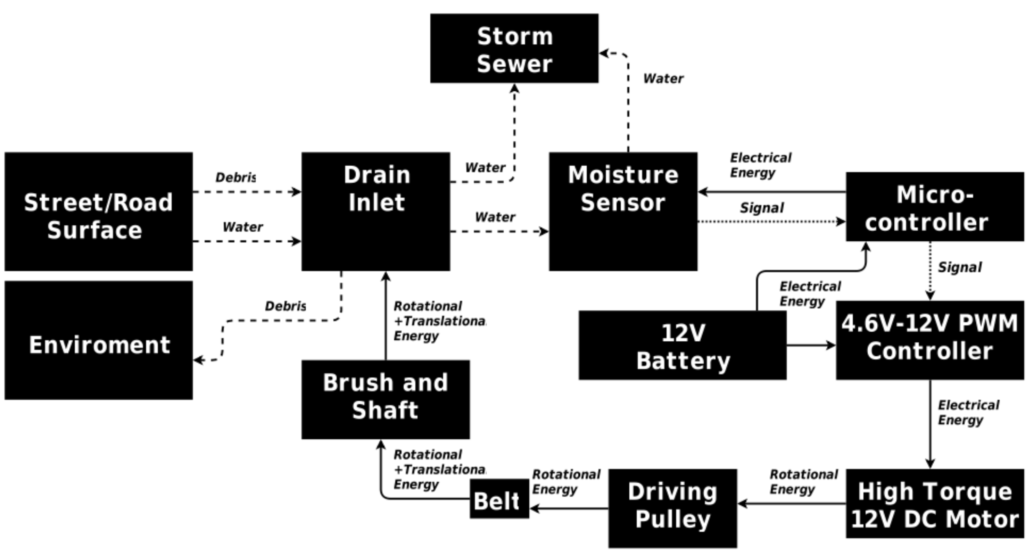


Figure 6-1 Function Decomposition of Concept Design

In order for our product to achieve functional success, it is imperative that the subsystems within the product interface as according to plan. *Figure 6-1* shows a schematic diagram of our design, and includes the interactions between the various components and subsystems within the design. One of the major selling points of our product is a design retrofittable to an existing storm drain grate. The structural subsystem features mounting brackets that will interface with the existing storm drain, allowing the system to be suspended beneath the inlet. The structural subsystem will interface with the power transmission subsystem at the location where the pulleys will be mounted on the triangular truss pulley support frames. These frames will be designed to provide enough support to the pulleys so that the power transmission subsystem can operate without being disturbed by any unwanted vibrations. The power transmission subsystem will interface with the electrical system at the location where the motor shaft interfaces with the driver pulley. The motors, powered by the 12V batteries, will turn and cause the driver pulley to rotate.

Process Determine Configuration Design

In configuration design, we establish the shape and general dimensions of components. The form or configuration of a part develops from its function however; the possible forms depend strongly on available materials and production methods used to generate the form. In addition, the configurations are dependent on the spatial constraints that define the envelope in which the product operates and the product architecture. Due to the nature of designing for a retrofit, the configuration design of our system is highly dependent on the spatial constraints defined by the boundaries of the storm drain grate.

Critical Structural Component

Within our design, the most critical part is the truss frame; part of the structural subsystem. The truss frame forms the backbone of the system. It is responsible for supporting all subsystems within the design, and its failure would result in a total failure of the product. That is why we seek to design the truss structure for maximum strength, while attempting to minimize defects, stress, and strain concentrations.

For maximum strength, the truss is designed with a triangular structure. This will ensure maximum stiffness. To minimize the chance of buckling, the individual truss sections will be constructed from metal sections that carry a geometry not likely to buckle (90 Degree A-36 Steel Angles). We intend to join the truss members with welds, as A-36 steel takes well to numerous forms of welding. By using a fixed connection, we will minimize the chance of losing fasteners due to vibration, ensuring maximum rigidity. Finally, to prevent corrosion, we will finish the steel frame with a coat of black paint.

- Triangular Truss Pulley Support Frames
    - Material: ¾ ”x ¾” x 1/8” A-36 steel angle brackets
    - Finish: Painted
    - Dimensions: 3.75” x 15.25” x 1.00”
    - DFM: We designed the truss structure to be simple enough so that it can be manufactured by cutting metal segments and welding them together. We will save money by manufacturing these parts ourselves.

Critical Power Transmission Component

- Flat Belt Idler Pulley
  - Material: Nylon (lightweight and corrosion and abrasion resistant)
  - Dimensions:
    - Diameter = 4 inches
    - Width = 1 inch
  - DFA: We selected an idler pulley with a built in bearing. This is an example of integral architecture. This single component shares two functions: it acts as a bearing and it acts as a pulley. Using fewer components will reduce the amount of time required for assembly and thereby reduce the cost to pay a technician to install the system.

Critical Electrical Component

- 12V DC Motors – The Nextrox Mini 30RPM High Torque Gear Box Electric Motor
  - Dimensions:
    - Diameter: 37 mm
    - Total Length: 70mm
  - Torque: 120 N*cm
  - Amp Draw: 200-600mA
  - DFA: This motor has the high torque low RPM output that we needed for our application. We selected the 30RPM model based on the target brush RPM of 100RPM, as determined by early prototype testing. In order to determine the necessary motor rpm, we performed some simple gear reduction ratios. The magnitude of the tangential velocity of both the driving pulley and brush shaft are the same due to the belt, assuming no slippage. So, a D=10mm shaft rotating at 100RPM (10.47rad/s) will carry a tangential velocity of 0.0523m/s. In order to achieve this, the pulley (D=10.6cm) will need to rotate at 0.987rad/s, or 9.43RPM. Coupled with the PWM controller, the motor will easily achieve the target RPM.

Custom Parts & Standard Parts

In order to simplify the process of manufacturing and assembling our product, we have taken into consideration which parts are standard parts that should be purchased and which are custom parts that need to be manufactured. In general, it is beneficial to purchase and use standard parts because they are readily available and there is no additional cost associated with manufacturing them. If tasked with designing for mass production, then we could determine the additional cost per unit associated with the custom part. Using the number of units being produced and sold along with those numbers we could then determine how many units we would need to sell in order to see an additional profit. The task is to build one functioning prototype, so using as many standard parts as is possible will help to keep our costs down.

Standard Parts

The standard parts, which we plan to purchase, include the battery, motors, motor mounting brackets, pulleys, brushes, and fasteners. The 12 V DC battery we need is for sale online in the McMaster-Carr large cell battery catalog and can be found by searching for part 71805K82. This specific part is a rechargeable large cell battery for starting and continuous use. It is deep cycle, so it can handle many charge/deep discharge cycles, making it ideal for our application. The wide variety of parts available in the catalog allows us to select and purchase an existing battery that is well suited for our application.

The motors we would like to purchase are for sale on Amazon.com. The Nextrox Mini 12V DC 30RPM High Torque Gear Box Electric Motor offers the high torque and low RPM output that we need for our application.

The flat belt pulleys we would like to purchase are for sale in the McMaster-Carr flat belt pulley catalog. We will be using flat-belt idler pulleys and flat-belt drive pulleys, both with outer diameters of 4 inches. The drive pulley we have selected can be found by searching for part 6231K28. It is made of a composite material which minimizes belt slippage and wear. The idler pulley we have selected can be found be searching for part 6235K17. It is made of nylon, which is lightweight and corrosion and abrasion resistant. The idler pulleys rotate freely on built in bearings, which reduces wear and vibrations. The wide variety of parts available in the catalog has allowed us to select pulleys for our design without having to design and create custom parts.

The brushes we have selected to use are 6-inch diameter nylon wheel brushes. They are for sale in an online catalog through Brush Research Manufacturing and can be found by searching for catalog number NWA-6. Fasteners will be required for assembly of our product. We have not yet selected specific fasteners however, we plan to design accordingly so that the use of standard bolts and welds will be sufficient for our application. For a complete list of standard parts, refer to the Bill of Materials located in the Appendix.

Custom Parts

The intended function of our product is very specific. Currently, there are no other systems designed to be retrofittable to a standard storm drain grate. The custom parts, which we plan to manufacture specifically for our product, include four triangular truss pulley support frames, eight mounting brackets, eight lubricated roller tracks, four flat belts, two driving shafts, and two brush shafts. Each of the aforementioned parts will require varying levels of customization for manufacturing.

The parts that will require the highest level of customization are the triangular truss pulley support frames, the mounting brackets, and the roller tracks. The triangular truss pulley support frames are similar in design to some standard trusses, but they will need to be manufactured to our specified dimensions. These parts will be fabricated out of ¾ "x ¾" x 1/8" steel angle brackets. We plan to cut the steel angle into segments of specified lengths, and join them together by welding. The dimensions of these support frames are critical to the quality of our design. A proper support fit and alignment will ensure that the pulleys within the power transmission subsystem are able to function properly.

The driving shafts and brush shafts will be purchased as standard parts, but will need significant modifications prior to their assembly and integration into the system as a whole. In order to fabricate the brush shafts, we will modify 3/8" steel rods by cutting them to the required length. We will use a similar process to manufacture the driving shafts, however we have selected ¼” steel rods for these. Modifying these existing parts to meet our requirements will allow us to achieve a customized part without sacrificing material strength all while being financially responsible.

Another material option for the truss support and shafts would be a durable, stiff, water/corrosion-resistant plastic. It’s a lighter and less expensive alternative to metal, but it would not necessarily guarantee the same lifespan as metal. A plastic like PVC is common, extremely affordable, and used for plumbing purposes because of its water resistance. PVC would need to be purchased in a sheet and rod form, then cut to size for the shafts and machined or water jetted for the truss support. A second option is to use a thermoplastic that can be injection molded; the cost of molds is steep, but they can be reused many times. This process is less expensive when parts are made in bulk.

The mounting brackets are to be fabricated out of a high strength metal capable of suspending the weight of the entire system. We will select a high strength steel and bend the steel into a geometry that will allow the part to hook onto the existing storm drain grate. The strength of this material will be critical to the quality of our design. If this mounting hook fails due to high stress concentrations, the entire system would collapse and fall into the storm drain. Because of the function of these brackets, we are hesitant to consider other materials, like plastics, that could crack or deform under the stress of vehicles driving over them. A metal such as 4130 Steel Alloy would be extremely reliable.

The flat belts will require minimal custom manufacturing, but will feature a highly custom design. We will design the belt according to belt design theory; a good resource for belt design is Shigley’s Machine Design, Ninth Edition. We will then refer to a belt catalog and select the belt with the most appropriate material, width, thickness, and the like. The length of the belt will be the only parameter that will require the belt to be made-to-order. This customization is justifiable because using a belt with a proper length will afford power transmission through the tension in the belt. McMaster Carr offers custom length belts and a wide variety of belt styles (weather resistant, extra texture, etc.)

Failure Modes & Effect Analysis (FMEA)

The Sweeping Bristle Roller is a product that excels through the plethora of dynamic parts that make up the assembly. Pictured in *Appendix H*, the entire FMEA spreadsheet is pictured. There are two main functions of the product: translational brush movement and rotational brush movement. Combining storm-intensive weather with the multitude of dynamic parts exposes the entire assembly to potentially severe failure modes. The functionality of the prototype is vastly decreased if one the of the main functions are no longer operational. In the case both functions have failed, the product relinquishes the ability to clear debris from atop the storm grate. In order to combat against failed functionality in both degrees of motion the systems have been separated and sport individual failure modes.

The rotation of the brush sports the more severe failure methods. The most severe failure mode would come by the motor seizing. If the motor seizes the entire power transmission and cleaning mechanism will fail to operate. The brush would simply be moving along the length of the grate. The occurrence of this failure mode is rather low because of the quality of the motors that are available for selection. Additionally, while it will be nearly impossible to tell when a motor will fail before its lifespan, it is easily to replace within the system once failure has been detected. The least severe failure comes with the belt. After prolonged use the belt will fatigue and begin to loosen or tear. This will cause slipping in the pulley system which will affect the speed at which the brush is able to rotate. However, belt fatigue is easy to detect and it is almost always expected. In order to prevent being taken by surprise, belt inspection can be a routine process. The most significant failure mode can be found in the corrosion of the battery terminals. Since the battery will be operating in wet conditions it is expected the battery terminals will corrode, but because the battery will be located below street level it will be impossible to foresee. Much like an inspection would be put into place for belt fatigue, an inspection would be imperative for battery conditioning.

Although translational and rotational functionality has been separated, these two operations sport similar failure modes. Much like brush rotation, translation can suffer from the motor seizing and the battery terminals from corroding. Since the operation of the slot brushes has been separated to two different transmission systems even if the motor seizes on one side the other motor should continue to function. It would take a chain of unfortunate events for both motors to seize - for example, the battery would have to fail. In addition to the shared failure modes, translation sports a unique failure. Because the prototype will function to sweep debris from on top of the grate, it is possible that rigid materials such as branches could get caught in the track which would prevent the brushes from translating along the grate slots. The prototype will make use of a low RPM, higher torque motor which would allow the brushes to plow through passive interferences. So while the severity may be rated a bit high, it should not occur too often and the pile up of debris would be easily detectable.

It is possible that even well designed system can fail to achieve functional success. Human error needs to be considered as a source of contribution to potential error. Human error can occur in the form of vandalization of the product, failure to properly maintain the product, or attempting to maintain the product but failing to follow the correct procedures. It is the job of the group to brainstorm potential failure modes and make decisions that would allow the prototype to function in a way that would prevent it from failing often. Through prototype testing potential failure modes that were not discussed should be highlighted and addressed.

7 Manufacturing and Process Cost Analysis

Prototype Assembly

Being that the majority of the prototype's design was a unique system of metal framework and unusual brushes, most of our parts were not out-sourced. All of the support framing was made of either ¾ in. steel angle, 1 in. steel square flat bar, or 3/8 in steel rod. It was purchased as stock and then each piece had to be cut to its desired length. After the steel was cut, it could be welded together to make the main support subsystem and the pulley frames subsystem which are then welded together (*Appendix G*). Also, the driver shafts had to be cut to length from the steel rod and welded to the frame for the pulleys to be mounted.

Each of the eight brushes were made in house as well. A 2-inch diameter wooden dowel rod was purchased to be used as the cores for the brushes. Eight 1 in. thick sections of the dowel rod were cut off to make to eight cores. Then a ¼ in. hole needed to be drilled through the center of each core where the brush rod would go through. On the round surface of the core, 16 staggered holes were cut ½ in. deep into the core so the nylon bristle bundles could be inserted. These bristle bundles came from a push broom that was purchased. The bristles were made up of reinforced nylon which made for a great material because it was rigid yet had elastic properties. Using pliers, bundles of bristles were pulled out and inserted into wooden cores, sealed with wooden, expansive adhesive.

The parts we did have to outsource were the pulleys and electric motors, but these parts still needed customizing for our design. With having the disturbance of the brush rod in between the belt and pulleys, the belt would constantly slip off of the pulleys. Slightly larger diameter discs had to be cut out of thin particle board and glued to both sides of the pulley to act as guides to keep the belt from coming off the pulley. With the motors, the output shaft would not work with the bore diameter of the pulleys that were purchased. The output shaft was ¼ in. in diameter and the bore diameter of the pulleys were 3/8 in. Steel rod with 3/8 in. diameter had to be machined and integrated onto the motors' output shafts, these are called the driver shafts (appendix G). Using a lathe, a ¼ in. hole was cut to a depth of ½ in. into steel rod. Using an extremely strong epoxy the steel rod was placed on the motor's output shaft.

To assemble this design, all the components need to be mated to the main support and pulley frames. The two motors secured onto steel angle mounts by permanent adhesive and zip-ties. Now all four pulleys can be placed on a driver shaft. There are two timing belts that are put on to each of the pulley systems. The brush rod with eight mounted brushes is placed in between the belt and pulley frame, see final assembly pictures in appendix G for better detail. At this point, all the mechanical systems are in place for the final assembly.

The power source and micro-controller still need to be wired to the two motors. A simple positive and ground come from each motor and feed into ports on the micro controller. Also a positive and ground wire is ran from the 12 volt battery to the micro-controller. A custom relay switch was made to give the ability to tell the system when to start and stop. With all electric sources connected, the final assembly is complete.

