COVER PAGE

Title of Design: FRM- Foreign Object Debris Removal Machine

Design Challenge Addressed: Airport Operation and Maintenance

University name: Roger Williams University

Team Member(s) names: Ryland Brickner-McDonald and Mohamad Ghulam

Number of Undergraduates: 2

Number of Graduates: 0

Advisor(s) name: Dr. Linda Ann Riley

Executive Summary

This report presents a solution to Technical Design 1, Airport Maintenance and Operations area, for the 2014-2015 ACRP University Design Competition. One of the suggested challenges listed under this area involved designing a system that would improve methods for foreign debris detection and removal from runway surfaces.

To address this challenge, the RWU Consulting Team (RWUCT) has conceptualized, designed, and fabricated the Foreign Object Debris Removal Machine (FRM). This machine is unique compared to existing systems in that no extra vehicle is needed to sweep the tarmac. Rather the FRM is retrofitted under baggage carts between the front and rear axles. Furthermore, the FRM costs a fraction of current sweepers on the market, approximately $900. The motivation for designing this system results from many aircraft incidents that occurred due to FOD on the runway and tarmac. Four primary design goals were considered when developing this machine; 1. create a system using existing airport ground vehicles to clean the tarmacs as they travel, 2. utilize the movement of these vehicles to power the sweeping mechanism, 3. ensure that all material (metallic and non-metallic items) are swept up and stored in a place other than the tarmac; and last 4. fabricate a system that can be easily attached to and detached from ground vehicles. Ultimately, this machine has been designed for use underneath baggage carts to enhance the safety of airports and all vehicles that travel the apron and surrounding areas. Reducing the impact of FOD damage at airports will help improve the airport and FAA's safety record, reduce damage and maintenance costs that FOD represents for airlines and make air travel safer for passengers.

The FRM system was designed and prototyped with input from industry experts and airline management. It has been designed and tested as a full scale system on an existing baggage cart in partnership with Delta Airlines.

Table of Contents

Problem Statement

This report addresses the ARCP design challenge within the Airport Maintenance and Operation category. The Roger Williams University Consulting Team, RWUCT, has been tasked to explore new methods for maintenance of pavement surfaces and to ensure that all ground vehicles, especially aircraft, are not damaged by FOD. The team, through extensive research and experimentation, has developed a new type of FOD removal mechanism (FRM). This system uses pre-existing ground vehicles for its mode of operation instead of an additional vehicle, as with previous FOD removal systems. This reduction in ground vehicles moving about an airport's tarmac will also reduce potential accidents and runway incursions.

The FRM is an effective, efficient, inexpensive, and motorless FOD removal system for collecting debris on airport tarmacs, while reducing ground traffic because of the elimination of traditional FOD collection vehicles. One of the FAA's top priorities is to keep pavement surfaces free of foreign objects. In response to this, airport operators, certified under 14 Code of Federal Regulations Part 139, are required to keep these surfaces free of debris. This is accomplished by regular visual inspections and the recent innovation of automated systems to ensure that runways are always clear of debris. Having debris on pavement surfaces can cause major damage to aircraft engines if ingested or damage the propeller mechanism. In response to the need for an effective, low-cost FOD removal system, RWUCT presents the FRM system.

This system picks up and collects debris from airport tarmacs and is mounted underneath baggage carts. The system is comprised of drive wheels, a gearing assembly, bristles, and a hopper to hold the collected material until disposal is necessary. In addition, it is designed to easily attach to and detach from baggage carts using an intermediate frame between the sweeper and baggage cart. The simple gear assembly is also designed to ensure that only one of the drive wheels is fixed to the axle so the other rotates freely. This configuration allows the machine to go in reverse without any adverse effects. Furthermore, the baggage cart possesses the same maneuverability for baggage tug operators because the wheels of the sweeper do not need to rotate in unison.

The RWUCT suggests that FRM is an essential piece of equipment for airports that use baggage carts due to its ease of retrofitting. Essentially, our product takes a ground vehicle that already exists and employs it in a multi-purpose use. This allows for constant FOD sweeping, if necessary, without the need for additional tow vehicles roaming the airport. The use of baggage carts also ensures that the busiest, and most likely areas that FOD concentration is highest, the tarmac around airport gates, will always be cleaned so potential debris does not make way to runways and restricted taxiways where airplanes could be damaged.

Background

What is foreign object debris (FOD)?

Foreign object debris can be highly detrimental to aircraft ground operations. FOD is any unwanted piece of material - steel, plastic, asphalt, passenger item - on a pavement surface around an airport that could potentially damage an aircraft and/or ground vehicle. ICAO Annex 14 Recommendation, Pavements-paragraph 9.4.2 states, "The surface of pavements (runways, taxiways, aprons, etc.) should be kept clear of any loose stones or other objects that might cause damage to airplane structures or engines, or impair the operation of airplane systems. Although this is presented as a recommendation, many countries have adopted this as a requirement.

Maintenance costs directly related to FOD damage can be very expensive, resulting in airlines and airports spending millions of dollars every year. An engine overhaul to repair FOD damages can cost upwards of $2 million and an engine replacement approximately $10 million. Indirect costs from FOD include: flight delays and cancellations, schedule disruptions, potential injury, and additional work for airline staff. Ultimately these costs affect airlines' customers, finances and time.

FOD is generated from many sources, but it is most commonly generated from airport infrastructure, normal operations, personal belongings, and caterings activities. The corrosion, maintenance, and construction of the airport infrastructure can also contribute to FOD. According to Boeing, pieces of concrete can break loose from holes in pavement or from fatigue corner cracks and building materials can fall from construction vehicles or be blown from gate areas onto airplane maneuvering areas (Figure 1). Broken pieces of pavement can collect at the edge of the gate area and be carried onto the airplane maneuvering area by the tires of vehicular ground support equipment.

Figure 1: FOD can be generated from broken pieces of pavement

In addition, service roads that cross taxiways should be monitored closely to prevent the vehicles using these roads from moving FOD onto the taxiways. Refueling, catering, cabin cleaning, and baggage and cargo handling can also produce broken materials. Baggage pieces, including bag tags and wheels, can break off luggage and fall onto the apron. Maintenance activities at the gate require a variety of small objects, such as rivets, safety wire, and bolts, which become FOD when they are inadvertently left behind.

Figure 2: FOD generated from engine ingestion

According to Boeing, FOD typically peaks during the early spring when airports often begin construction activities, and during the winter because of operations in snow and ice. FOD can collect both on and below ground support equipment stored or staged adjacent to the gate area. Unfortunately for airports, jet blasts, and windy conditions can easily transport FOD from one side of an airport to another within a very short amount of time, creating the potential for hazardous material to be thrown onto a runway where an aircraft's tire could be punctured, or worse, an engine could ingest it. It can also create runway FOD when an airplane transitions from a 150-ft-wide runway onto a 75-ft-wide taxiway.

Figure 3: FOD collected at the gate

Finally, personal belongings are significant sources of airport FOD. For instance, pens, coins, identification badges, hats, soda cans, paperwork, and any other objects that airport or airline personnel carry can become FOD if accidentally left in an inappropriate location (Figure 3).