The only items that were out-sourced and were not customized were the two timing belts. Every other piece of the final assembly was either manufactured in house or out-sourced and then manufactured in some way to make them fit the design. This resulted in an extremely long manufacturing time and assembly time because so many alterations were needed. If this were to be implemented for large scale manufacturing, many things would be different to rid of a lot of the machining and welding. Molds could be made for the metal structures, and injection molding would be a much more efficient way to manufacture the brush cores. Overall, it proved to be a rather complex build for what seemed to be a simple design.

Product Cost Analysis

In any engineering project, costs and revenues will occur at various points of time in the future. Product cost refers to the cost to create a product and includes direct labor costs, direct material costs, and overhead costs. A product cost analysis is a form of engineering economic analysis that allows the engineer to understand to cost of production before actually beginning to produce the product. One might say that the engineering economist is essentially an educated fortune teller. By considering the costs of our prototype, anticipating the manufacturing methods of our final product, and applying the fundamentals of engineering economy to our specific project, we can price our product so that once it hits the market, the revenues we realize will be a reflection of the hard work that went into the product development process.

We have estimated an annual production of 1,000 units for our first year. This number is based on our intention to target the installation of our product onto storm drain grates at sump locations across the Baltimore-Washington area. The demand for our product has the potential to skyrocket after the first year if municipalities across the state, or even country, hear about the product's functional success. In the event that demand increases, production would need to be increased. An increased annual production would require a reevaluation of the product cost analysis however; the following analysis is based off of our first year production estimate of 1,000 units.

Cost of Materials

Material Cost Analysis of a Grated-Inlet Multi-Brush Cleaning System						
Subsystem	**Materials**	**Total Quantity**	**Total Price**	**Per Unit Price**	**Units in Product**	**Cost of Part**
Structural Subsystem:	A-36 Steel Angle (Inches)	48	6.57	0.136875	130	17.79375
	A-36 Steel Flat Bar (Inches)	48	6.48	0.135	102	13.77
	A-36 3/8" Steel Rod (Inches)	36	4.97	0.138055556	7.2	0.994
	3/8" Stainless Nut	1	0.5	0.5	2	1
	3/8" Stainless Bolt	1	0.5	0.5	2	1
Brush and Drive Subsystem:	Timing Belt Pulley	1	11.8	11.8	4	47.2
	Timing Belt	1	10.58	10.58	2	21.16
	1/4" Zinc Rod (Inches)	36	3.47	0.096388889	24.5	2.361527778
	7" Nylon Brush	1	2	2	8	16
	Nylon Drive Shaft Adapter	1	0.36	0.36	2	0.72
Electrical and Control Subsystem:	12V Battery, Deep Cycle	1	39.95	39.95	1	39.95
	12V DC 30 RPM Gearbox Motor	1	12	12	2	24
	Dual Motor PWM Controller	1	4.97	4.97	1	4.97
	Microcontroller	1	4.95	4.95	1	4.95
	18 Guage Wire (Feet)	500	45.77	0.09154	12	1.09848
	Humidity Sensor	1	2.39	2.39	1	2.39
				Initial Cost of Purchased Materials:		199.3577578
				Bulk Discount (35%):		69.77521522
				Discounted Cost of Materials:		**129.5825426**

Figure 7-1: Cost of Materials Spreadsheet

The cost of material is the sum of costs of all the parts which are required to manufacture the product. Our product has three subsystems; the structural subsystem, brush and drive subsystem, and the electrical and control subsystem. Figure 7.1 shows the cost of materials required to produce one grated-inlet multi-brush cleaning system. The cost to purchase all of the materials is $199.35 per unit. However, because we intend to produce 1,000 of these units during our first year of production, it would be most cost effective to buy the materials in bulk. The benefit of buying material in bulk is that bulk discounts are offered. For this cost estimation, a bulk discount rate of 35% can be applied to all purchased items. Therefore, the discounted cost of all materials required to produce one of our products is $129.58.

Cost of Labor

The cost of labor is the sum of all wages paid to employees, as well as the cost of employee benefits and payroll taxes paid by an employer. The cost of labor is broken into direct costs and indirect costs, or overhead. For the scope of this product cost estimation, we will be making some assumptions. The first assumption is that the cost of employee benefits and payroll taxes paid will be lumped into the estimation of direct labor costs. The second assumption is that the indirect costs will be estimated using an overhead multiplier as 85% of the direct labor costs. In order to fabricate the grated-inlet multi-brush cleaning system, we will need to hire a machinist and a welder. The hourly wage of a machinist is $20 per hour and the hourly wage of a welder is $25 per hour. In order to reduce the cost of labor, we will either hire one person who is skilled enough to do both of these tasks or hire two people who with each of these skills who work in the same shop. Eliminating the need to transport the materials from the machinist to the welder will eliminate the need to pay a transporter.

The machinist will be required to cut the raw steel flat bar and steel angle bar into the lengths specified by the dimensions labeled in our drawings. We estimate that a skilled machinist should be able to perform all of the cuts needed for one unit of our product in ½ hour. This means that the cost of hiring a machinist will account for $10 of direct labor cost.
The welder will be required to attach the steel parts into the orientation specified by the dimensions labeled in our drawings. We estimate that a skilled welder should be able to perform all of the welds needed for one unit of our product in ½ hour. This means that the cost of hiring a welder will account for $12.5 of direct labor cost.

The cost of direct labor paid for a machining and welding is $22.5. The estimated cost of indirect labor paid is 85% if this cost of direct labor, or $19.13. Adding the direct cost and indirect cost of labor gives us our estimated overall cost of labor to be $41.63.

Product Cost Per Unit

The product cost per unit can be estimated as the sum of the cost of materials after a bulk discount and the cost of labor accounting for the cost of overhead. We have determined an estimate of the cost of a grated-inlet multi-brush cleaning system to be $171.21. We believe that this is a reasonable cost which leaves us room to set a price point that would allow for an acceptable profit margin.

8 Prototype and Testing

The prototyping process of this project is vital to the development and understanding of major parameters within the scope of this project. The goal of the final prototype, unlike the initial prototype, will be to mimic the functionality of the final design as closely as possible. Major subgroups will definitely be highlighted with the final prototype: Power Source, Power Transmission System, Mounting System, and Brush Cleaning Mechanism Systems.

Prototype Fabrication

Cleaning Mechanism System

The cleaning mechanism and tracking systems are the most important portion of the prototyping phase. A track needs to be constructed that will allow the rods with the brushes to move in a translational motion while rotating against the direction of travel. The material of the track will need to be extremely durable and have water resistant properties. Originally, it was believed that a thermoplastic elastomer would be used to create the track because of the high elastic moduli which would have been great for durability and reliability. However, the track has been made up of a metal frame because it was cheaper than we originally thought. The metal frame was custom made; it was comprised of flat metal bars welded together. In early stages of design, it was believed 3D Printing would be used because it was a great way to make a custom-made track; however, welding provided the same flexibility while allowed the use of a stronger material – steel.

In regards to the actually brush mechanisms that will be aligned in the slots, there are many design and construction options available. For the first prototype, a quarter-inch rod was used as an axis of rotation for the brush. Using washers and bolts to secure the brush allowed the orientation to be modified easily. This configuration is beneficial to the adaptability of the system – it will allow the product to be installed onto different grate sizes. For the final prototype, the brush quality will increase greatly. Originally, the brush was made from a cheap toilet bowl scrubber, but for the final prototype the goal was a high-density nylon spindle brush (*Figure 8-1*). After researching, the nylon brushes provided a little amount of flexibility in dimensions, so custom-brushes were made. For the brush spindle rod, thermoplastic elastomer (such as PA 6 GF30) was considered, but in the end steel coated in Plasti-Dip at the ends was used in order to increase rod strength while increasing the friction coefficient. A majority of the track parts were picked up from local hardware stores, but there were a couple of items that were custom ordered in order to keep the machining to a minimum.

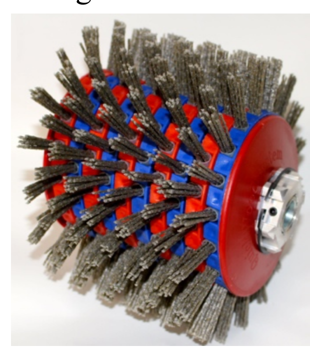


Figure 8-1 High Density Nylon Spindle Brush.

Power Transmission System

The system will obtain energy from a motor that is implemented into a pulley belt system. The main focus of the first type of prototyping was to find an optimal speed at which the brush could rotate and remove the most amount of debris from atop of the storm grate.

Trial	*First Trial*				*Second Trial*				
Speed (RPM)	50	100	150	200	50	75	100	125	150
$\boldsymbol{M_{street}}$ **(g)**	16	14	10	8	16	14	22	20	8
$\boldsymbol{M_{inlet}}$ **(g)**	22	24	26	24	34	35	28	30	42
$\boldsymbol{M_{drain}}$ **(g)**	2	2	4	8	0	1	0	0	0
Effectiveness (%)	40%	35%	25%	20%	32%	28%	44%	40%	16%

Table 8-1 Results of RPM testing.

In *Table 8-1*, the results of the testing are shown. In the first trial, 40 grams of wet leaves were placed atop of the storm grate that was constructed from the lid of a plastic storage container. The brush, rotating at the specified speed, would move along the length of the storm drain slit 6 times in 30 seconds. Once the trial was complete, the leaves outside to storm drain area would be recorded as the mass on the street. The leaves in the drain would be recorded as the drain mass and the leaves that remained atop of the storm grate would be counted as the inlet mass. The effectiveness was a parameter that compared the mass on the street to the starting mass. For the second trial, the speed range was decreased in order to pinpoint the rotational speed that would be optimal for clearing grates, and it was determined to be 100 RPM. Therefore, the prototype must be equipped with a motor and transmission system that would provide the proper amount of torque and 100 RPM to the cleaning mechanism.

The transmission system was constructed with a pulley and belt system (*Figure 8*-2). The motor will power the belt and pulley system which will transfer power to the rods in the tracking system that lays beneath the storm grate. Initially, a low RPM, high torque motor is being considered. The high-torque, low RPM motor provides enough power to move the brushes along the grates without having too much difficulty. It is estimated that the size of the disks attached to the motors will have to be approximately 4 inches in diameter. This should be able to transfer enough torque and keep the system rotating at the appropriate 100 RPM. Chain systems were considered, but given the nature of the product operations, the reliability of metal chains would be put into question under consistently wet conditions. Constructing the transmission system would be the first task because accounting for the limitations in the transmission system would eliminate a majority or the issues within the construction process. Fortunately, not much machining would be necessary in order to construct

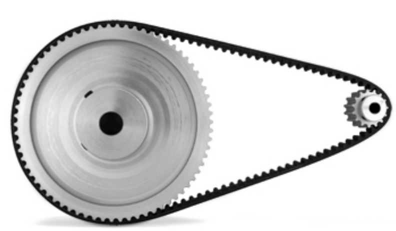


Figure 8-2 Pulley & Belt System.

the transmission system. If anything, the belt would need to be fit to the size of the pulley in order to assure that there would be minimal slipping.

The storm drains that the product is being modeled to fit come with eight 1.25 inch slots. So, the working area within this storm drain is very limited. If the product was to make use of another possible transmission system or gear ratio system, not only would it consume space, but it would lower the redundancy of the system. With a one gear ratio system, if one brush stops working, the whole system will surrender functionality. Given the space constraint, using multiple gear transmission systems would not be feasible because of the other parts that must be included in the prototype such as the mounting and brush track systems. For this product, the use of two-pulley systems would alleviate the problem of redundancy without the issue of a space constraint. Both Motors will be used to operate the pulley track but they will work to provide more power to the pulley track. If one motor stops working the other motor will be able to operate the pulley track, but it would work less efficiently.

Mounting System

The mounting system will require the most machining of the subgroups. The options that were available for Transmission System and the Cleaning Mechanism System are not available in this case because the product is of custom geometry. it was expected that this system could be something that was ordered from an online supplier. However, with the time constraints of the prototyping phase, the group opted to make the mount custom. By welding flat metal, it was possible to create the mounting system. It is expected that there will be a lot of material removal in the form of drilling, sawing, and sanding in order to create a bracket that can fit onto the control grate size. Similar to the other subsystems, the materials that will be used will need to have a respectable elastic modulus somewhere between 120 and 190 GPa. Additionally, they will have to be water resistant materials. The material cannot be porous because it could cause complications during the machining process. Ultimately, the material that was chosen was steel. Steel provided the strength and durability required while allowing us to assemble it in anyway fit. Creating a mount with an excessively high safety factor is necessary because of the amount of stress that will be put on the product by the water and possible debris that falls through the grate.

Power Source

During the conceptual design phase, the official source of power was undecided. Using the Pugh Chart, it was determined that water would be the most preferred energy generation concept. However, after the first prototype it became increasingly obvious that water would not provide the energy necessary to operate the system properly. This will be a major shortcoming with the final prototype. By using water energy, the group thought it was a great way to integrate the system into the environment without being too intrusive; however, it was quickly realized that this was not a feasible concept. Water would not be able to provide the energy necessary to keep the system functioning. Below there are calculations that show that harnessing water energy is not feasible because of the energy demands of the brush system alone. Instead, the prototype will function off of a 12 V water resistant battery, a humidity sensor, and an electric motor.

As aforementioned, the first prototyping process determined that the optimal rotational speed would be 100 RPM. With that it was possible to calculate the total rotational kinetic energy that was required for the cleaning mechanism without considering energy loss, friction, or other detriments.

$$\omega = 100\ \frac{rot}{min} \times \frac{1\ min}{60\ sec} \times \frac{2\pi}{1\ rot} = 10.47\ {}^{rad}/_{s}$$

Component	**Mass (kg)**	**Inertia ($kg \cdot m^2$)**	**Kinect Energy**
Rod	0.094	1.90×10^{-6}	1.04×10^{-4}
Bolts (x8)	5×10^{-4}	1.19×10^{-7}	6.5×10^{-6}
Brush	0.016	5.74×10^{-6}	3.14×10^{-4}
Washer (x2)	0.006	1.51×10^{-6}	1.66×10^{-4}

Table 8-2 Results of RPM testing.

Total System Rotational KE = $5.904 \times 10^{-4} J$

Next, it is necessary to calculate the translational kinetic energy. Once the translational kinetic energy is found, it will be possible to determine the total kinetic energy required for the system to operate successful.

$$12\ in \times \frac{2.54\ cm}{1\ in} = 30.48\ cm \times \frac{1\ m}{100\ cm} = \frac{0.3048\ m}{30\ sec} \times 6 = 0.06096\ {}^{m}/_{s}$$

Translational KE = $\frac{1}{2}(0.126\ kg)(0.06096\ {}^{m}/_{s})^2 = 2.34 \times 10^{-4}\ J$

$$Total\ KE\ Required = 2.34 \times 10^{-4}\ J + 5.904 \times 10^{-4} J = \mathbf{8.244 \times 10^{-4}\ J}$$

Given the energy required for the system to operate, it is possible to use a potential energy equation to figure out the required height necessary for water to operate the system. In order to make this calculation, there are three assumptions made:

1. There is a general assumption that run off from 8,000 square feet of pavement runs into one drain consistently (Ben-Joseph). This is an appropriate value because given the standard cul-de-sac oriented neighborhood, the cul-de-sac sports an area of approximately 7,900 square feet (Ben-Joseph).
2. The amount of rainfall per hour is derived from the average rainfall in College Park, in a year. In order to make a usable rate, it was assumed rain would be consistent, throughout the year. So the average amount of rain per year (43.53 in/yr) became 0.0050 in/hr (Graphiq Inc).
3. Additionally, the runoff coefficient had to be determined. Since a storm drain is located on the street, the coefficient would be between 0.3 and 0.75; in order to approximate the runoff in extreme conditions the runoff coefficient of 0.75 would be used (LMNO Engineering).

Flowrate of Runoff Water = $(0.75)\left(5.00 \times 10^{-3}\ {}^{in}/_{hr}\right)(0.184\ acres) = 6.90 \times 10^{-4}\ \frac{ft^3}{sec}$

$$6.90 \times 10^{-3}\ ft^3 \times \frac{28.32\ kg}{1\ ft^3} = 0.0195\ kg$$

$$8.244 \times 10^{-4} J = \frac{1}{2} mgh = \frac{1}{2}(0.0195\ kg)(9.81\ {}^{m}/_{s^2})(h)$$
$$h = 0.0086 \text{ m} = 8.60 \text{ mm}$$

The resulting height seemed favorable, but there are a number of shortcomings that come with water energy. Primarily, the efficiency of the system will definitely not be 100%. On average water technology functions in between a 30% and 60% efficiency. Second, waterfall is not consistent. The calculations were made assuming that waterfall would be consistently providing 0.0195 kilograms a second. Additionally, because the product is meant to clear debris from atop of the storm grate, there will be debris affecting the flowrate of water into the storm drain area. Finally, assuming there is one storm drain per an 8,000 square foot area is a vast under-estimate. Realistically, the amount of water available to be harnessed would be much less and concentrated in a stream of water instead of an elevated body of water. Therefore, water energy cannot be harnessed and instead electric power would be more reliable.

Storm Grate

The storm grate is necessary in order to exhibit the key functionalities of the prototype. Originally the grate was going to be made up of PVC piping materials. The PVC would provide a rigid material that could be easily machined and constructed into the form of the grate. It has a decent elastic modulus of about 52 MPa. While it does not mirror the strength and rigidity of a normal grate, it is high enough for the purpose of the prototype. Additionally, PVC pipes are made of a water immune material so using wet leaves for testing will not have any negative effects on the grate. Ultimately, we elected to make the grate out of wooden planks. Wooden planks provided a degree of flexibility that was not considered during early fabrication stages. The wooden planks could be put together using wood screws; there would be little to no hassle. The PVC presented a obstacle when it came to machining because of their hallow nature. In order to machine the grate, we cut wooden 2x4 planks at a length of 18 inches with a thickness of 1.5 inches. Using 2-inch wood screws and a drill the planks were assembled and subsequently spray painted black.

Testing Procedure & Analysis

Once the prototype is fully assembled, there will be a variety of test runs on individual systems as well as the prototype as a whole. In order to make sure the sub systems are performing the way they are supposed to be, each sub system will go through a functionality test.

Power & Transmission Systems

Testing and analysis for the power and transmission systems is only a check to make sure the system is running efficiently. Since the product is harnessing power from a battery instead of the proposed water energy, the prototype needs to be efficiently drawing power in order to keep the time between services maximized. The first test will look at the functionality and control of the power source through the testing of the humidity sensor. Since the system is only supposed to draw power under wet conditions the humidity sensor must be strictly calibrated to sense precipitation instead regularly humidity during the spring and summer seasons. In order to test the sensor, water, placebo humidity, and other substances will be placed in the environment with the sensor to see if it activates the controller. The group aims to have the controller only activate when water is present.

Once the sensor has been appropriately tested, the wiring will need to be investigated to make sure that wire temperature is not changing drastically when the prototype is in use. Increase in wire temperature will negatively impact the amperage drawn by the motor. By putting the prototype under prolonged testing and monitoring the temperature of the wires using heat sensors, the group will be able to assess the need for a heatsink. If the proper gauge wire is used for the prototype this will not be an issue.

Finally, the efficiency of the battery will have to be tested. In order to prolong the life of the battery the group is hoping to minimize the power draw from the battery when in use. Currently the pulley system is set to be comprised of two pulley disks, one for the motor and another for the brush mechanism. When testing the prototype under normal conditions, the group can use an oscilloscope and current probes to assess the power draw from the battery. If that proves to drain the battery too quickly, more disks can be put into place in order to reduce the demand the motor places on the battery.

Cleaning Mechanism

Currently there are a plethora of brush variations that are being considered for the final prototype. In order to determine the brush type that will used in the final prototype an experiment will need to be performed in order to test the effect of bristle density on the effectiveness of the system. The following procedure will be used in order to accurately assess the performance of the brushes:

1. The testing canvas will be clearly identified into sections.
2. A specified mass of wet debris will be selected and randomly distributed atop the storm grate while the brushes are in the rest position
    a. The rest position is the when the brush is located at either end of the grate slot and it is under no rotational momentum.
3. The brush will be prepped and reach a speed of 100 RPM.
4. The system will engage and translate around the track 3 full times.
5. Once the brush returns to rest position the amount of debris will be separated into three categories:
    a. Grate Mass
    b. Street Mass
    c. Drain Mass
6. An effectivity rating will be determined based upon the relationship of starting mass and street mass.

Using an ANOVA test and hypothesis tests the group will be able to analyze the brushes and determine if there is a statistical difference between the brush results. As long as there is a statistical difference between the initial prototype and the final prototype, there will be confirmation that the use of reinforced nylon bristles was a better choice compared to the toilet brush bristles. The group is expecting to realize effectiveness north of 80%. In the first prototype, the effectiveness reached a peak of 45%; with a prototype that is well developed it is expected the effectiveness will be double what it was in preliminary stages of conceptual design.

Mounting System

After the mounting system is assembled, the most important testing that it will undergo will be compressive and tensile strength testing. If the mounting bracket of the product fails, the whole system will be useless to the general public. As aforementioned, the elastic modulus should not fall below 120 GPa. The sturdy material will be needed to support the frame of the prototype but to assure that the prototype does not give away under extreme conditions. Statistical test methods will not be necessary, but testing in varying temperatures and weather conditions will be imperative to ensure the mounting bracket will remain sturdy through an elongated period of time.

Final Prototype Testing

At the beginning of the testing phase there was one goal set for the final prototype. The final prototype was to be more efficient than first prototype. Because the first prototype was not developed the efficiency rating, at its peak, was at 45 percent (shown in *Figure 8-3*). Knowing that the design would be more complete and the machining would be more perfected, it was believed that the efficiency rating would at least double, so the target efficiency rating was placed just north of 80 percent. Using a very similar testing procedure as before, we set to prove that, at a bare minimum, the final prototype was more efficient than the first prototype. Ultimately by proving that our prototype was becoming more efficient in clearing debris off the storm grate we could believe that there was a defined application in the real-world for a grate cleaner.

First Prototype Raw Data

Trial Number	Initial Mass of Leaves (g)	Mass Left On Grate (g)	Mass Cleared from Grate (g)
1	40	22	18
2	40	24	16
3	40	26	14
4	40	24	16
5	50	34	16
6	50	35	15
7	50	28	22
8	50	30	20
9	50	42	8

Trial Number	**Effectiveness**
1	45%
2	40%
3	35%
4	40%
5	32%
6	30%
7	44%
8	40%
9	16%

Figure 8-3 First Prototype Raw Data

Final Prototype Testing Procedure

The testing procedure for the final prototype mimicked the procedure for the initial prototype. However, given the cleaning system was driven by high torque, low RPM motors the purpose of the testing was not to find which speed was the most efficient. So instead, the final prototype was tested to discover its peak efficiency, its average efficiency, and its ability to repeat test results. These were significant because the most critical Engineering Characteristic, according to the House of Quality, was reliability by a significant margin.

The following procedure was used in order to accurately assess the performance of the brushes:

1. The testing canvas will be clearly identified into sections.
2. 54 grams of debris (dry leaves) will be selected and randomly distributed atop the storm grate while the brushes are in the rest position
   a. The rest position is the when the brush is located at either end of the grate slot and it is under no rotational momentum.
3. The system will engage and translate back and forth on the track 3 full times.
4. Once the brush returns to rest position the amount of debris will be separated into two categories:
   a. Mass removed from the grate
   b. Mass remaining atop the grate
5. An effectivity rating will be determined based upon the relationship of starting mass and street mass.

Prototype Data & Analysis

Trial Number	Efficiency	Trial Number	Efficiency
1	67%	11	76%
2	50%	12	61%
3	63%	13	63%
4	50%	14	69%
5	56%	15	85%
6	56%	16	46%
7	67%	17	59%
8	80%	18	74%
9	85%	19	65%
10	72%	20	83%

Table 8-3 Efficiency Data of Final Prototype

Through 20 trials, the results were promising. In all but one trial, the efficiency was equal to or greater than 50%. This was very promising because it shows that in an overwhelming majority of cases the concept will be able to clean a substantial amount of debris off the top of the grate. This speaks to the reliability of the product; it shows that the product can continuously clear debris from atop the grate in order to maximize the flowrate. Sporting an average efficiency of 66 percent, this prototype has vastly surpassed the effectiveness of the first prototype. Although it did not meet the goal of an average efficiency of 80 percent, but with such a large standard deviation (11 percent) it is possible to reach the goal efficiency. Using a hypothesis test, we can confirm that the efficiency of the final prototype is more than 150% greater than the efficiency of the first prototype.

- The null hypothesis would be that the efficiency of the final prototype is at least 75% ($H_0: \mu = 75\%$).
- The alternative hypothesis would be that the efficiency of the final prototype is less than 75% ($H_A: \mu < 75\%$).

Using calculated data, we will be able to calculate the t-statistic.

$$\bar{x} = 66\%$$
$$\mu = 75\%$$
$$s = 11\%$$
$$n = 20$$
$$df = n-1 = 19$$
$$\alpha = 0.05$$

$$t^* = \left| \frac{\bar{x}-\mu}{s/\sqrt{n}} \right| = \left| \frac{66-75}{11/\sqrt{20}} \right| = 3.659$$

Given the t-statistic chart in *Figure 8-4* we can determine the p-value for the hypothesis test.

16	0.000	0.690	0.865	1.071	1.337	1.746	2.120	2.583	2.921	3.686	4.015
17	0.000	0.689	0.863	1.069	1.333	1.740	2.110	2.567	2.898	3.646	3.965
18	0.000	0.688	0.862	1.067	1.330	1.734	2.101	2.552	2.878	3.610	3.922
19	0.000	0.688	0.861	1.066	1.328	1.729	2.093	2.539	2.861	3.579	3.883
20	0.000	0.687	0.860	1.064	1.325	1.725	2.086	2.528	2.845	3.552	3.850
21	0.000	0.686	0.859	1.063	1.323	1.721	2.080	2.518	2.831	3.527	3.819
22	0.000	0.686	0.858	1.061	1.321	1.717	2.074	2.508	2.819	3.505	3.792
23	0.000	0.685	0.858	1.060	1.319	1.714	2.069	2.500	2.807	3.485	3.768
24	0.000	0.685	0.857	1.059	1.318	1.711	2.064	2.492	2.797	3.467	3.745
25	0.000	0.684	0.856	1.058	1.316	1.708	2.060	2.485	2.787	3.450	3.725
26	0.000	0.684	0.856	1.058	1.315	1.706	2.056	2.479	2.779	3.435	3.707
27	0.000	0.684	0.855	1.057	1.314	1.703	2.052	2.473	2.771	3.421	3.690
28	0.000	0.683	0.855	1.056	1.313	1.701	2.048	2.467	2.763	3.408	3.674
29	0.000	0.683	0.854	1.055	1.311	1.699	2.045	2.462	2.756	3.396	3.659
30	0.000	0.683	0.854	1.055	1.310	1.697	2.042	2.457	2.750	3.385	3.646
40	0.000	0.681	0.851	1.050	1.303	1.684	2.021	2.423	2.704	3.307	3.551
60	0.000	0.679	0.848	1.045	1.296	1.671	2.000	2.390	2.660	3.232	3.460
80	0.000	0.678	0.846	1.043	1.292	1.664	1.990	2.374	2.639	3.195	3.416
100	0.000	0.677	0.845	1.042	1.290	1.660	1.984	2.364	2.626	3.174	3.390
1000	0.000	0.675	0.842	1.037	1.282	1.646	1.962	2.330	2.581	3.098	3.300
z	0.000	0.674	0.842	1.036	1.282	1.645	1.960	2.326	2.576	3.090	3.291
	0%	50%	60%	70%	80%	90%	95%	98%	99%	99.8%	99.9%
	Confidence Level										

Figure 8-4 First Prototype Raw Data

Using linear approximation, we can determine the p-value for the t-statistic.

$$\frac{3.850 - 3.552}{99.9 - 99.8} = \frac{3.659 - 3.552}{q - 99.8}$$

$$q = 99.804$$

With 19 Degrees of Freedom our t-value exceeds a 99.8% confidence level. The p-value associated with this would be 0.00196. Since the p-value is much smaller than the confidence value, the null hypothesis has to be rejected in favor of the alternative hypothesis. This means that the efficiency of the final prototype is not equal to 75% and it is indeed less.

The results of this statistical testing show that the prototype officially failed to meet our goal. In order to achieve the goal that we had sought after in the initial stages of the preliminary design we will have to refine an aspect of the design. Through refining the fabrication methods of the prototype and making the brush material more sturdy we were able to increase the efficiency of the final prototype by 150%. So, future testing with different materials might show an increase in efficiency with a much more rigid material.

Human Factors Considerations

Human interaction with this product will be kept to a minimum because all of the mechanisms will be hidden underground. It is expected that the product will have to be friendly with pedestrians, bike riders, and automobiles. This is the main reason the product will be installed below street level. In order to ensure that the product is not intrusive to everyday life, it will be oriented in a way that the brushes are extruded enough to clear debris from atop the grate but no further. In order to assure the height of the brushes is not a hindrance, the group can seek the outside opinion of peers. Additionally, the goal is to keep the components of the prototype as simple and light weight as possible. Since the prototype will utilize electrical energy instead of water energy it would require more frequent service appointments. Being lightweight will make installation easier as well as the service appointments. In the case the prototype needs to be removed from the grate the lightweight materials will make it easier for the workers to readjust, dismantle, or swap parts.

9 Product Design Specification

<table>
<tr>
<td>
Product Identification:

Mechanical system that periodically clears storm drain grate surface of debris to allow rainwater to drain effectively to prevent street flooding.
Fits inside of any standard storm drain reservoir and does not require drain grate to be changed or customized.
Will require professional installation by contractor or appropriate county/state personnel.
Will require scheduled maintenance to assure all subgroups are performing as intended.

Special Features:

Adjustable pulley position

Key Performance Targets:

Allow little to no debris through the drain grate.
Retrofittable to standard storm drains
Generate kinetic energy through the use of a pulley/belt system and a motor.

User Training Required:

Installation manual
Service manual

Service Environment:

Temperature range: 25°F-130°F
Operating with surrounding turbulent water flow.
Corrosive environment towards most metallic materials
Will encounter vibration and impact forces from passing vehicles and bicycles

</td>
<td>
Market Identification:

The target market for this product will be for any city council/municipality that has urban areas that encounter streets that flood due to storm drains becoming blocked.
Demand: Within the municipality market, the need for storm water management systems in the United States is expected to exceed $105 billion over the next 20 years (Water Environment Foundation).
Initial launch: Design Day- University of Maryland, College Park.
Initial production run: 1 prototype
Competing Products:

Current products only focus on filtering debris out of water that passes drain grate.
No products on the market involve clearing debris from the drain grate to ensure drain flow.

</td>
</tr>
<tr>
<td>
Key Project Deadlines:

Prototype Due Date: Design Day, 12/6/2016

</td>
<td>
Physical Description:
Dimensions:
</td>
</tr>
</table>

<table>
<tr>
<td>

Final Report Due: 12/8/2016
Digital Poster Due: 12/9/2016

</td>
<td>

To be able to be integrated into an existing storm drain with no changes, the dimensions of the design needed to be constrained the drain system.
Refer to engineering drawings (Appendix G) for specific dimensions of prototype design.

Material:

Grate: Cast Iron (Standard)
Custom components:

Pulley Frame: Steel
Brush Shafts: Steel coated in Plasti-Dip
Motor Mount Bracket: Steel
Mount Bracket Supports: Steel
Pulley Wheel: Thermoplastic Elastomer
Timing Belt: Plastic

Maximum Weight Target:

Approximately 70 kg
Needs to be light enough to lift for installation and removal for maintenance.