History of FOD Events

According to reports by the Aviation Safety Network, (a Flight Safety Foundation service), FOD has been responsible for a number of minor to deadly aviation incidents within the past 45 years as presented in Table 1.

Date	Location	Incident Description	Casualties	Airplane Damage
4/18/1972	Addis Ababa-Haile Selassie International Airport, Ethiopia	Vickers VC-10 tire blowout due to FOD. They aborted takeoff	43 fatalities	Beyond repair

		before crashing off the runway.		
6/27/1985	San Juan-Luis Munoz Marin International Airport, Puerto Rico	MD-10 tire blowout due to FOD. They aborted takeoff before crashing off the runway.	0 fatalities	Substantial
7/25/2000	Paris-Charles de Gaulle Airport, France	Concorde tire blowout due to FOD. Rubber was ingested into engines resulting in engine loss and eventually crashed.	109 fatalities	Destroyed
3/26/2007	Hamton-Newport News/Williamsburg Airport, VA	Learjet 36A tire blowout due to FOD. They aborted take-off before crashing off the runway.	0 fatalities	Substantial

Table 1: Accidents caused by FOD in the aviation industry reported by the Aviation Safety Network

As the reports indicate, there have been minor and major accidents cause by FOD, all of which involve tire punctures. Although not documented as accidents, FOD also damages aircraft in minor ways. These minor damages occur often enough to result in the industry spending millions of dollars every year. It is because of these accidents and damages that the RWUCT decided to focus its efforts on solving the problem of foreign object debris at airports.

Figure 4: Damaged fan blades cause by FOD

Literary Review Supporting the Design of FRM

Overview of Research Process

The design team used numerous resources to gather as much information as possible to design a system to effectively pick up debris from pavement surfaces at airports. In the early stages of our design, we focused our research on existing FOD removal mechanisms as well as patent searches to determine if the concept of mounting a sweeper to the bottom of baggage carts at airports had already been designed and commercialized. Information under FOD Resources on the FAA.gov webpage and other related articles on FOD helped us further understand the main concerns airports faced and what our goals would involve to accomplish our task.

FOD Systems Currently In Place

There are many systems in place that currently detect and pick up FOD at airports. There are basically two categories of FOD removal machines currently used: one category consists of radars and the other category consists of the ‘picker-uppers’, the category we are focusing on.

Radars are used for FOD detection, more specifically, runway FOD detection. Radars are used on the runway because it is a large area with constant air traffic and rarely contains a piece of debris. If the radar system does detect a piece of debris, it notifies a ground operator so it can be removed swiftly without causing any delays. In addition, radars can also be mounted to vehicles creating mobile radar stations.

The second category of FOD removal consists of sweepers, vacuums, magnets, and mats. All of these systems serve the same purpose - that is, picking up FOD on airport tarmacs. There is no detection system for debris on these systems; they simply pick up debris wherever they go, all requiring an additional vehicle for towing and transportation purposes.

Although the radar and sweeping systems currently work at reducing the amount and effect of FOD at airports, all mats, sweepers, vacuums and magnetic bars require an additional vehicle for transportation around an airport. More notably, all of these sweepers cost at least

$5,000. Thus, there is a need for a sweeper that can pick up objects in an efficient and inexpensive way, but without an additional ground vehicle roaming the airport.

Problem Solving Approach for Design Process

After focusing on the topic of the technical design challenge and assessing the problem statement, the team began brainstorming potential designs. Extensive research was undertaken focusing on current systems in place, damages and maintenance costs of FOD, causes/sources of FOD at airports and an innovative way to create a new model of sweepers. At first we began by making a small tabletop model of what our sweeper would consist of, and identified our greatest challenges of our project at that time - determining how our sweeper would move about an airport's tarmac and finding a way for our machine to be strictly powered from wheel rotation so as not to require an additional power source to rotate the bristle system. After more research and conceptualization, the team focused on having baggage carts serve a multi-purpose at airports and initially utilizing the idea of a manual push lawn-mower for our sweeping mechanism.

Team Composition

Our team consisted of a civil and mechanical engineer. With two different backgrounds, individual research as well as discussions during weekly meetings and advice from our faculty advisor, we conceptualized and further improved our design. Major areas of focus for the team included: airport and airline's needs, safety and risk assessment, cost analysis, and communication with experts in this field. The team brainstormed to find a unique, innovative and cost effective solution to FOD removal at airports. After much thought and research, we decided to focus on pre-existing vehicles at airports to house our sweeper to reduce the need for an additional tow vehicle. One ground vehicle that seemed a natural focus was baggage carts. This is due to their constant movement around the tarmac; especially gate area movement around airplanes where the largest amount of FOD is located. With that knowledge, the team decided to create a sweeper that could be attached underneath baggage carts; therefore, larger airports became the focus because smaller airports do not need baggage carts. The team's design tasks for the FRM included: research, risk and safety assessment, engineering analysis, tabletop models, prototyping, SolidWorks Modeling, full-scale fabrication, and experimentation.

Research Process

As our project progressed from a largely research based project to conceptualization and a design based project based upon research we previously completed, new challenges and ideas emerged that required research throughout the entire process from start to finish. This on-going research helped us stay current on our topic. Consequently, we became experts on FOD control at airports, damages it creates and past events from history. The first semester was focused on prevention and removal of FOD at airports, tabletop models and conceptualization ideas. As our ideas and research slowly began to mesh together, we created our first scaled prototype.

Development Methods

The conceptualization phase of our product consisted of a tabletop model and two scaled prototypes. Our first scaled prototype, FRM 1, was created with a manual push lawnmower (Figure 5). This was chosen because the rotation of the blades to cut grass is powered by the rotation of the drive wheels, and does not require a motor; instead, a simple interior gear ratio mechanism allow the blades to rotate at a much faster angular velocity than the drive wheels, creating an efficient and simple machine. To change the lawnmower into a sweeper, the team experimented with the lawn mower and disassembled unnecessary parts that were used to cut grass. Once all the extra

Figure 5: Our first prototype, FRM 1

parts were removed, a bristle system was needed to sweep items off the ground. For this, the team used small nylon bristles removed from a common household toilet scrubber, and wrapped them around the lawnmower blades. This transformed the rotating blades of the lawnmower into a rotating cylindrical bristle system capable of picking up items from the ground. This was a good start in the prototyping process, but after items were being swept up by the bristle system, a collection system was needed to safely hold the collected material.

Figure 6: Our second prototype, FRM 2

For the next scaled prototype, FRM 2, the manual push lawnmower used in FRM 1 was further developed by creating a collection system to hold the debris swept up by the bristles (Figure 6). For the collection system, a drawer was required that could easily be accessed by a worker to remove the collected debris. Because the drawer needed to have depth to it so material would not fall out after being collected, a method for transporting the material, which is at ground level, to a higher elevation was designed. To do this, a ramp was employed. The ramp was an important piece of the design; without it, the prototype would only sweep material in a mostly horizontal direction, completely avoiding the collection system and making the machine pointless. The ramp in FRM 2 was placed directly behind the bristle system and a few inches from the ground so it would not hit the ground if a baggage cart went over a bump but would also still be low enough for material being shot back from the bristles to travel up the ramp and into the collection hopper. FRM 2 was a major improvement from FRM 1, but it still had drawbacks. After conducting a design of experiments with a debris field made up of common FOD items, the bristle system did not allow for larger materials to be picked up due to the small bristle radius.