</td>
</tr>
<tr>
<td>
Financial Requirements:

Product must be affordable enough to where it can be implemented on large quantity scale for city councils who agree to invest.
Cost of Product: Approximately $130.00

First prototype cost approximately $27.

Capital Investment Required: Startup fund preferably government grant.

</td>
<td>
Life Cycle Target:

Life Cycle Expectancy: 20 Years
Maintenance: Expect maintenance inspections every 3-4 months to ensure full functionality.
End-of-Life strategy: Repair if customer requests. If not, company will remove and recycle and/or refurbish parts.

</td>
</tr>
<tr>
<td>
Social, Political, and Legal Requirements:

All safety and environmental regulations will be met.
Standards: Research all storm drain regulations in regards to public roads safety and EPA regulations.

</td>
<td>
Manufacturing Specifications:

All initial non-standard functional and support structures will be made in house.
Molds can be made after from these parts for large production runs.

</td>
</tr>
</table>

• Our product cannot contaminate the rainwater supply so material selection must be checked for restrictions. • Any moving parts cannot obstruct roadways or interfere with passing vehicles, cyclists, pedestrians, etc. • Patent Potential: Yes. While there are patents the cover individual components, there is no assembly on the market that has a functionality like the Sweeping Bristle Roller.	• Suppliers for standard components of design: lowest price opportunity

10 Social, Economic, and Environmental Considerations

The desired effect of this product is a positive one; its goal is to remain affordable so that cities can implement it for everyone's benefit. To make sure that it is truly benefitting communities on a local and global scale, an analysis of its production, use, and disposal is necessary. From the materials chosen to the manufacturing processes, the team made design decisions would minimize negative social and environmental impact. A main concern was the use of lead-acid batteries, but the rewards of using batteries outweighed other design options.

Excluding the battery, a majority of the product is composed of a welded steel frame that weighs approximately 5kgs. According to Carbon Footprint, the carbon footprint of a general steel bar is about 2.77 kg of CO2 per kg of material; this puts the total footprint at 13.85 kg of CO2. By using recycled steel instead of virgin, we can reduce the footprint to 1.86 kg CO2 per kg of steel; the new total footprint is 9.3 kg CO2. The next significant material is nylon, of which the pulleys and brushes are made; the weight of these components is relatively light at about .5 kg. The carbon footprint of nylon itself depends on whether you choose nylon 6 or 6,6; both have nearly identical properties, but nylon 6,6 has a better carbon footprint. According to Carbon Footprint, the production of nylon 6,6 creates 7.92 kg CO2 per kg of nylon; this puts the nylon carbon footprint at 3.96 kg of CO2. Most of the product (again, excluding the battery) has a carbon footprint of 13. 96 kg CO2 per product.

The two main fabrication techniques used in manufacturing this product are plastic injection molding and TIG welding. Polyamide (nylon) injection molding has a carbon footprint of approximately 7.75 kg CO2 per kg of nylon (Krauss). At .5 kg of nylon, the footprint is 3.875 kg CO2. Welding is another manufacturing process that not only contributes to air pollution, but can also be hazardous to those welding. Ozone, nitrous, carbon monoxide, phosphine, and phosgene gases are released during welding depending on the type of welding and other parameters; these particles are released from different metals as they are heated up and create fumes (Golbabaei and Khadem). It is often optimal to weld in areas with low air circulation so that the shielding glass is not blown away from the weld; this can result in weld fumes building up around a person. Shielding gases such as carbon dioxide and argon are also dangerous in large quantities. TIG welding releases a lower amount of fumes compared to other types of welding, making it a reliable and safe method for constructing our product.

The most important part of our design to consider was the battery; the team selected a lead-acid deep cycle battery because it is designed to deeply discharge over long periods of time and can be recharged. The carbon emission per kg of lead acid battery is 1.14 kg CO2 (Torell); the battery used for this product weighs 40 lbs (18.14 kg). The battery's carbon footprint is 20.7 kg CO2.

A rechargeable battery produces less waste because a battery does not need to be thrown out and replaced each time it fully discharges. After several years, the batteries will need to be replaced because they will no longer hold charge well (Torell). A major concern with disposing of lead-acid batteries is the fact that lead and sulfuric acid are dangerous substances, but 98% of lead in these batteries is highly recyclable; the batteries will likely be recycled after use rather than left in a dump. Another concern about the batteries is that they will be placed in a storm drain near flowing water. If the battery were to break, bust open, etc, and the water is funnelled into a natural habitat, it could be extremely dangerous for wildlife. As a result, the team needs to consider design options for keeping the battery secure and above the water. There is some extra maintenance associated with making sure the battery is not corroded.

The other options for powering the product relied on water power or using electricity off the grid. Water power coming from the rainwater flowing into the drain or the water already flowing through the drain would have been a completely clean option, in the sense that it would not produce atmospheric pollution. This option was not favored, though, because the flow of water is extremely unreliable. The next option, using power from the electric grid, was deemed extremely reliable but too labor intensive. Each drain grate that used our product would need power lines brought to it. As a result, a battery was chosen because it would require minimal maintenance and still supply a reliable power source for a temporary amount of time.

11 Concluding Statements

Although ideation is usually not an easy task, the flow of the process was helpful in organizing the thought progression. Upon entering the class, the need for a project topic was immediate. By coming together as a group and brainstorming, it was possible to come up with a list of issues that had been experienced in everyday life. Some of the ideas were constraining, while others seemed to come with room for expansion. By following the first couple of steps of the Product Development Process, the group was able to solidify a project idea, and begin conducting research on what was necessary for the project to succeed. By using development techniques, ideas were able to evolve into concepts with the help of CRs and ECs. Decision Matrices such as the House of Quality, Pugh Chart, and AHP were used in order to focus the thought process and realign the concepts in order to get ready to move onto the next stage.

Through these processes, we narrowed down our concepts to one that will balance reliability, flow rate, and debris allowance. The subsystem prototype was difficult to use, but the testing conducted using it provided valuable information. The RPM testing helped us choose appropriate motor specs, a power supply, and a belt system that unifies translational and rotational brush movement. Our next challenge was to design a setup that will allow the prototype to operate in conditions as realistic as possible; this is necessary to perform testing and receive accurate results. We have selected drain grate dimensions that are representative of the average grate; this will help us achieve valid test results.

Another concern was that our belt system, motors, or batteries may not operate as we planned. We needed to be prepared for this potential outcome and keep an open mind about our design decisions. For example, if the belt system does not catch, we may need to change the belt to a different material, add a texture, or eliminate the belt entirely. If the belts do not stay on their tracks, and adding track bearings in order to keep the belt from walking off the pulley systems.

Currently, at the end of the semester, the prototype is nowhere near ready for commercialization. The amount of time and effort we put into fabricating the process has not gone for naught but it has showed us the flaws in our design. While we were able to achieve one of the most important aspects of the project, retrofitability, it has come at the cost of efficiency. Additionally, given the monetary constraints that were implemented on the class we were unable to obtain the battery that was ideal for our design. Instead we used a car battery that was hooked up to our motors using standard gauge wire. Further prototyping is necessary in order to ensure that all aspects of the concept are functioning the way they are intended in order to move on the commercialization stage. The strengths of our prototype come in the cleaning mechanism. While the brushes were custom-made they seem to function exactly the way they were envisioned to. For commercialization, sturdier brushes would be made; the core of the brushes would ideally be metal compared to wood. Honestly, there will need to be around half a dozen more prototyping and testing phases before the group feels comfortable with doing an initial commercial design.

If we were able to go back and do this project from the beginning, there would be a couple things that would be different. First of all, hopefully there would be much more time to plan out the fabrication of the final prototype. Given the schedule, there were about 2 weeks allotted to fabrication which was not enough time to order the parts, receive them, and machine them to fit the design of the prototype. Additionally, there was no consideration for the amount of time it would take to get all the machining done. Given the inexperience of the group with machining, some of the time was spent fixing the mistakes that were made instead of moving forward in the design which delayed portions of the machining work that had to be done. Finally, the amount of mechanical parts that we used seemed to overwhelm us in the end. We had to check all the mechanical portions of the prototype multiple times in order to make sure they fit into the frame and worked as they were intended. Overall the design process was a major help throughout this project, but the length of the process is a detriment. Being such a thorough process means it is necessary to invest time in order to make sure each of the steps are thoroughly reflected upon. Given the length of the semester it really is not possible to thoroughly implement the entire process.

Appendix

A Works Cited

Ben-Joseph, Eran. "Residential Street Standards & Neighborhood Traffic Control: A Survey Of Cities' Practices And Public Officials' Attitudes". http://nacto.org/docs/usdg/residential_street_standards_benjoseph.pdf. Web. 10 Nov. 2016.

"Carbon Footprint Ltd - Emissions Factors For Carbon Life Cycle Assessments". *Carbonfootprint.com*. N.p., 2016. Web. 7 Dec. 2016. <http://www.carbonfootprint.com/factors.aspx>

Graphiq Inc.,. "Maryland Average Rainfall - Average And Year To Date Data". N.p., 2016, *https://rainfall.weatherdb.com/d/d/Maryland.*. Web. 10 Nov. 2016.

Golbabaei, Farideh and Monireh Khadem. "Air Pollution In Welding Processes — Assessment And Control Methods". *Current Air Quality Issues*. 1st ed. 2016. Web. 8 Dec. 2016. <http://www.intechopen.com/books/howtoreference/current-air-quality-issues/air-pollution-in-welding-processes-assessment-and-control-methods>

Hanser Verlag, Carl. "The Carbon Footprint Of An Injection Molding Machine". *Kunststoffe International* 2016: 50. Web. 8 Dec. 2016. <http://www.kraussmaffei.com/media/files/kmdownloadlocal/en/I-PDF_Kraussmaffei_KUint_2015_06-07S_47ff_.pdf>

Highway Maintenance Workers". *Data USA*. N.p., 2016, https://datausa.io/profile/soc/474051/#demographics. Web. 2 Oct. 2016.

"Liberty Mutual Manual Materials Handling Tables". *Libertymmhtables.libertymutual.com*. Web. 2 Oct. 2016.

LMNO Engineering, Research, and Software, Ltd.,. "Rational Equation Calculation, Q=Cia". N.p., 2015, *http://www.lmnoeng.com/Hydrology/rational.php.*. Web. 10 Nov. 2016

Pritchard, Christian. *The day Beacon Way touched the bay*. 2010. *Facebook*. Digital Photograph. 2 Oct. 2016.

"Resources: Flood Facts". *FloodSmart*. N.p., 2016, https://www.floodsmart.gov/floodsmart/pages/flood_facts.jsp. Web. 3 Oct. 2016.

Summary Of Natural Hazard Statistics For 2015 In The United States. 1st ed. National Weather Service, 2016, http://www.nws.noaa.gov/om/hazstats/sum15.pdf. Web. 8 Nov. 2016.

Texas Department of Transportation,. *Hydraulic Design Manual*. Texas Department of Transportation, 2016, http://onlinemanuals.txdot.gov/txdotmanuals/hyd/hyd.pdf. Web. 2 Oct. 2016.

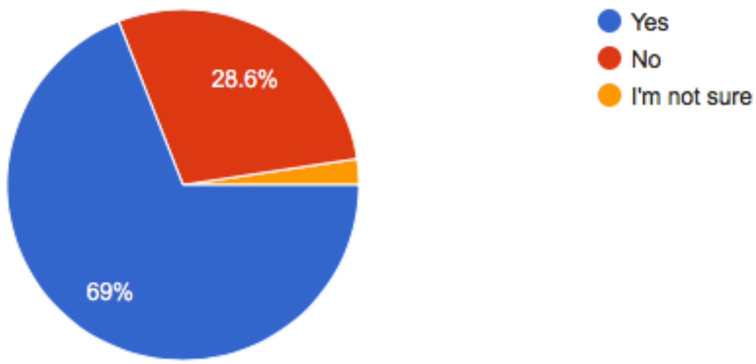
Torell, Wendy. *Lifecycle Carbon Footprint Analysis Of Batteries Vs. Flywheels*. Schneider Electric White Papers, 2016. Web. 8 Dec. 2016. APC. <http://www.apc.com/salestools/VAVR-9KZQVW/VAVR-9KZQVW_R0_EN.pdf>

Urban Storm Drainage Criteria Manual: Volume 1, Chapter 7. Urban Drainage and Flood Control District, 2016, http://udfcd.org/wp-content/uploads/uploads/vol1%20criteria%20manual/07_Streets%20Inlets%20Storm%20Drains.pdf. Web. 3 Nov. 2016.

B Survey Results

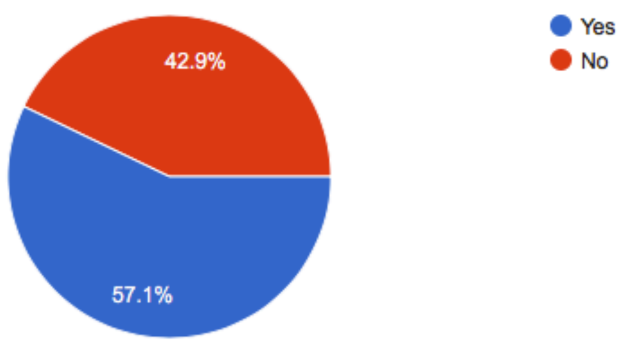
Do you live in an area that has storm drain grates similar to this one?

(42 responses)



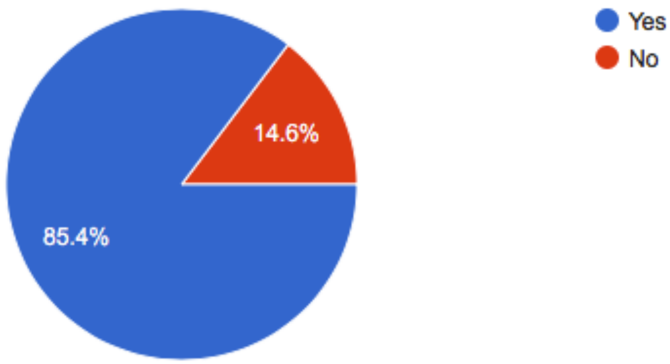
Have you ever been inconvenienced or felt that you were in the way of danger due to flash flooding?

(42 responses)



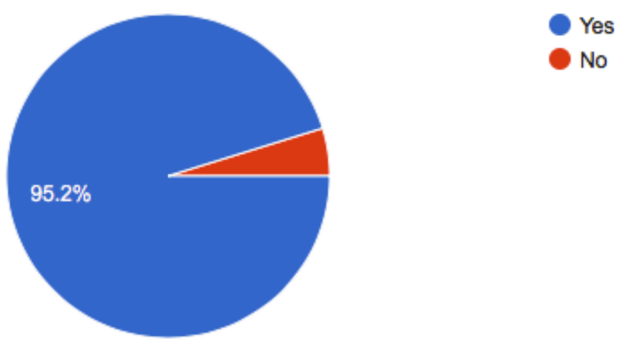
Does debris, such as leaves or trash, accumulate on the street in your neighborhood or on the streets on your commute to work or school?

(41 responses)



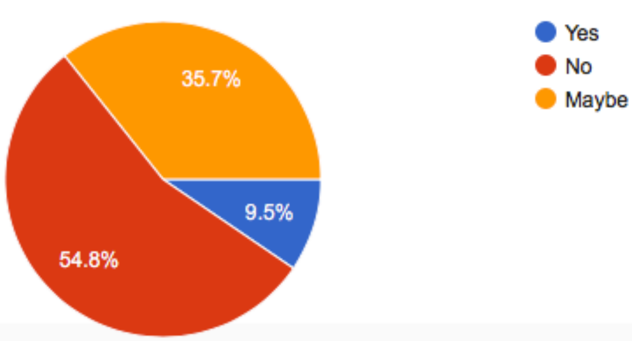
Do you think the presence of debris along the curbside increases the chance of flash flooding?