Another, more concerning problem with the design was the internal gear system. During the experiments, there was common slippage in the gears as the bristle system made contact with the ground and eventually, the machine actually started to rip itself apart. If this was implemented at an airport on a commercial level and the FRM started to break apart as it cleaned FOD from the tarmac, it could contribute to the debris needed to be collected.

As the team assessed the experiments conducted, a major improvement to the prototyped FRM at that point was needed. To address the problems experienced in the experiments, a tabletop model made from K'nex of the current lawnmowers design was created to try and solve the problems at a smaller scale before creating a larger scaled FRM 3 (Figure 7 and 8). From the tabletop model, the major design flaw with the concept, the internal gear system, became very apparent. Unlike a person cutting a lawn who is moving at walking speed over a compressible surface such as grass, the FRM would be implemented at an airport underneath a baggage cart traveling at upwards of 15 miles per hour and experiencing bumps on a very hard, pavement surface. This created forces that an internal gear system of this type could not tolerate. In addition, while creating the model, if some piece of the internal system failed, the entire model had to be disassembled to even get to the part that failed. In a large scale production, the maintenance of a small broken part could cost an airline more

Figure 8: Tabletop model made from K'nex

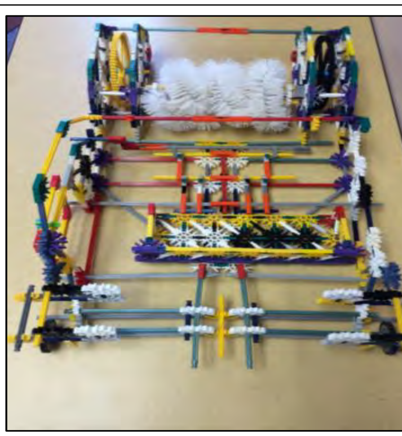

Figure 7: Tabletop model made from K'nex

money than it would save by using the FRM. After considering these options, a new design was needed.

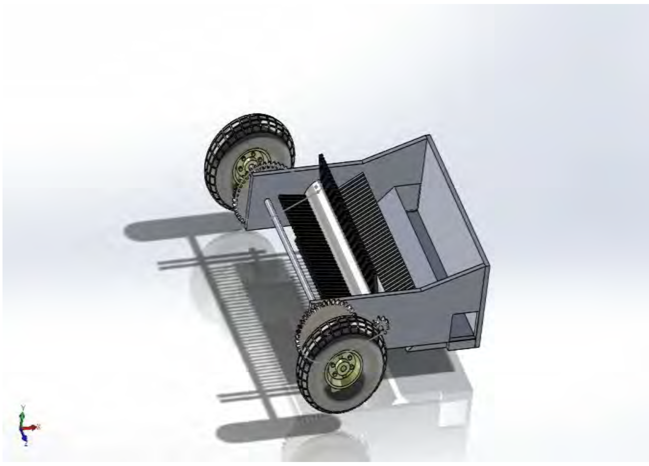

Figure 10: SolidWork's model of our final design

Figure 9: The actual final FRM design

For the next design, and what would become our final design, the team took what was learned from the previous concepts and adjusted the design (Figure 9). The major problem of the past prototypes was a faulty, unreliable, and high maintenance internal gear system. Fortunately, all other components of previous concepts worked very well at what they were designed to do, so the gear system was the only change we needed to make. After brainstorming a few ideas, a spaced out external gear system became the focus of the next design. This design included the same gear ratio mechanism as previous prototypes, but the two gears were not in direct contact with one another and the drive wheels and bristle system were not one unit. Instead, the drive wheels and the bristle system both had their own axles, and the gears attached to each axle with a chain connecting the two together (Figure 10).

The full scale functioning prototype was evaluated based on safety, efficiency and effectiveness, ease of attachment/detachment from baggage carts, simple manufacturability and cost. The final design shown in Figure 11, was completed with side panels and a cover for the hopper to ensure all material would be collected in the hopper system. Using feedback from experts in the field and FAA expert advisors, the final prototype represented an implementable system at airports.

Figure 11: The final FRM prototype in place under a baggage cart

Safety and Risk Management

The team employed a risk assessment to meet and comply with the FAA Airport Foreign Object (FOD) Management Advisory Circular. The FRM will be implemented in larger airports that use baggage carts in every day operations. Because major airports with baggage carts are located in different climates, we ensured that the FRM could easily be removed from baggage carts in the event of a snow storm where it would be very inefficient for the sweeper to be picking up snow, although that could be another use of the FRM. Additionally, the bristle system complies with the requirements stated in the FOD Advisory Circular; FOD power sweepers should contain a majority of plastic bristles so they will not detach from the broom and produce a FOD source.

Additional reasons that made the baggage cart the best pre-existing ground vehicle for our sweeper was its large unused space in between the two wheels, its large width of roughly 6 feet, and how low of a ground clearance it has – all of these essential for housing a sweeping mechanism that could pick up debris on an airport's pavement surface.

Description of Technical Aspects of FRM

Development of FRM

Figure 12: Our baggage cart acquired from Delta Airlines at Logan International in Boston

The fully functioning FRM was designed at full scale and attached under a baggage cart acquired from Delta Airlines at Boston's Logan Airport (Figure 12). It is designed for safety, efficiency and effectiveness, and ease of attachment/removal to and from baggage carts. To ensure these design goals were met, the frame is constructed out of 1/8" hollow tube steel and sheet metal for strength considering the potential adverse conditions at airports. The bristle system, acquired from Liberty Brush Manufacturing, LLC, is made of a hollow inner tube with a spaced out spiraled polypropylene bristle to assure both small and large debris can be collected from the tarmac. Lastly, the FRM can be easily attached and removed from baggage carts by the use of bolts and an interface that lies between the sweeping mechanism and a baggage cart.

To demonstrate proof of concept, the prototype was tested on asphalt and concrete to ensure it is capable of picking up items from either surface. The overall objective of the FRM system is to aid in reduction of debris from our nation's airports. This will improve airport safety and lower overall costs spent by airlines and airports. This system is designed to work at airports that have baggage carts, which usually means larger, more commercial airports; however, this system could be used at any airport, provided they use baggage carts.

Technical Analysis

To determine the angular velocity of the bristles, the angular velocity of the drive wheels was calculated. According to Paul Remillard from Boston's Logan Airport, the maximum linear velocity of a baggage cart is roughly 15- 20 mph. Given that the maximum linear velocity of the drive wheels is the same as the maximum velocity of the baggage cart and the diameter of the drive wheels is 13 inches (D = 13 inches), the angular velocity of the drive wheels can be calculated as shown below in equations 1 and 2.