(42 responses)



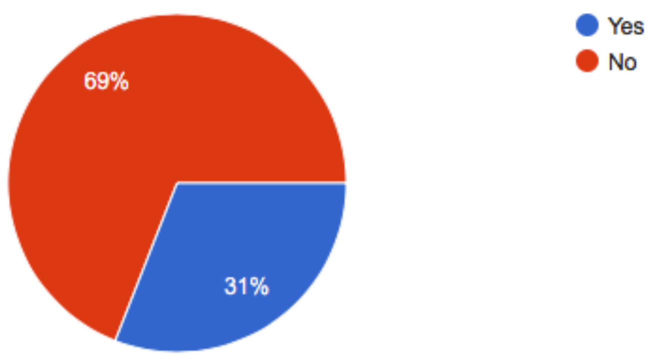
Would you object to your local municipality using tax revenue to purchase a product that automatically clears obstructed grates?

(42 responses)



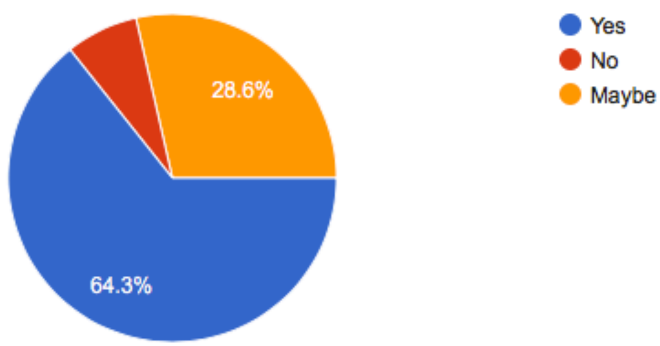
Do you or anyone you know take the time to manually clear out clogged grates?

(42 responses)

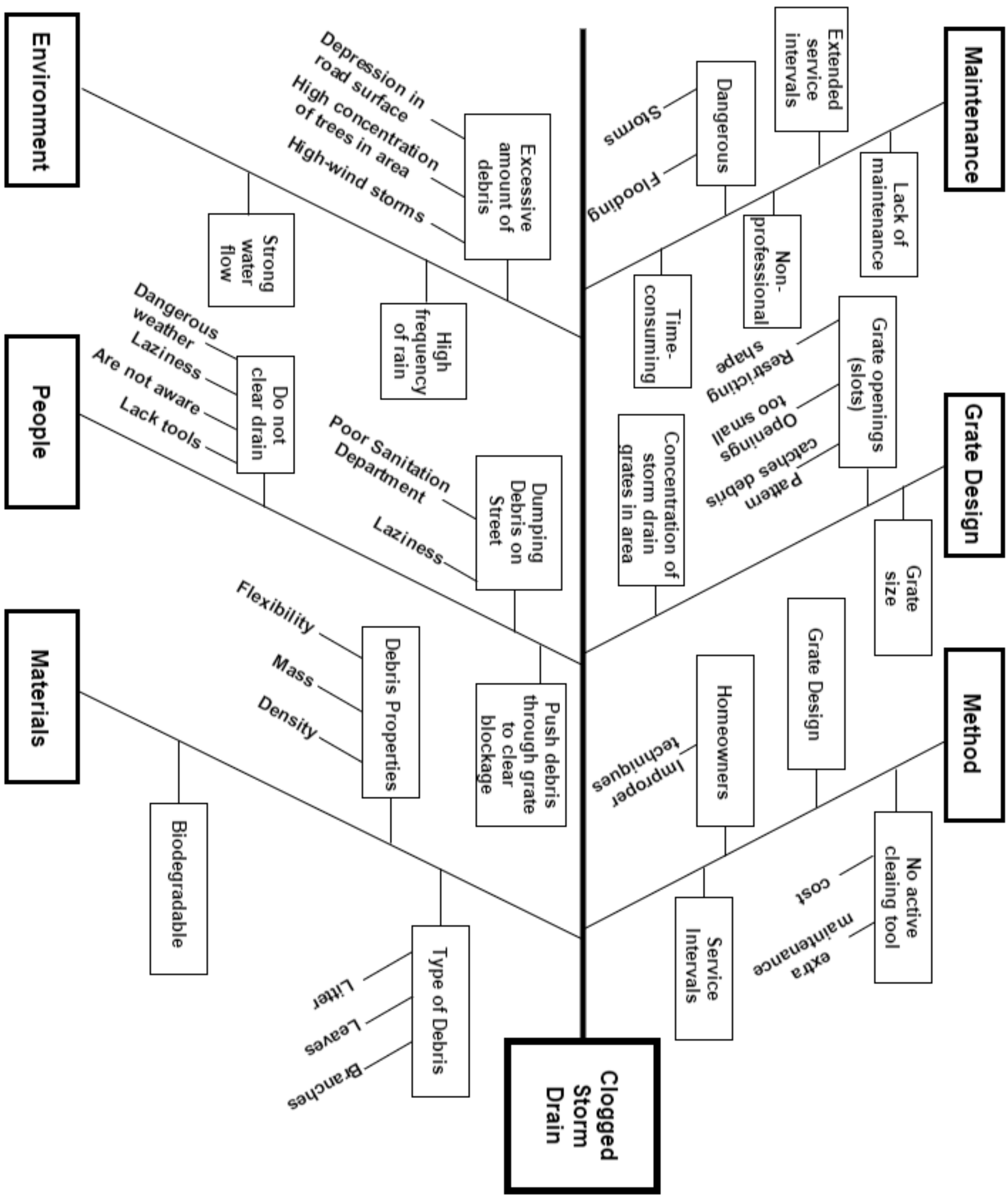


Would you consider curbside debris accumulation a problem in need of a solution?

(42 responses)



C Fishbone Diagram



D Pugh Charts

Pugh Selection Chart for Storm Grate Concepts

Selection Criteria	Description	Human Manual Labor w/ Rake	Concepts 1	2	3	4	5
Water Flowrate	Amount of water that will be able to flow through the grates while cleaning debris from the grate.	D	S	S	S	S	S
Durability	Measure of the strength and resilience of cleaning mechanism parts (springs, human bones/muscles, bolts, etc.)		+	+	+	-	-
Safety	Rating of the danger presented by any piece of the mechanism. Consider humans standing out in hurricanes, sharp objects protruding from grates, harmful substances exposed to the environment.	A	+	+	+	+	+
Debris Allowance	Amount of debris that may slip through the grate during operation.	T	+	+	-	S	-
Energy Dissapation	Measure of how much effort/energy is required of for the mechanism to effectively clean the surface of the grate.	U	+	+	+	+	S
Reliability	Measure of how often the system will be operating without jams, difficulties, or other impairments.		+	-	-	+	-
Intrusiveness	Measure of the ability for cars or pedestrians to travel over the grate while cleaning processes are ongoing without being disturbed or damaged.	M	S	S	+	+	+
# of Pluses			5	4	4	4	2
# of Minues			0	1	2	1	3

Figure 1: Pugh Chart for Storm Grate Concepts

Pugh Selection Chart for Energy Generation Concepts

Selection Criteria	Description	Battery w/ Motor	Concepts 1	2	3	4
Energy Required (Effeciency)	Measure of energy that will need to be built up and used to clean the grate during rainfall.		-	-	-	-
Durability	Measure of the resilience of the power source (lifetime of the springs, water wheel, and catch basin, and the amount of reuses on electrical power source).	D	+	+	-	-
Impact on the Environment	Measure of how the power source can negatively impact the environment. Consider battery acid flowing into marine life, rust of metal spring components, or other effects of water wheels and catch basins.	A	+	+	+	+
Energy Storage Capacity	Measure of the amount of energy that can stored for system usage.	T	-	-	-	-
Service Intervals	Measure of the amount of time that will pass before the power source will need to be changed, maintained, or compensated.		S	S	+	+
Weather Resistance	Measure of weather effects such as rain, ice, snow, or extreme temperatures on the power source system.	U	S	S	+	+
Reliability	Measure of the how often the system will be operating without jams, difficulties, or other impairments.	M	-	-	+	+
Cost	Amount of money and time it would take to implement this solution to storm grates across the country.		+	+	+	-
# of Pluses			3	3	5	4
# of Minuses			3	3	3	4

Figure 2: Pugh Chart for Energy Generation Concepts

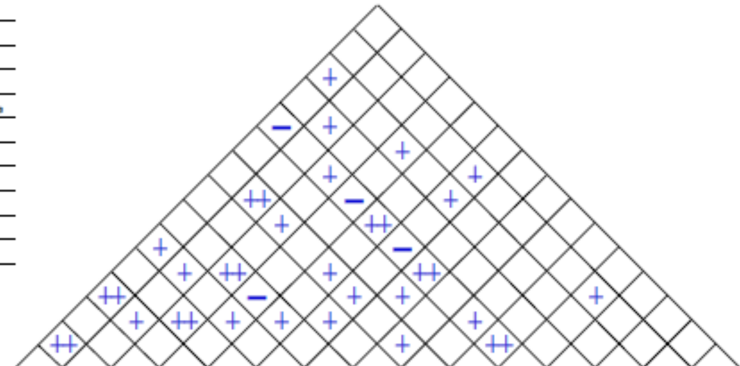
E House of Quality

Title: Storm Drain House of Quality

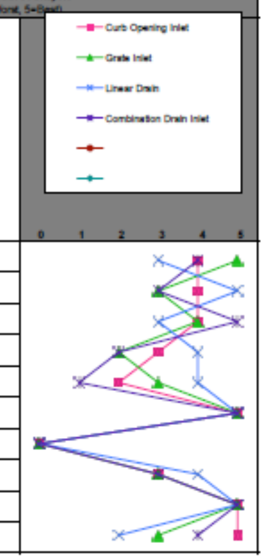
Author: Team 32

Date: 10/1/18

Notes: Target or Limit Values are determined from research based on the average storm drain found on the street. Some of the values will require further research and testing in order to determine the optimal value.



Row #	Max Relationship Value in Row	Relative Weight	Weight / Importance	Demanded Quality (a.k.a. "Customer Requirements" or "Whats") \ Quality Characteristics (a.k.a. "Functional Requirements" or "Hows")	Flow Rate (m^3/s)	Size/Dimensions (m, m^2, m^3)	Material Strength (MPa)	Debris Allowance (cm^3/s)	Material Rigidity (GPa)	Power Consumption (Whr)	Service Intervals (yr)	Noise Level (dB)	Mass (kg)	Liquids and Solids Resistivity (IP Rating)	Reliability (yrs to failure)	Reflectivity (Reflection Coefficient)	Hydrocarbon Tolerance (%)	Operating Temperature (°C)		Curb Opening Inlet	Grate Inlet	Linear Drain	Combination Drain Inlet
				Column #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	Competitive Analysis (0=Worst, 5=Best)			
				Direction of Improvement: Minimize (▼), Maximize (▲), or Target (x)	▲	x	▲	▼	▲	▼	▲	▼	x	▲	▲	x	▲	x					
1	9	14.3	5.0	Durable		O	Θ	▲	Θ	▲	Θ		O	O	Θ			O		4	5	3	4
2	9	11.4	4.0	Safe	O	▲	Θ	O	Θ	▲	O	▲		O	O	O	▲	▲		4	3	5	3
3	9	14.3	5.0	Handle Heavy Rain	Θ		▲	Θ	▲	O	▲	▲		Θ	Θ		▲			4	4	3	5
4	9	5.7	2.0	Discrete Appearance/Hidden	▲	Θ		▲				Θ				Θ				3	2	4	2
5	9	8.6	3.0	Inexpensive		O	O	▲	O	O	Θ		O		O		▲	▲		2	3	4	1
6	9	8.6	3.0	Energy Efficient				O		Θ		O					O	▲		5	5	5	5
7	3	8.6	3.0	Retrofittable		O				▲	▲		▲							0	0	0	0
8	9	5.7	2.0	Environmentally Friendly				O		O		O					Θ			3	3	4	3
9	9	8.6	3.0	Waterproof	O						O			Θ	▲					5	5	5	5
10	9	14.3	5.0	Will not Clog with Debris	Θ			Θ		O	▲				O					5	3	2	4
				Target or Limit Value	0.002 m^3/s	1m x 0.75m x 1.5m	275 MPa	5 cm^3/s	41 GPa	400 Whr	5 yrs	60 dB	70 kg	IP Rating: IP58	20 yrs	Albedo Coefficient 0.10	Hydrocarbons soluble 50%	20°C					
				Difficulty (0=Easy to Accomplish, 10=Extremely Difficult)	8	4	3	8	3	7	7	3	4	3	9	5	6	2					
				Max Relationship Value in Column	9	9	9	9	9	9	9	9	3	9	9	9	9	3					
				Weight / Importance	322.9	157.1	271.4	382.9	271.4	240.0	302.9	120.0	77.1	282.9	388.8	85.7	111.4	71.4					
				Relative Weight	10.6	5.2	8.9	11.9	8.9	7.9	9.9	3.9	2.5	9.3	12.1	2.8	3.7	2.3					



Legend

Θ	Strong Relationship	9
O	Moderate Relationship	3
▲	Weak Relationship	1
++	Strong Positive Correlation	
+	Positive Correlation	
−	Negative Correlation	
▼	Strong Negative Correlation	
▼	Objective Is To Minimize	
▲	Objective Is To Maximize	
x	Objective Is To Hit Target	

Powered by QFD Online (http://www.QFDOnline.com)

F AHP Spreadsheet

Criteria Comparison

	Reliability	Debris Allowance	Flow Rate
Reliability	1.00	0.50	0.33
Debris Allowance	2.00	1.00	0.33
Flow Rate	3.03	3.00	1.00
SUM	6.03	4.50	1.66

Criteria Comparison (Normalized)

	Reliability	Debris Allowance	Flow Rate	Average
Reliability	0.17	0.11	0.20	0.16
Debris Allowance	0.33	0.22	0.20	0.25
Flow Rate	0.50	0.67	0.60	0.59

Reliability	Conveyor w/ Rubber Pushers	Roller Brushes	Slot Pushers
Conveyor w/ Rubber Pushers	1.00	2.00	3.00
Roller Brushes	0.50	1.00	2.00
Slot Pushers	0.33	0.50	1.00
Sum	**1.83**	**3.50**	**6.00**

NORMALIZED

Reliability	Conveyor w/ Rubber Pushers	Roller Brushes	Slot Pushers	*Average*
Conveyor w/ Rubber Pushers	0.55	0.57	0.50	*0.54*
Roller Brushes	0.27	0.29	0.33	*0.30*
Slot Pushers	0.18	0.14	0.17	*0.16*

Debris Allowance	Conveyor w/ Rubber Pushers	Roller Brushes	Slot Pushers
Conveyor w/ Rubber Pushers	1.00	2.00	5.00
Roller Brushes	0.50	1.00	1.00
Slot Pushers	0.20	1.00	1.00
Sum	**1.70**	**4.00**	**7.00**

NORMALIZED

Debris Allowance	Conveyor w/ Rubber Pushers	Roller Brushes	Slot Pushers	*Average*
Conveyor w/ Rubber Pushers	0.59	0.50	0.71	*0.60*
Roller Brushes	0.29	0.25	0.14	*0.23*
Slot Pushers	0.12	0.25	0.14	*0.17*

Flow Rate	Conveyor w/ Rubber Pushers	Roller Brushes	Slot Pushers
Conveyor w/ Rubber Pushers	1.00	0.33	0.33
Roller Brushes	5.00	1.00	1.00
Slot Pushers	3.00	1.00	1.00
Sum	**9.00**	**2.33**	**2.33**

NORMALIZED

Flow Rate	Conveyor w/ Rubber Pushers	Roller Brushes	Slot Pushers	*Average*
Conveyor w/ Rubber Pushers	0.11	0.14	0.14	*0.13*
Roller Brushes	0.56	0.43	0.43	*0.47*
Slot Pushers	0.56	0.43	0.43	*0.47*

	Reliability	*Debris Allowance*	*Flow Rate*
Conveyor w/ Rubber Pushers	*0.54*	*0.60*	*0.13*
Roller Brushes	*0.30*	*0.23*	*0.47*
Slot Pushers	*0.16*	*0.17*	*0.47*

	Aggregated
Conveyor w/ Rubber Pushers	**0.314522751**
Roller Brushes	**0.383438842**
Slot Pushers	**0.347500058**