Since we have the diameter we can find the radius by using equation 1:

$$r = \frac{D}{2} \qquad \textit{Equation 1}$$

$$r = \frac{13}{2}$$

$$r = 6.5\ inch$$

Where;

D = diameter of the drive wheels in inches

Converting from inches to meters:

$$(6.5\ \ inches) * \left(\frac{1\ \ meter}{39.37\ \ inches}\right) = 0.1651\ \ meter$$

Converting the 15 miles per hour to meters per second:

$$\left(\frac{15\ \ miles}{1\ \ hour}\right) * \left(\frac{1609.34\ \ meters}{1\ \ mile}\right) * \left(\frac{1\ \ hour}{60\ \ \text{minutes}}\right) * \left(\frac{1\ \ minute}{60\ \ seconds}\right) = 6.706 \frac{meters}{second}$$

Lastly, calculate the angular velocity using equation 2:

$$\omega = \frac{V}{r} \qquad \textit{Equation 2}$$

$$\omega = \frac{6.706\ \ \left(\frac{m}{s}\right)}{0.1651\ \ \ m}$$

$$\omega = 40.6178 \ \ \frac{rad}{s}$$

Where;

V = the linear velocity of the drive wheels in m/s

R= the radius of the drive wheels in meters

Since the drive wheel is connected to the bristle using gear and chain mechanism, equation 3 was used to find the angular velocity of the bristles.

$$\omega\ L = e\ \omega F \qquad \textit{Equation 3}$$

Where;

***ω L* = the angular velocity of the last gear (smaller gear) that is attached to the bristles**

***e* = the train value**

***ωF*= the angular velocity of the first gear (bigger gear) which is attached to the drive wheel**

The train value e was calculated using equation 4

$$e = \frac{Number\ of\ driving\ tooth\ numbers}{Number\ \ of\ driven\ tooth\ numbers} \quad \textit{Equation 4}$$

$$e = \frac{42}{17}$$

$$e = 2.471$$

Where;

Number of driving tooth (bigger gear is attached to the drive wheel) = 42 teeth

Number of driven tooth (smaller gear is attached to the bristles) = 17 teeth

Finally, the angular velocity of the bristles was calculated using equation 3:

$$\omega L = (2.471) * \left(40.6178 \frac{rad}{s}\right)$$

$$\omega L = 100.35 \frac{rad}{s}$$

To ensure that the FRM's attachment of the baggage cart would not fail, a material and bolt analysis was performed on the connection from the horizontal frame to the baggage cart – the connection being a piece of sheet metal that measures 1/8 inches thick, has a length of 5 ½ inches, a width of 3 inches and has 2 holes. Because the baggage carts flange thickness is ¼ inches and the horizontal frames thickness is 1/8 inches, the team concluded that the connection to the baggage cart would be stronger than the connection to the horizontal frame; therefore, if something was going to fail first, it would be the sheet metals connection attached to the horizontal frame. The team assumed that the tensile forces present on the sheet metal that attached the horizontal frame to the baggage cart was zero because a large majority of the whole system is supported by the drive wheels; therefore, the forces acting in the y-direction would be negligible, when compared to the forces acting in the x-direction. With a tensile force of zero, the only remaining force to test was its shear strength. The first calculation performed on the connection piece was for design shear; the overall equation needed to perform this calculation is shown in equation 5:

$$R_n = (\emptyset)(0.6)(F_u)(A_{nv}) + U_{bs}(F_u)(A_{nt})$$

OR *Equation 5*

$$R_n = (\emptyset)(0.6)(F_y)(A_{gv}) + U_{bs}(F_u)(A_{nt})$$

Because the tensile forces in the problem are zero, equation 5 can be reduced to:

$$R_n = (\emptyset)(0.6)(F_u)(A_{nv}) \text{ OR } R_n = (\emptyset)(0.6)(F_y)(A_{gv})$$

Where;

R_n= Resistance strength to shear block

Ø = Resistance factor, 0.75

F_u= Ultimate strength (ksi) (A36 steel=58 ksi)

F_y= Yield strength (ksi) (A36 steel=36 ksi)

A_{av}= Net area subjected to shear (inches^2)

A_{gv}= Gross area along the shear surface (inches^2)

To calculate A_{nv}, equation 6 is used:

$$A_{nv} = Width\ of\ sheet\ metal - (\#\ of\ holes)(D_e + thickness) \qquad \textit{Equation 6}$$

Where;

D_e= Effective hole diameter:

$$D_e = diameter\ of\ hole + \frac{1}{8} inch$$

$$D_e = \frac{1}{2} inches + \frac{1}{8} inches$$

$$D_e = \frac{5}{8} inches$$

Plugging back into equation 6, A_{nv} can be calculated as follows:

$$A_{nv} = 3\ inches - (2\ holes)(\frac{5}{8} inches + \frac{1}{8} inches)$$

$$A_{nv} = 1.5\ inches^2$$

To calculate A_{gv}, equation 7 is used:

$$A_{gv} = (Width\ of\ sheet\ metal)(thickness\ of\ sheet\ metal)(\#\ sides\ in\ shear) \qquad \textit{Equation 7}$$

$$A_{gv} = (3\ inches)(\frac{1}{2}\ inches)(2\ sides)$$

$$A_{gv} = 3\ inches^2$$

Plugging everything back into equation 5:

$$R_n = 0.75(0.6)(58ksi)(1.5inches^2) \quad \text{OR} \quad R_n = 0.75(0.6)(36ksi)(3inches^2)$$

$$R_n = 39.15\ kips \quad \text{OR} \quad R_n = 48.6\ kips$$

The lower R_n value is chosen because that is the force at which the sheet metal will shear first. In this case, the R_n value will equal 39.15 kips.

Next, the bolts that attach the horizontal frame to the baggage cart need to be tested for their shear strength.

To test for shear failure, equation 8 is used:

$$\emptyset R_n = 0.75(F_{nv})(A_b) \qquad \textit{Equation 8}$$

Where;

$\emptyset R_n$= Design resistance strength

F_{nv} = Nominal unit shear strength (ksi) (F_{nv}=68 ksi)

A_b =Area of double shear (area of failure) (inches^2): $= \frac{\pi}{2}d^2$ where d is the hole diameter

Plugging back into equation 8:

$$\emptyset R_n = 0.75(68\ ksi)(0.39\ inches^2)$$

$$\emptyset R_n = 20.03\ kips$$

When comparing the two resistance strengths, the lower number of the two is when the connection will fail, that is, 20.03 kips, or 20,030 pounds. It is safe to assume that the FRM's connection will not experience a force close to that, and therefore the connection is designed with adequate strength for the FRM.

Mechanical Components

The function of the FRM system is to sweep pavement surfaces free of FOD. To accomplish this, the system is comprised of many components, each serving a specific purpose. This includes: framework, drive wheels, gears and chain, a bristle system, a collection system, and a horizontal frame to connect the sweeper to the baggage cart.

Figure 13: The framework for the final design

The framework for the FRM system is made from 1/8 inch hollow tube steel (Figure 13). This tube serves as the component that holds the structure together. Consequently we wanted to assure that the material we used could hold up to the stress that the machine experienced while riding under a baggage cart. In order for the bristles to rotate without the use of a motor, we used drive wheels that are connected to the bristle system by use of gears and a chain (Figure 14). This gearing concept is similar to our first scaled prototypes where we used a manual push lawnmower; however, this design allows the gearing components to be external, instead of internal. Having the gearing outside of the drive wheels and spread out by the chain will improve ease of maintenance and creates a more user friendly system.