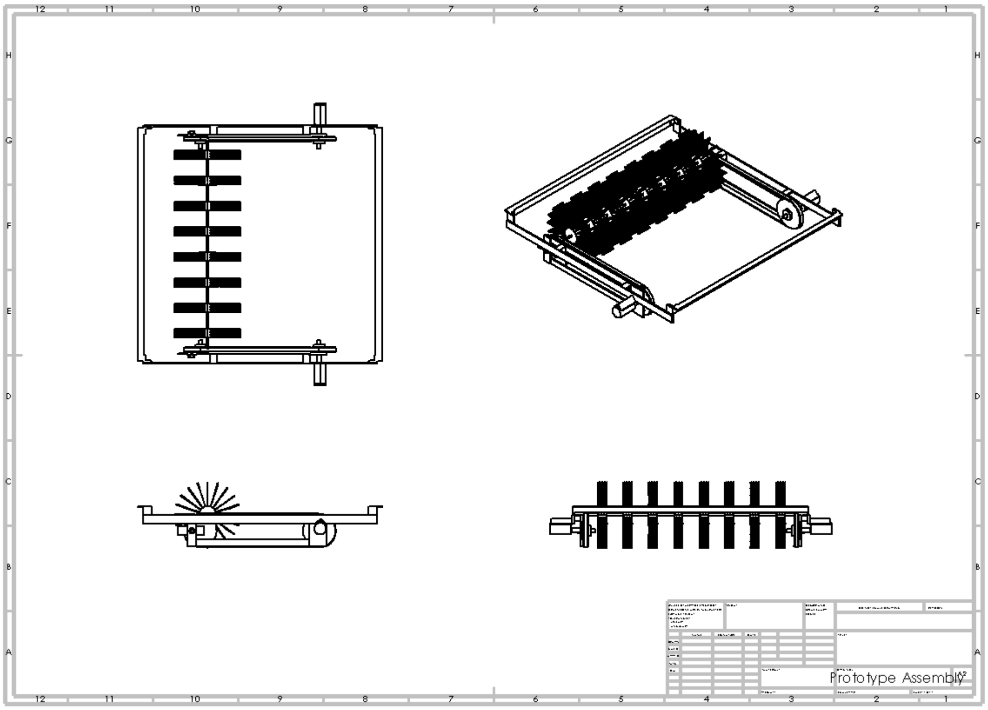
G Bill of Materials

Level	Part Number	Name	Description
0	100-001	Grated Inlet Multi-Brush Cleaning System	
1	110-001	Structural Subsystem	Provides Structual Support and guide for brush rollers
2	110-002	Pulley Frame	Frame to support assembly
3	110-002-002	A-36 Steel Angle	Structural Metal for Frame Construction
3	110-002-003	A-36 Flat Bar	1" Flat bar, (1/8" Thick)
3	110-002-004	3/8" Nut	For belt tension adjust, Welded to Frame
3	110-002-005	3/8" Bolt	For belt tension adjust
3	110-002-006	Welding Materials	Welding Materials
2	110-002	Main Support	Frame to support assembly
3	110-002-002	A-36 Steel Angle	Structural Metal for Frame Construction
3	110-002-003	A-36 Flat Bar	1" Flat bar, (1/8" Thick)
3	110-002-004	Welding Materials	Welding Materials
2	110-003	Adjustable Pulley Axle	Fabricated to adjust belt tension and pulley position
3	110-003-002	A-36 Steel Rod (3/8")	Axle
3	110-003-003	A-36 Flat Bar	1" Flat bar, (1/8" Thick)
1	111-001	Brush and Drive Subsystem	Allows brush to rotate and translate
2	111-002	Timing Belt Pulley (DRIVE), 3.8" Diameter	Bore: 0.375"
2	111-003	Timing Belt Pulley (IDLER), 3.8" Diameter	Freely rotating pulleys opposite of driving pulleys w/ built in bearings
2	111-004	Timing Belt	Belt for driving rollers with grooves to ensure smooth translation/rotation
2	111-005	Nylon Wheel Brush, 7" Diameter, <1.5" Width	For moving debris
3	111-005-001	Solid Cylinder	Drill Holes to Hold Bristles - Wooden Railing Rod ~2" Diameter
3	111-005-002	Broom Bristles (NYLON)	Nylon Bristles - From Hand brush/broom
3	111-005-003	Glue	Attach Bristles to Cylinder
2	111-006	Driving Shaft (0.375")	Shaft between motor and driving pulleys, 2.18" Long, 3/8" Diameter
2	111-007	Brush Shaft	Shaft that guides 8 brushes, Cut to length
3	111-007-02	Steel Rod, 3/4" Diameter, 24.5" Long	Shaft that guides 8 brushes, Cut to length
3	111-007-04	Rubberized Undercoat	Dipped on ends of rod for grip
2	111-008	Driver Shaft Adapter, 0.5" Diameter	Spacer bored to provide connection b/w motor shaft and drive shaft, 1" long
1	113-001	Electrical/Control Subsystem	Detects presence of water and powers machine
2	113-002	12V Battery, Deep Cycle	Rechargable Battery for long term power
2	113-005	12V DC 30rpm High Torque Gearbox Motor	Converts electrical power to mechaincal work
2	113-006	Dual motor PWM Controller	Provides speed control for motors
2	113-007	Microcontroller	Communicates with humidity sensor to activate cleaning
2	113-007-001	Wiring	
3	113-007-002	Red Wire (18 Gauge)	Positive Connections, Max load
3	113-007-003	Black Wire (18 Gauge)	Negative Connections
3	113-007-005	Solder	Wire connections
3	113-007-006	Switch	On/Off Control
3	113-007-007	Zip Ties	Wire Management

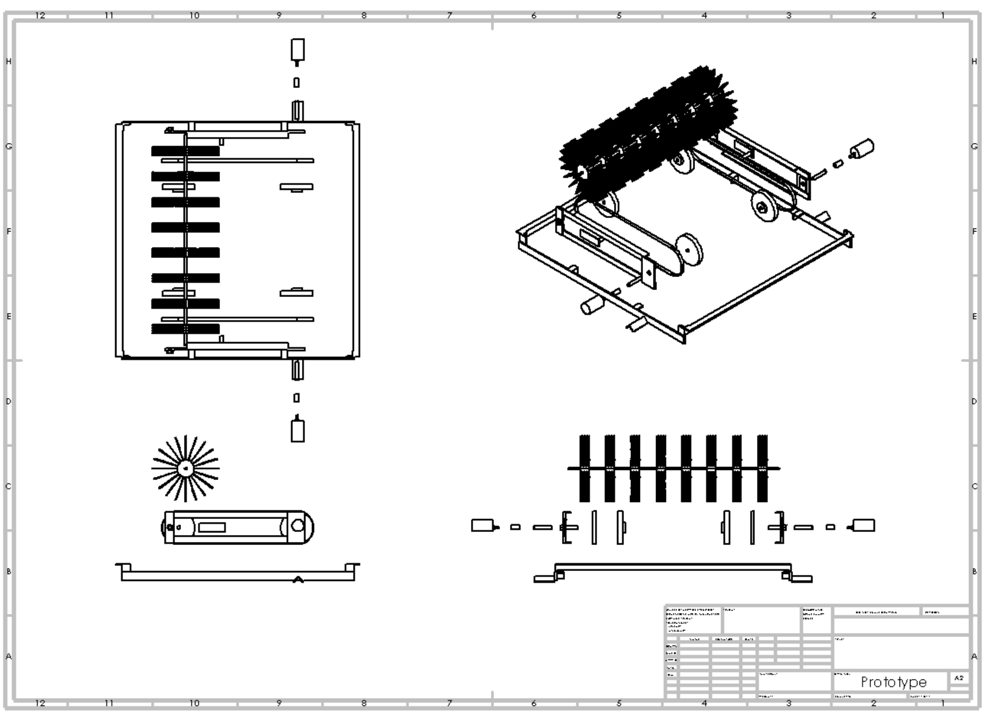
Level	Part Number	QTY	Unit	Group	Manufacturer
0	100-001	1	EA	Assy	Team 32
1	110-001			Assy	
2	110-002	2	EA	Sub.Assy.	Team 32
3	110-002-002	As Required	Feet	Mat	Everbilt
3	110-002-003	As Required	Feet	Mat	Everbilt
3	110-002-004	2	EA	Mat	Everbilt
3	110-002-005	2	EA	Mat	Everbilt
3	110-002-006	As Required	Feet	Mat	Everbilt
2	110-002	1	EA	Sub.Assy.	Team 32
3	110-002-002	As Required	Feet	Mat	Everbilt
3	110-002-003	As Required	Feet	Mat	Everbilt
3	110-002-004	As Required	Feet	Mat	N/A
2	110-003	2	EA	Sub. Assy	Team 32
3	110-003-002	2	inches	Mat	Everbilt
3	110-003-003	2	inches	Mat	Everbilt
1	111-001			Assy	
2	111-002	2	EA	Part	SDP SI
2	111-003	2	EA	Part	SDP SI
2	111-004	2	EA	Part	SDP SI
2	111-005	8	EA	SubAssy	Team 32
3	111-005-001	8	EA	Mat	Team 32
3	111-005-002	As Required		Mat	Team 32
3	111-005-003	As Required		Mat	Team 32
2	111-006	2	EA	Part	Team 32
2	111-007	2	EA	Part	Team 32
3	111-007-02	2	EA	Mat	Everbilt
3	111-007-04	As Required		Mat	Plasti-Dip
2	111-008	2		Part	Team 32
1	113-001			Assy	
2	113-002	1	EA	Part	Interstate
2	113-005	2	EA	Part	uxcell
2	113-006	1	EA	Part	Arduino
2	113-007	1	EA	Part	Arduino
2	113-007-001			Sub.Assy.	Team 32
3	113-007-002	8	Feet	Part	Southwire
3	113-007-003	8	Feet	Part	Southwire
3	113-007-005	As Required		Part	N/A
3	113-007-006	1	EA	Part	Team 32
3	113-007-007	1	PK	Part	Commercial Electric

H Part Drawings

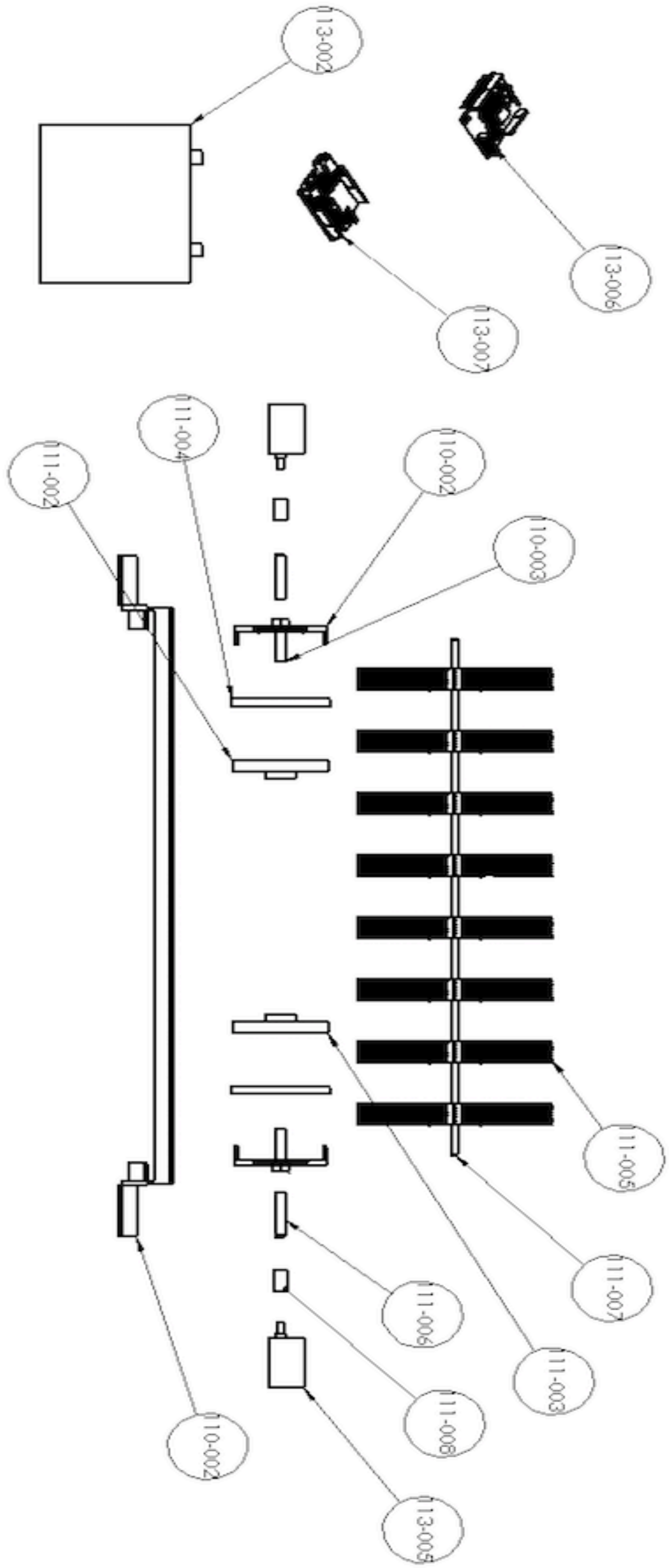
Standard Assembly View



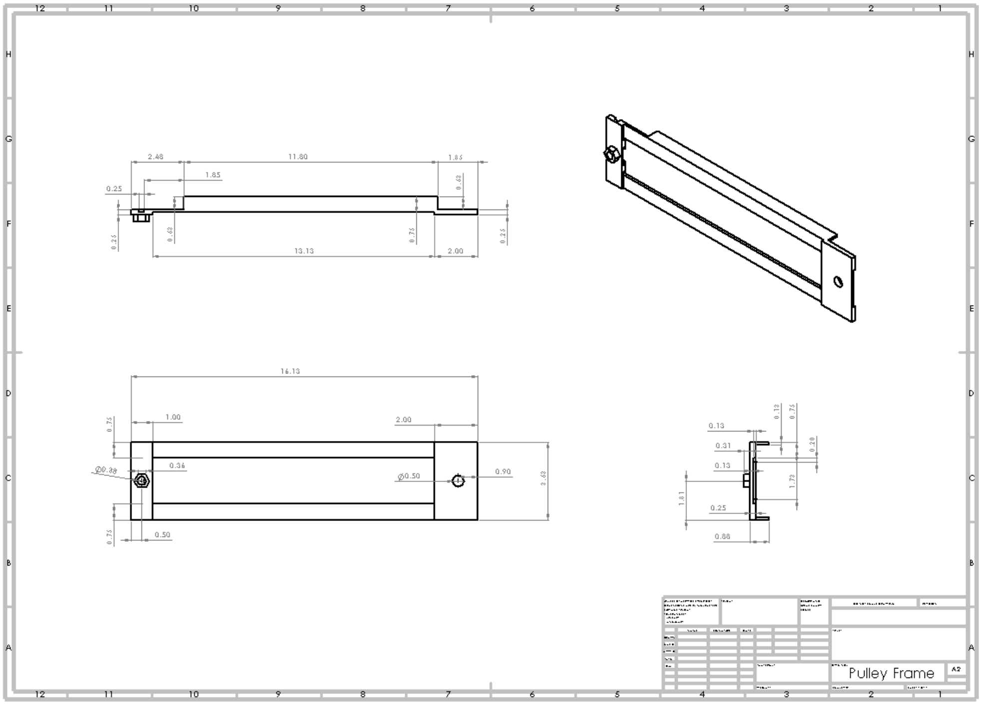
Exploded Assembly View



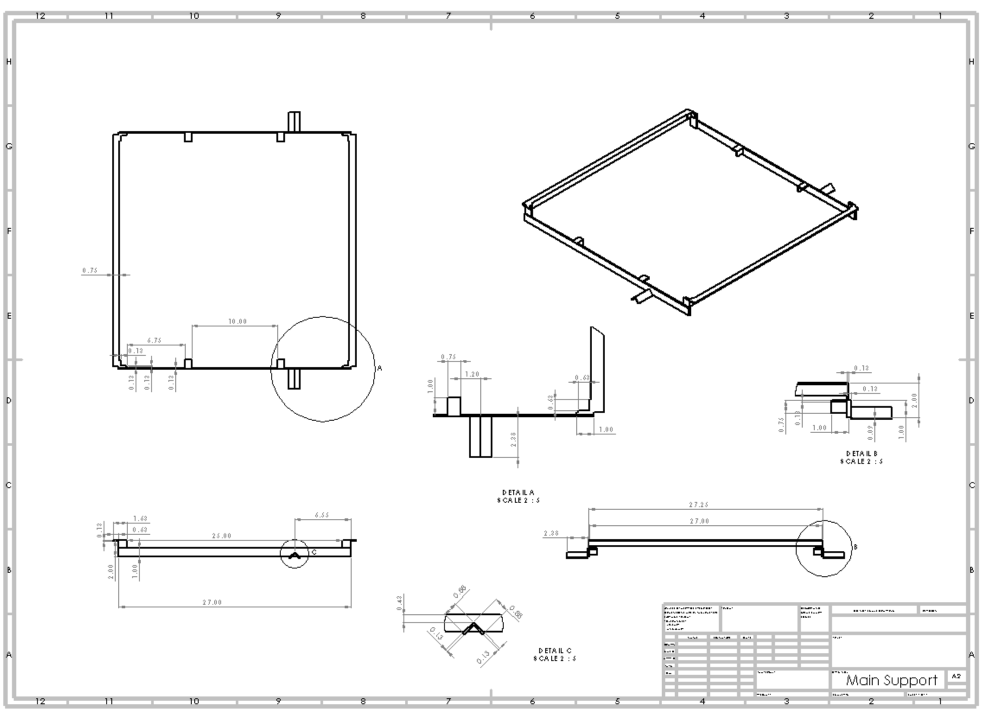
Exploded Assembly View with BOM Part Numbers