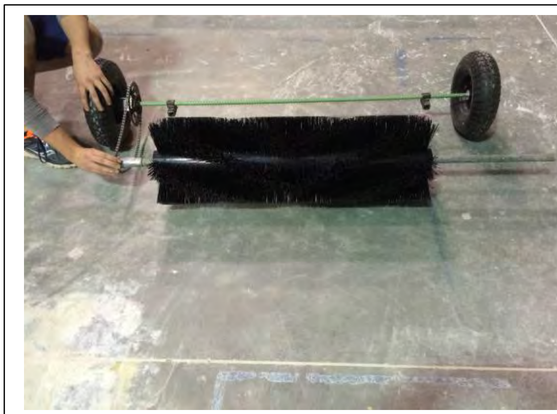

Figure 14: Only one drive wheel is connected to the bristle system using gears and a chain mechanism

Originally in our full scale prototype we had both the drive wheels permanently fixed to a rotating axle, along with two separate fixed gearing systems - one on each side and both fixed to the rotating axle. This allowed for the gears to rotate at the same rate as the drive wheels, but also made the entire axle rotate at the same rate at all times. The problem with this approach is that baggage carts take turns; in a turn, one wheel has to rotate at a faster rate than the other due to the longer distance it has to travel. To correct this problem, we decided to change the design of our drive wheels, axle and gearing system.

Figure 15: The gear driving drive wheel

Figure 16: The free rotating wheel

We first changed the rotating axle to a fixed axle, removed one of the two gearing systems and allowed the drive wheel associated with the removed gear to rotate freely about the fixed axle. On the other drive wheel, we attached the remaining gearing system to the drive wheel itself, as seen in Figure 15. These changes reduced the number of moving parts, as well as allowing the baggage cart to turn and go backwards because the two wheels could now rotate at different speeds.

Because the FRM uses drive wheel rotation to power the bristle system, the rotation of the bristles is directly proportional to the baggage carts speed. To improve the rotational velocity of the bristles and allow them to sweep as much debris as possible, the focal point of the FRM, we emulated a bicycles gearing system (Figure 16). In a multi-speed bike, the fastest you can go is when the chain of the front derailleur is rotating around the gear with the largest diameter and the back derailleur is rotating around the gear with the smallest diameter. In the FRM system, the drive wheel acts as the front derailleur and the back derailleur acts as the bristle system. That is, we connected a larger gear to the drive wheel and a smaller gear to the shaft of the bristle system, and connected the two gear together using a chain. The large to small gear ratio allows the bristles to rotate at a much faster rate than the drive wheel rotates, creating a more effective and efficient system at collecting FOD from airport pavement surfaces.

To collect the material after it is swept up by the bristle system, the FRM is fitted with a collection system. This system consists of a ramp and a removable hopper. The ramp is in place to ensure any material that is swept up will end up in the removable hopper. The ramp is important in our design because without a ramp, there would be no way to completely guarantee materials ending up in the hopper. Once material ends up in the hopper, an airport worker can remove the hopper, which is similar to a drawer, and place the FOD into an appropriate trash bag. A ramp was first designed in plywood for testing before the final metal material was fit and welded.

Figure 17: The hopper and ramp

The last component of the FRM is the interface that connects the frame to the baggage cart. We used an additional horizontal frame made of 2 by 4 metal as seen in Figure 18 and 19, and permanently connected it to the framework. The horizontal frame attached to the sweeper is the component connects the system to the baggage cart.

Figure 18: The horizontal frame welded to the framework

Figure 19: The horizontal metal frame

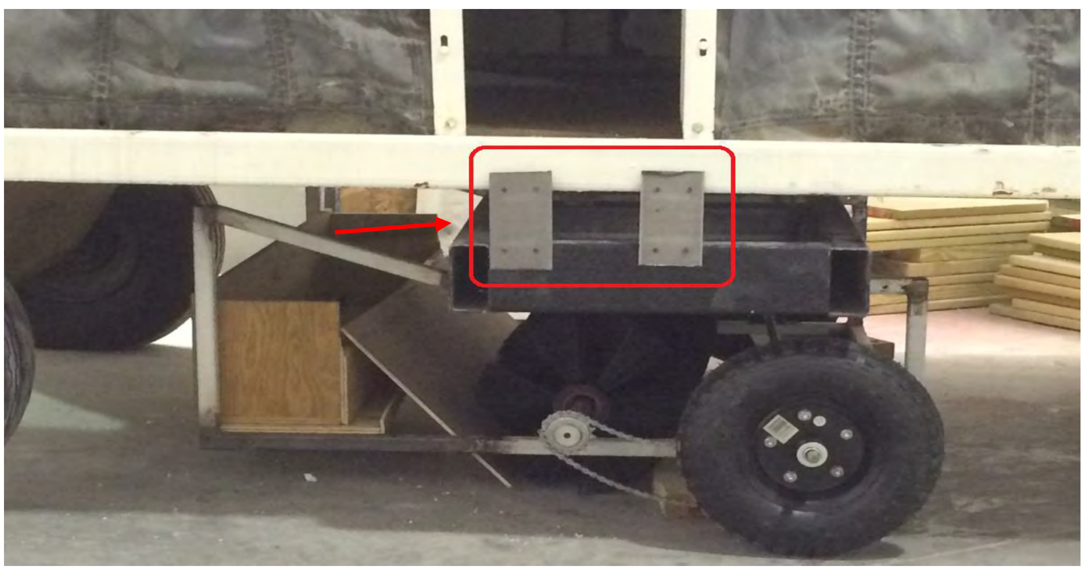

Figure 20: The sheet metal bolted to the flange of the horizontal frame and the flange of the baggage cart

To connect the large horizontal frame interface above the sweeping mechanism to a baggage cart, we used two pieces of thick sheet metal, and bolted the side flanges of the horizontal frame to the bottom half of the sheet metal; as well as bolting the top half of the sheet metal to the flanges on the sides of the baggage cart (Figure 20). Having an interface that separates the moving parts of the sweeping mechanism to the baggage cart connection insures that if a connection were to fail, it would not rip the entire machine apart.

The large horizontal frame interface in between the baggage cart and the sweeping mechanism runs the full width of the baggage cart allowing for the side flanges of each component to be flush with one another. This permits the piece of sheet metal to easily be connected to each flange, resulting in the connection from the baggage cart and the sweeper. Unlike the large frame interface that runs the entire width of the baggage cart, the sweeping mechanism only runs about two-thirds of the length. This is because both of the drive wheels and the one gearing system are located outside of the framework and space is needed for each component. It was also designed this way to reduce costs of the FRM construction, especially the bristle system, which is the most expensive individual piece of the FRM.