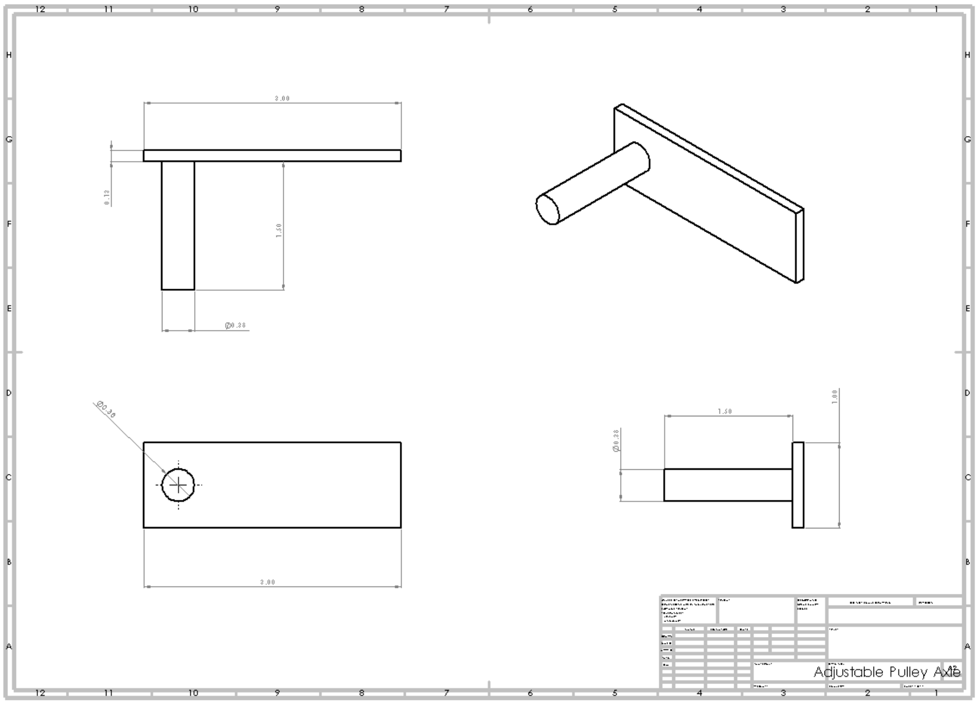
Name: Pulley Frame
Part Number: 110-002



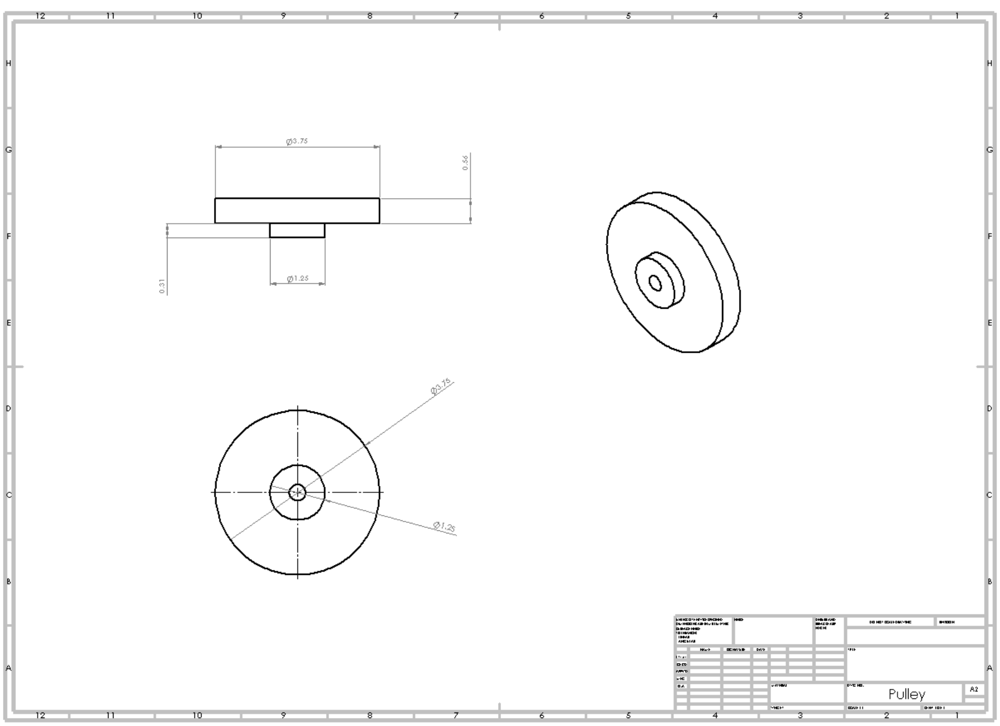
Name: Main Support
Part Number: 110-003



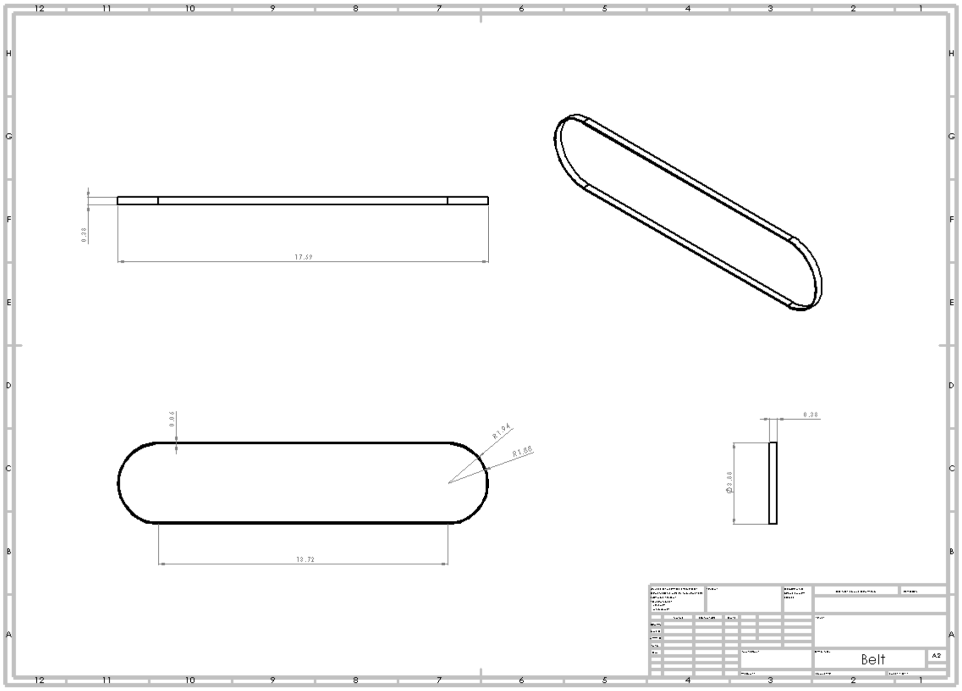
Name: Adjustable Pulley Axle
Part Number: 110-004



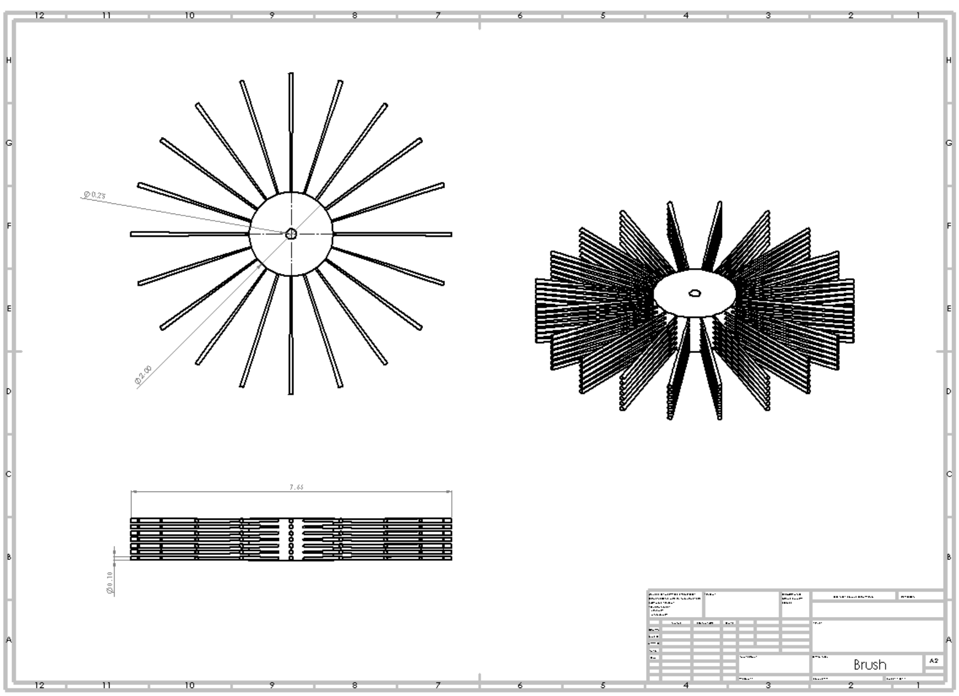
Name: Pulley
Part Number: 111-002 and 111-003



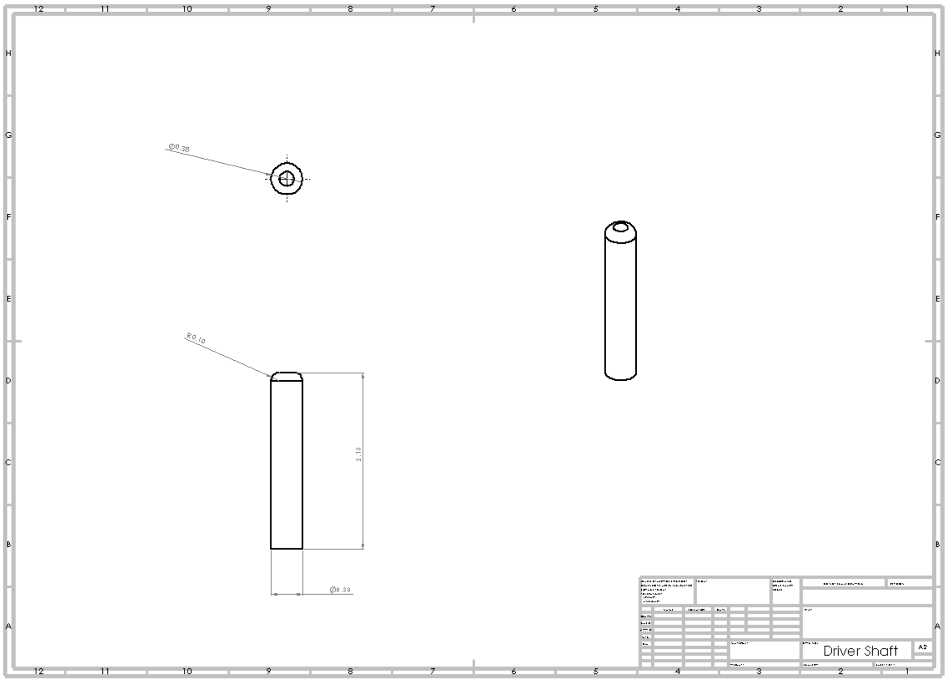
Name: Belt
Part Number: 111-004



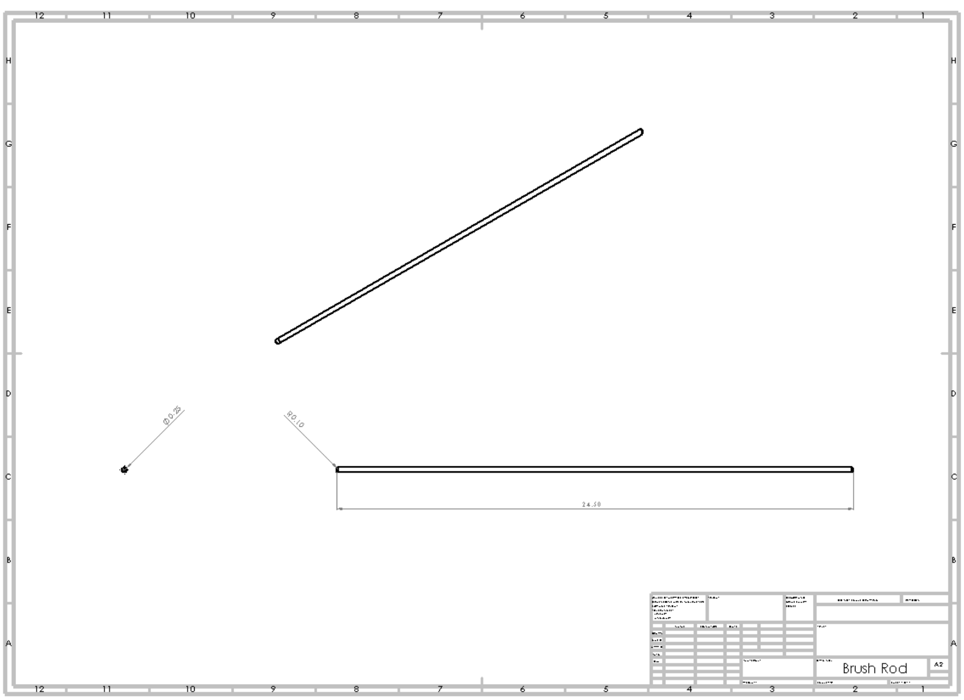
Name: Wheel Brush
Part Number: 111-005



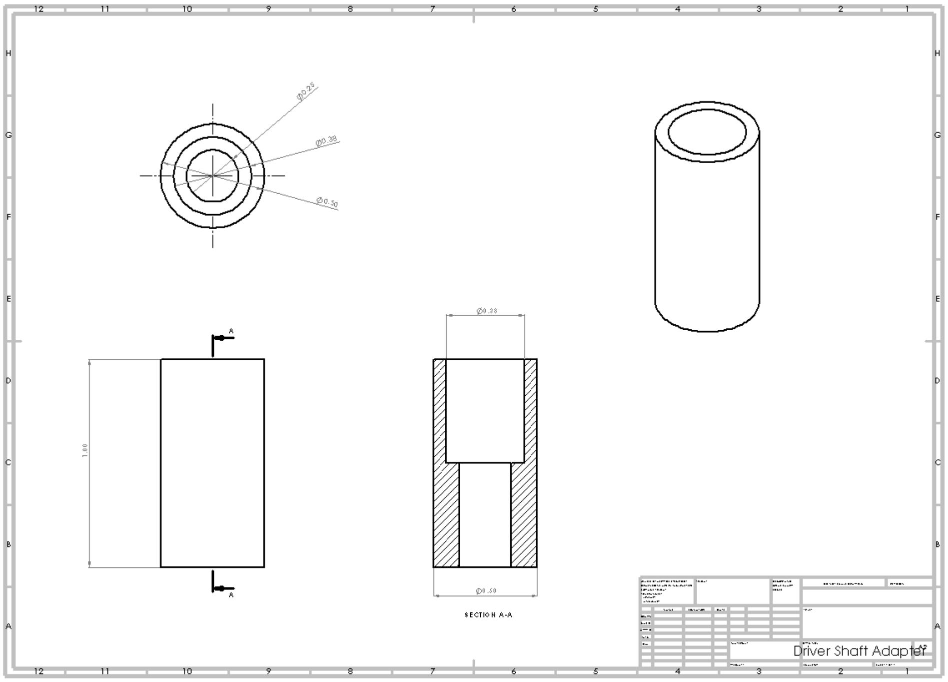
Name: Driving Shaft
Part Number: 111-006