Interactions with Airport and Industry Experts

Background Information

To successfully prove proof of concept, we knew we would need a baggage cart to complete our final product for testing. We contacted several companies that sold baggage carts and received information on baggage cart dimensions to help better define our system's size. As our models moved toward a finalized state and closer to full scale production, one of our main objectives was to acquire a baggage cart to test our full scale final design. We began our search by using the Expert Advisors for ACRP University Design Competition for Addressing Airport Needs in the competition web page and sent emails to industry individuals we thought would have information on baggage carts; who owns them, top manufactures, any 'baggage carts graveyards', and/or any research facilities that would have an extra cart to spare. We learned that baggage carts are owned by the individual airlines at their respectable airports and there are companies that sell new and refurbished carts. We also became familiar with the term 'ground support engineer' (GSE). Equipped with that information, we began contacting vendors and airlines in search of a baggage cart.

The Search for a Baggage Cart

After learning that airlines owned their own baggage carts, we started by calling reservations numbers. We quickly learned that the reservation lines for airlines only had information about flights and could provide no contact information for airport operations staff. To possibly make our search easier, we contacted companies that advertised refurbished baggage carts online. Unfortunately, even a refurbished cart cost over $1000, which exceeded our budget.

We returned to contacting different airlines, but instead of calling the reservation lines, we found a website that contained all of the airlines corporate numbers. After countless hours of searching, we called Southwest Airlines. We were put in contact with the ground support engineer manager at Dallas' airport. He said he had scrap baggage carts he would be willing to give us, but because they were in Dallas, and we are in Rhode Island, the shipping would be too expensive. From this we learned that we needed to contact an airline directly through a corporate number, as well as assuring we were put in contact with a ground support engineer from an airport within driving distance to pick the cart up.

Delta Airlines and Logan International Airport

After many more days of searching by corporate numbers and calling individual airlines at Boston's Logan Airport and T.F. Green Airport in Providence, we called the Delta Airlines corporate number. We were put in contact with a ground support engineer, Jim Heinzel, at Atlanta's Hartsfield Airport. With his very generous help and guidance, he relayed our need for a baggage cart to Paul Remillard, another ground support engineer, at Boston's Logan Airport.

We spoke with Paul through e-mail and over the phone a number of times and within a few days he said that he could provide us with a used baggage cart free of charge that we could keep. A few days later, we rented a U-Haul truck and made our way north to Logan Airport to pick up our baggage cart. We met with Paul and discussed our project, what our ultimate goals were, and asked for input. He gave us many suggestions and information about baggage carts, airport ground operations, and how baggage carts are treated throughout the industry. He suggested to fabricate a sweeper 2-3 times stronger than what we envision due to accidents that could occur on an airports tarmac when in use. In addition, creating a stronger sweeper, although more expensive at first, will pay itself back over time. This also ensures that if the sweeper is attached below the first cart of a baggage cart train it will not fail and potentially cause damage to every cart thereafter. Additionally, some baggage carts have brake lines that run the length of the baggage cart to provide the back wheels with braking power. This is accomplished by a steel rod that about a half foot above the ground. We received a baggage cart with a front brake, so there was no brake line running down the length of the cart. In future prototypes of the FRM, the team could revise the current system to account for some baggage carts having this brake line. Lastly, all airlines prefer different types of baggage carts (this includes front or back wheel braking). While some carts differ in size, the dimensions are all very similar and making different styles of the FRM to accommodate with different sized carts would not be difficult. With the information Paul provided and actually owning a full-scale baggage cart to retrofit, we had a much better idea to how baggage carts work and move, as well as the exact dimensions that we needed to design our full scale FRM.

Bristle Information

To gather more information on the bristle system implemented on the FRM, the team spoke with Roger Williams University's facility manager, Matt Clement. We discussed the optimal type of bristle for our design and what makes bristle systems wear down. On campus, a large motor powered bristle system is used to clean sidewalks as opposed to a snow plow. Matt discussed the dangers of having the bristles too close to the ground with too much pressure being applied and how that can reduce the life of a bristle system. With this knowledge, we ordered an appropriate cylindrical brush and ensured in our design that the bristle system would not create enough down force to possibly damage the bristle system.

Commercial Potential and Projected Impacts of the FRM

Manufacturability

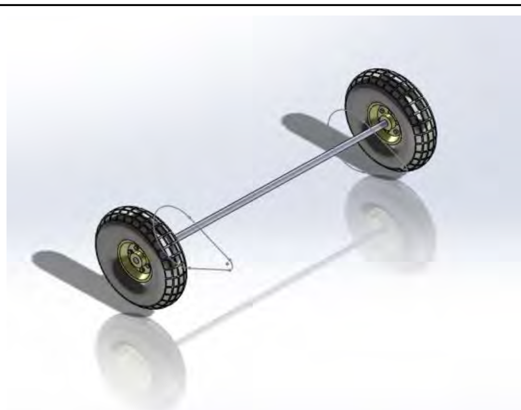

Figure 22: The drive wheels with the axle

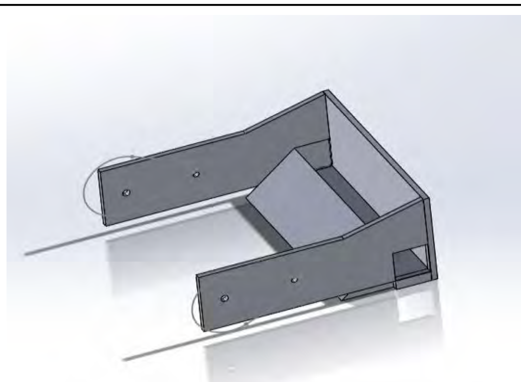

Figure 21: The framework of the FRM

The FRM system is designed to use common types of steel, gears, chain, and easily fabricated cylindrical bristles. The motivation for using these materials was to increase ease of manufacturability, and lower the costs. All steel and components are connected together by welds. The steel used for the frame of the sweeper is 1/8 hollow tube steel. This type of steel is inexpensive, readily available, and the sweeper's frame contains roughly 30 feet of this tube. These tubes were ordered pre-cut to reduce manufacturing time. The drive wheels are 13 inch pneumatic tires that again, are readily available and inexpensive. To connect the two wheels together, a fixed axle is needed. This is made of a cylindrical steel, and is pre-cut to 60 inches to reduce manufacturing time.

Gearing System and Chain

The gearing system and chain components are, once again, easily available and inexpensive. In the FRM prototype, a bicycle's front derailleur is used for the larger gear connected to the drive wheel and a one way gear is used for rotating the bristle system. They are connected together using a bicycle chain for the prototype purposes (Figure 23). The drive wheel's larger gear is directly connected to one of the drives wheels by a square, hollow piece of steel. This piece of steel is mounted to the inner hub of the drive wheel and the side of the larger gear. The simple system will reduce manufacturing time as only one gear system is needed, instead of two, and it is connected to the drive wheel instead of having to weld a gear onto a cylindrical axle.