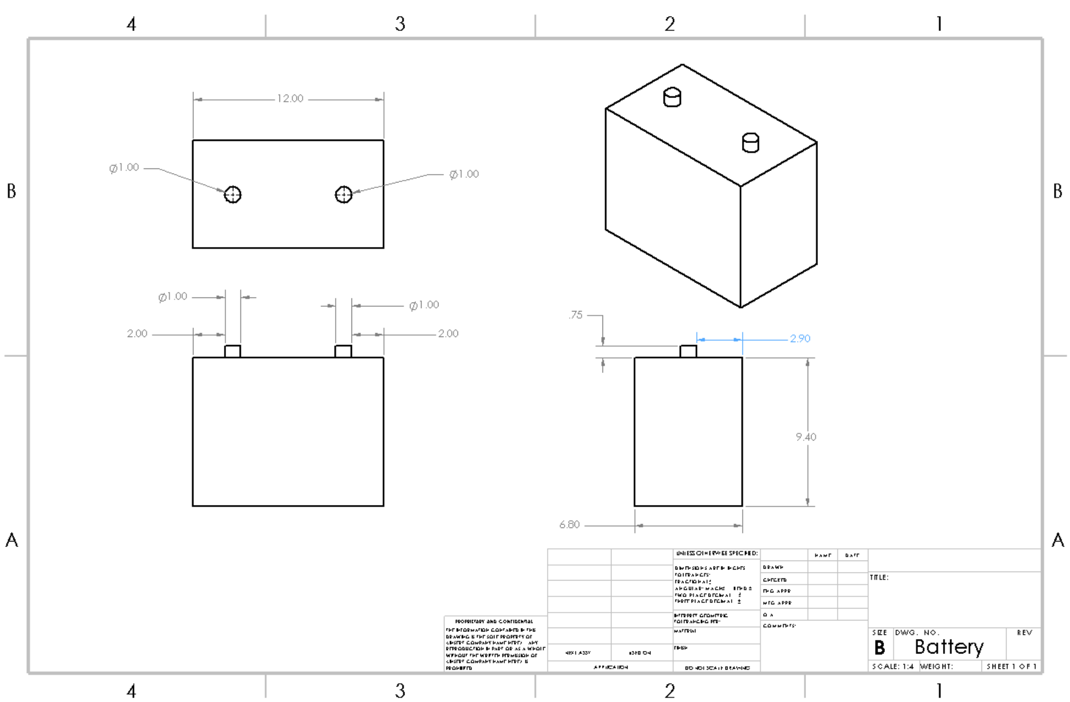
Name: Brush Rod
Part Number: 111-007



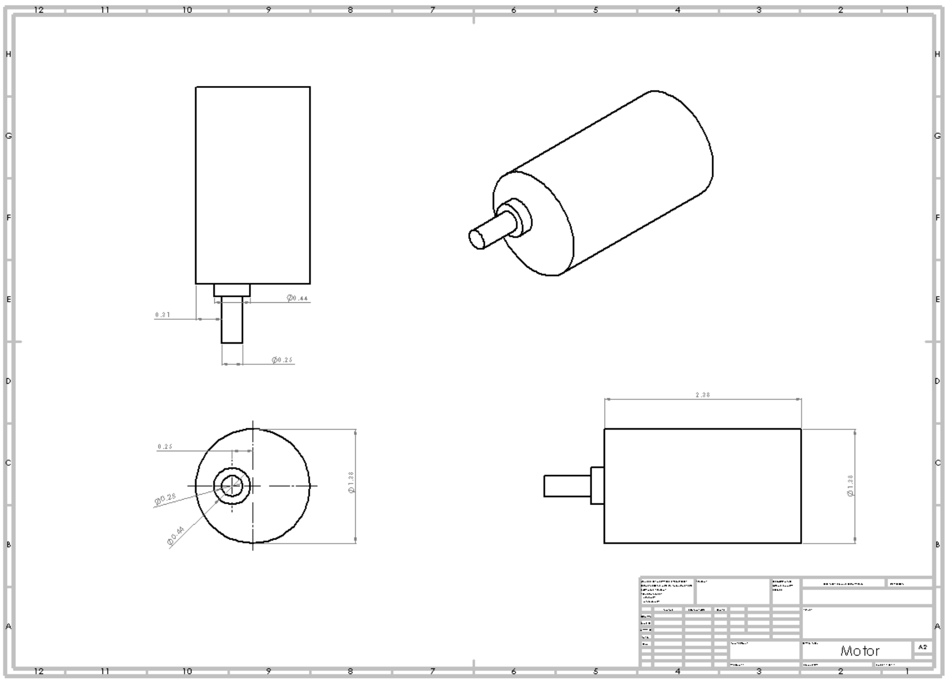
Name: Driver Shaft Adapter
Part Number: 111-008



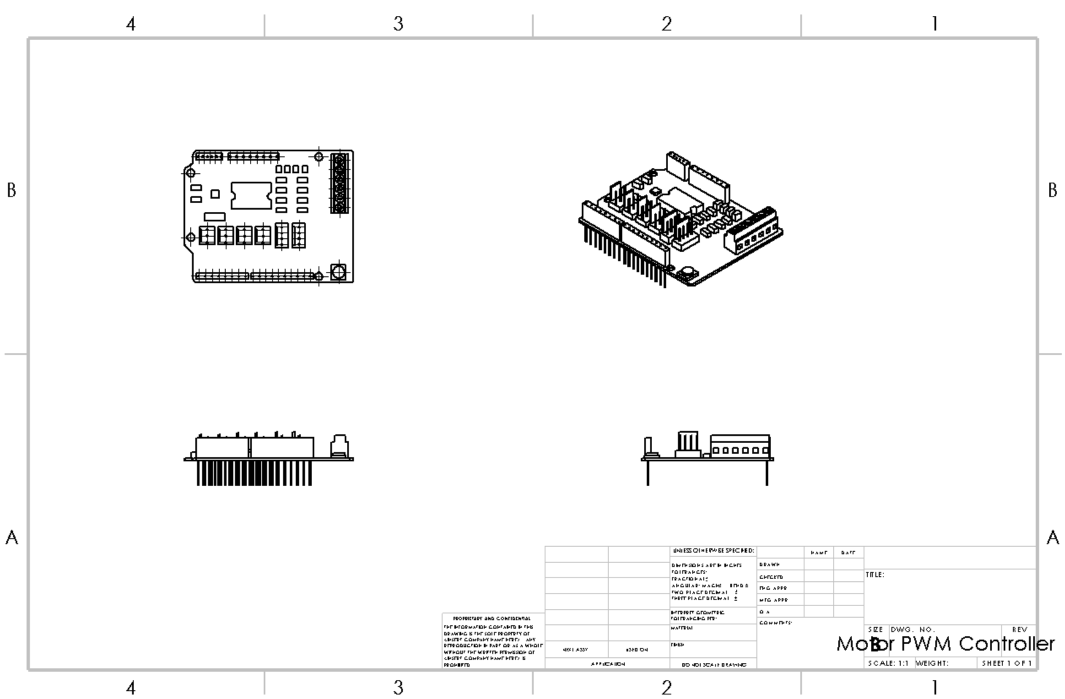
Name: Battery
Part Number: 113-002



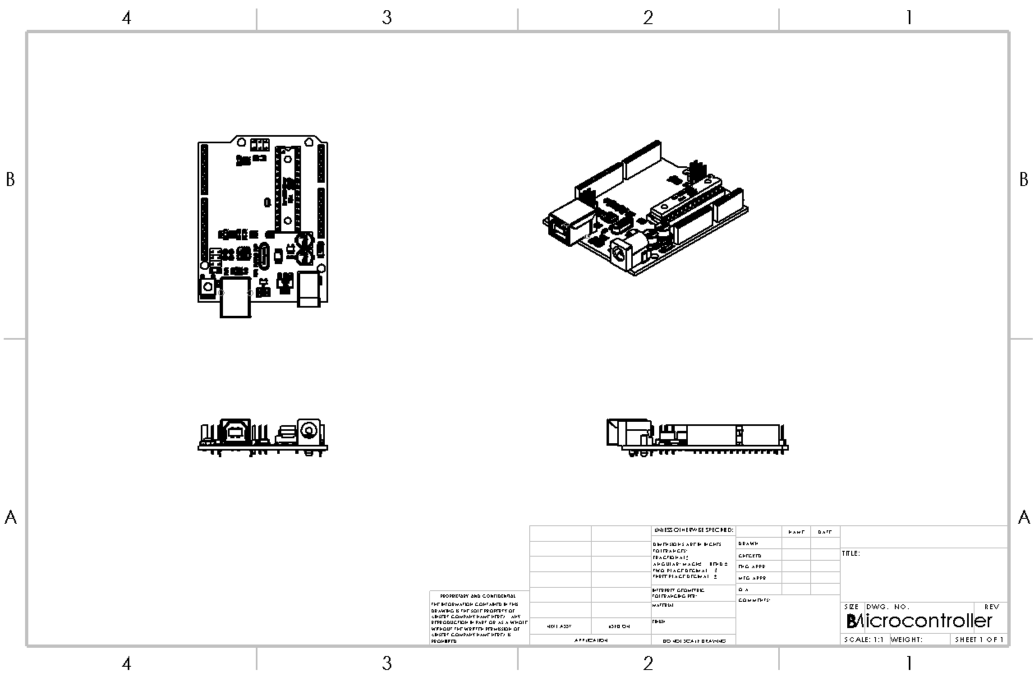
Name: Motor
Part Number: 113-005



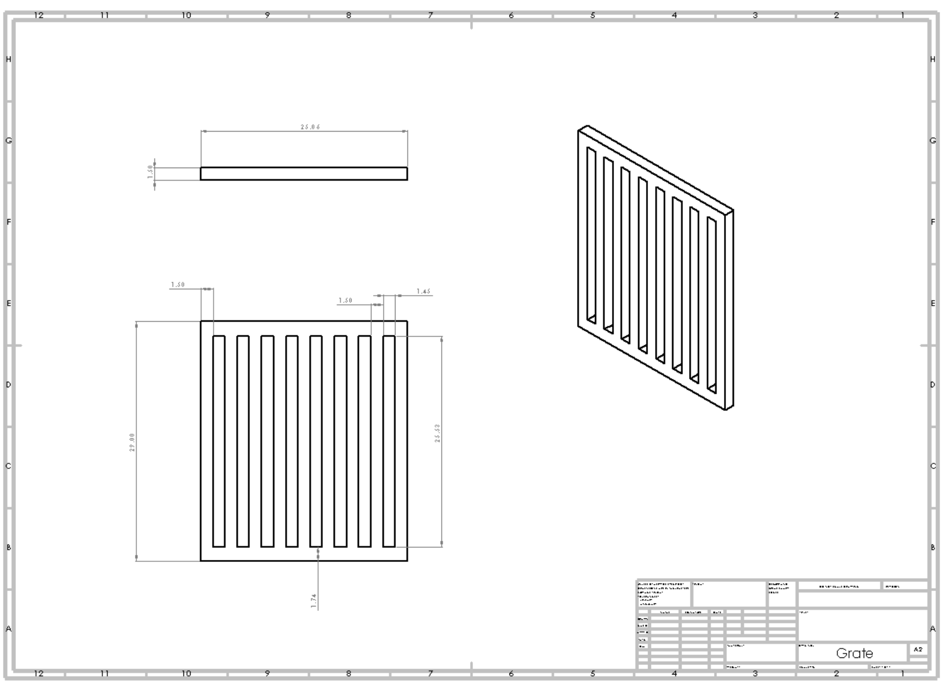
Name: Motor PWM Controller
Part Number: 113-006



Name: Microcontroller
Part Number: 113-007



Name: Standard Highway Drain Grate
Part Number: N/A



I Failure Modes & Effect Analysis

Failure Mode and Effects Analysis (FMEA): Design FMEA for Rotational and Translational Aspects of Moving Shaft with Mounted Brushes

Item / Function	Potential Failure Mode(s)	Potential Effect(s) of Failure	Sev	Potential Cause(s)/ Mechanism(s) of Failure	O	Current Design Controls	Det	RPN	Recommended Action(s)	Responsibility & Target Completion Date	Action Results: Actions Taken	New Sev	New Occ	New Det	New RPN
Item: Rotating/Translating Shaft With Cleaning										Responsibility is equal among Team 32	TBD ⇨				
Brush Rotates throughout cycle	Motor seizes	All system motion stops.	9	1.exceeds life expectancy 2. unexpected exposure to water 3. wires becoming disconnected	2	Concept prototype has not yet been built so there are no current design controls.⇩	10	180	Purchase electric motor with extended lifetime	11/11/16	TBD ⇨				
	Slipping occurs at point of contact between belt and shaft pulley.	Motor will not be able to effectively transmit power to shaft which will move brush and clear debris	4	1.Incorrect belt tension. 2. Debris between pulley and belt	4		7	112	Assure dimensions give tight fit between belt and brush shaft. Also use materials with high coefficients of friction.	11/17/16	TBD ⇨				
	Battery terminals corrode	Battery may not be able to supply maximum voltage to motor which will transmit power to system	5	Moisture exposure	6		10	300	Protect battery from the elements, enclose it with protective barrier or at least cover terminals to extend life.	11/17/16	TBD ⇨				
Brush Translates throughout cycle	Brush Shaft Jams on Pulley Frame.	1. Belt slips 2. Lose translation and rotation of shaft	7	1. Debris could obstruct path 2. Human tampering (vandalism)	3		4	84	enclose pulley frame/ track to reduce risk of debris entering and obstructing.	11/17/16	TBD ⇨				
	Motor seizes	All system motion stops.	9	1.exceeds life expectancy 2. unexpected exposure to water 3. wires becoming disconnected	2		10	180	Purchase electric motor with extended lifetime	11/11/16	TBD ⇨				
	Belt fatigue/ tear.	Motor will not be able to transmit power to shaft which will move brush and clear debris at all if belt tears.	9	1. Extended life cycle of belt 2. Stick getting caught in belt and causing it to break	4		4	144	Purchase thicker belt for design and also wider, these paramaters make the belt have a longer life especially with low work-load conditions.	11/11/16	TBD ⇨				

J Task Sheet

I Executive Summary:	Michael Kyei-Baffour
II Market Analysis:	Neil Winston
III Problem Identification:	Katherine Konecny; Scott Sterling
IV HOQ:	Matt Devine
V Conceptual Design:	Zachary King, Neil Winston, Michael Kyei-Baffour
VI Embodiment Design:	Zachary King, Katherine Konecny
VII Cost Analysis:	Zachary King
VIII PDS:	Scott Sterling
IX Prototype & Testing:	Michael Kyei-Baffour, Neil Winston
X Design Considerations:	Katherine Konecny
XI Conclusion:	Michael Kyei-Baffour
XII Engineering Drawings:	Scott Sterling, Matt Devine, Neil Winston

Compiling & Editing:	Katherine Konecny & Michael Kyei-Baffour