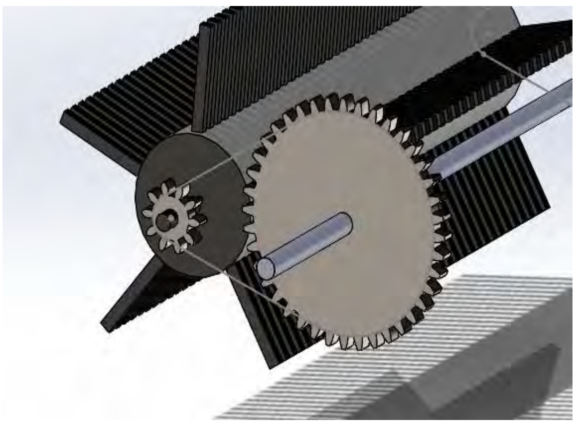

Figure 23: The two gears are connected via a chain

Bristle System

The bristle system can be ordered to exact dimensions through numerous bristle manufacturing companies. This is the most expensive piece of the FRM, but it is also the most important as this is the component that will sweep the FOD debris into the hopper. The brushes made of black polypropylene, the bristles contain a hollow tube for an axle to transverse, which is a 44 inch steel tube, and can be pre-cut to perfectly fit through the bristle system. At the end of this axle, the smaller, one way gear is attached. Using a one way

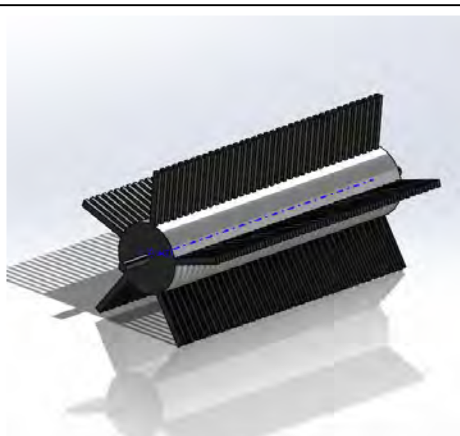

Figure 24: The black polypropylene bristle system

gear will reduce the negative impacts of the bristle system sweeping backwards if the baggage cart goes in that direction, as there is no hopper in front of the bristles to collect debris.

Hopper and Ramp

The ramp and hopper (Figure 25) are both constructed from thin sheet metal that reduces costs of the machine and still provides the needed strength of these components, as they will not be under great stress during normal operations. The large frame interface is made from 2 by 4 hollow tube steel. This piece of the FRM is one of the largest as it spans the entire baggage cart width of 64 inches. It contains two 64 inch pieces and four-one foot cross sections to connect the two longer sides together. The frames steel can be pre-cut ordered to specific dimensions to reduce the manufacturing time.

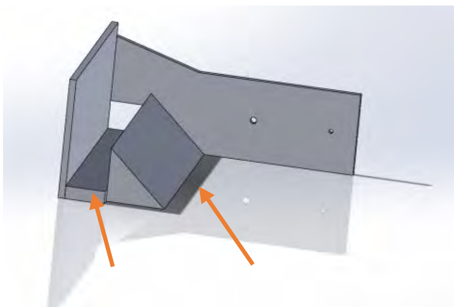

Figure 25: The hopper and ramp are constructed from thin sheet metal

To connect the entire system to the baggage cart, two pieces of sheet metal, 3 x 5.5 inch, with 2 bolts each side are used per side. The sheet metal can be pre-cut with holes for the bolts already drilled to shorten the manufacturing time. Lastly, the entire sweeper frame is surrounded by sheet metal to ensure that when debris is swept by the bristles, it will not go horizontally and miss the hopper. The ramp contain the debris' vertical movement and the sheet metal contains the debris' horizontal movement. The sheet metal also provides a pleasing aesthetic look for the entire FRM and is very inexpensive, especially for the job it needs to perform in the system.

To manufacture the system, RWUCT built a full scale model under a baggage cart with all of the materials and components just listed. It was constructed using tools common to any steel worker: a welder, a rotating drill to cut the steel to size, and basic hand tools. The system took approximately 2 weeks to construct. If the FRM were to move to fabrication on a commercial level, the time to manufacture the system would reduce drastically, especially if all material was delivered pre-cut and ready to assemble and experienced workers were employed to assemble the system.

Testing

To prove that the FRM operated as intended, testing was required. To test the system, RWUCT laid a debris field out on an asphalt and concrete surface to simulate conditions of airport pavement surfaces. The debris field consisted of the most common debris found at airports. According to the "Airport Foreign Object Debris Management" Advisory Circular, AC No. 15/5210-24, this includes: metals, rubbers, catering supplies, asphalt chunks, and plastic materials. Tests were performed to see if these items could be picked up at various speeds and on various pavement surfaces. After performing three tests on each surface and three different speeds, the amount of debris collected was upwards of 90%.

Operation

To implement the FRM at airports, the airport is required to use baggage carts. The FRM is designed to be mounted underneath baggage carts between the already existing wheels of the cart. To attach the system to the cart, holes are drilled into the sides of the cart to allow the sheet metal, which is already bolted to the large frame interface, to be bolted and attached to the cart. Once both sides are drilled to the appropriate sides, the FRM can be moved into place under the cart and the sheet metal can be attached to the sweeper and baggage cart for a secure attachment. When a baggage cart tug operator is driving a train of carts with the FRM attached to one, or all of the carts, they need not change any habits of their driving. The FRM is designed to be unobtrusive, sturdy, safe, and deal with any sharp turns or any backward motion.

The airport operators can attach and remove the FRM when they see fit. Because FOD is always being generated, it is advised to always keep at least one FRM system underneath a baggage cart train at all times. During different times of the year, snow and rain could affect the FRM's performance, as sweeping snow up would be counterproductive. It is at the airport operator's discretion to remove or attach the FRM to baggage carts to ensure all FOD is swept up. Overall, the FRM is designed as a seamless integration into an already existing airport activity. The only change is the requirement to remove the debris collected in the hopper at the end of the day; this process is very simple, as it only requires a worker to lean over and pull the hopper drawer out and dispose of the debris collected.

Maintenance

The maintenance required for the FRM is minimal. The components that require the most maintenance are the drive wheel, the gearing system and the bristles. Over time, the drive wheels will wear down and will either need to be retreaded or replaced. Because the large gear is attached to one of the drive wheels, this system could be a double replacement, where a worker replaces the drive wheel and large gear at the same time. In addition, the chain and the stresses placed on the gears will wear them down and they will need to be replaced; however, because of the FRM's simple, external design of a gear system, a worker can easily replace these components when they see fit. The final maintenance area for consideration is the bristle system. Over time the bristles will wear down due to constant contact with pavement surfaces and will become angled and shorter. Replacement of the bristle system is imminent; in order to do this, a new bristle system will have to be ordered and the system replaced on the FRM. The time period of replacing the bristle system due to wear and tear is based on how often the FRM is used. Constant use of the FRM will decrease the life expectancy of the bristle system, and vis-versa. The bristles on the FRM are made from polypropylene, have a lengthy life span because they do not absorb water, and it is less expensive than nylon. The average replacement time for the bristles is estimated to be 3-6 months.

Financial Analysis

As previously noted, FOD costs the aviation industry millions of dollars every year. The FRM addresses some of these costs and a cost-benefit analysis during the life of the system is calculated in addition to its net present value. This provides a detailed economic analysis for implementing the FRM at airports.

The FRM has the unique feature of not requiring an additional motor to power the bristles and does not require an additional vehicle to tow the mechanism around to accomplish its duty. Thus, the cost of the FRM is only comprised of its initial cost and maintenance. The initial cost of the machine is based upon the sum of the framing, drive wheels, gearing system, bristles, and collection system. The annual maintenance costs of the FRM was estimated to be an average of $500. Depending on how many systems are in place, the maintenance cost could go up or down. This is due to more use out of one machine or less use if multiple machines are working in shifts.

The service life of the FRM system will be measured in terms of 2 years. Although the majority of the system is made from steel which has a life span of upwards of 5 years, the gearing system and bristle system will wear our much faster due to its constant rotation and contact with the ground. These two components will require maintenance every 3-6 months depending on how often the FRM is used. The itemized budget of the FRM system construction is introduced in Table 2. As shown, the initial cost of the investment is less than $1,000.

Item	Description	Unit Cost	Qty/per foot	Detailed Amount	Amount
FRM Framing Material and Labor					$ 441.30
Carbon Steel	6' - 1/8" hollow tubing	$ 24.14	5	$ 120.70	
Box of welding electrodes		$ 9.00	1	$ 9.00	
Welding Labor	1 day	$ 75.00	1	$ 75.00	
Frame Interface	2" X 4" hollow tubing	$ 54.66	3	$ 163.98	
Side Panels	1/16" sheet metal	$ 31.94	2	$ 63.88	
Sheet metal and bolts	Attaches sweeper to baggage cart	$ 4.37	2	$ 8.74	
FRM Drive Wheels					$ 38.30
Pnuematic Tires	13" Drive Wheels	$ 14.00	2	$ 28.00	
Axle	5 ft. steel tubing	$ 2.06	5	$ 10.30	
Gearing System					57.58
Large Gear	7" spur gear	$ 36.65	1	$ 36.65	
Small Gear	3" spur gear	$ 20.93	1	$ 20.93	
Chain					
Bristles					$ 245.50
Bristles**	36" cylindrical bristles from Liberty Brush, LLC	$ 230.00	1	$ 230.00	
Axle	4' steel tubing	$ 15.50	1	$ 15.50	
Collection System					80.94
Hopper	1/8" sheet metal	$ 26.98	1	$ 26.98	
Ramp	1/8" sheet metal	$ 26.98	1	$ 26.98	
Hopper Frame	1/8" sheet metal	$ 26.98	1	$ 26.98	
Total Cost of FRM Sytem					$ 863.62
** received bristles at half price					

Table 2: Itemized Budget of the FRM

Another consideration was the minimum acceptable rate of return (MARR). The MARR was determined to be 5% because it is the minimum acceptable rate of return that airports would be willing to accept before implementing the FRM system. Therefore, the NPV of the system considering initial savings over alternative sweepers of $4,000, initial cost of $900, annual maintenance costs of $500, MARR of 5% and a two year service life is: $2,170.29. Following, the next step in the cost-benefit analysis is the equivalent annual cost which is the annual cost of owning and maintaining a product over its lifetime; this was calculated as $984.02.

The FRM system is designed to reduce FOD damage to aircraft at airports and make air travel even safer than it already is today. According to Boeing, in Table 3, just one piece of FOD could potentially damage an aircraft and cost the airline a significant amount of money.

Purchase cost of MD-11 engine	$8-10 million
Purchase cost of MD-80 engine	$3-4 million
MD-11 engine overhaul to correct FOD damage	$500,000-1.6 million
MD-80 engine overhaul to correct FOD damage	$250,000-1.0 million
MD-11 fan blades (per set*)	$25,000
MD-80 fan blades (per set*)	$7,000
*Fan blades are balanced and replaced as a set.	

Table 3: FOD and Maintenance Costs

Additionally, as stated previously in Table 1, FOD has caused many minor to major accidents in the aviation world. These accidents caused injury and/or caused casualties because of FOD. Having the FRM implemented in airports could potentially save lives and prevent accidents, making this system invaluable.

Conclusions

The FRM system is intended to reduce the amount of FOD on an airport's pavement surfaces. The implementation of this system will help airlines and airports cut costs associated with FOD damage and make air travel safer. Unlike all of the current FOD sweepers on the market, the FRM does not require an additional tow vehicle. This reduces the number of ground vehicles moving around the airport, thus enhancing safety. For airports with baggage carts, the FRM can be easily implemented in everyday use without causing significant changes in employee schedules or workloads. Furthermore, it gives the baggage cart a purpose other than just transporting baggage to and from airplanes.

The FRM is an affordable and effective concept addressing an airport's need to reduce FOD. The design was based on extensive research, talking with experts in the industry, and observing current systems already on the market. The FRM is a simple and efficient design to reduce the amount of FOD on aprons and tarmacs and damage to airplanes worldwide. It is extremely cost effective, costing around $900, and is much less expensive than any other FOD sweeper currently on the market.

The team expects that the safety, effectiveness, efficiency, and its ease of attachment and removal to and from baggage carts will reduce debris on an airport's pavement surfaces. It will help prevent damages to aircraft, reduce yearly costs to airlines, make air travel safer, and give the baggage cart a dual purpose. The FRM's benefits, the ability to be implemented into any airport with baggage carts, its cost effectiveness, and its ease of operations and maintenance makes the FRM a marketable product for commercial development.

Appendix A- Contact Information

Faculty Advisors

Linda Ann Riley Ph.D.
Engineering Program Coordinator and
Full-Time Professor of Engineering
School of Engineering, Computing and
Construction Management
Roger Williams University

lriley@rwu.edu

Anthony Ruocco, Ph.D.
Computer Science Program Coordinator and
Full-Time Professor of Engineering
School of Engineering, Computing and
Construction Management
Roger Williams University
aruocco@rwu.edu

Technical Mentor

Paul Remillard
Ground Support Engineer Manager of
Delta Air Lines, Inc. at Boston Logan
International Airport
Paul.remillard@delta.com

Students

Ryland Brickner-McDonald
Rbmcdonald800@g.rwu.edu

Mohamad Ghulam
Mghulam547@g.rwu.edu

Appendix B- Roger Williams University

The School of Engineering, Computing and Construction Management (SECCM) delivers a practical, hands-on approach to learning that enables graduates to adapt to rapid technological change, communicate and interact effectively with diverse populations.

The School of Engineering, Computing and Construction Management (SECCM) is a nationally-recognized leader in undergraduate education in the disciplines of Engineering, Computer Science, and Construction Management. The Engineering major is accredited by the Engineering Accreditation Commission (EAC) of the Accreditation Board for Engineering and Technology (ABET). The American Council for Construction Education (ACCE) accredits the Construction Management major.

The school curricula provide strong technical grounding within the selected discipline along with excellent written and oral communications skills. All of our programs incorporate the University's general education requirement, which assures students of an extensive and effective background in the transdisciplinary study of the social sciences and humanities. All our programs provide the option to attain additional specialization in technical or managerial subject areas. SECCM graduates are in high demand because they meet the need for professionals with the ability to adapt to societal change.

All Engineering majors are urged to take the Fundamentals of Engineering (FE) examination. Construction Management majors are encouraged to take the Associate Constructor examination. The SECCM supports these examinations by providing financial and administrative assistance for our students.

Appendix C- Non-University Partners

Delta Airlines at Boston Logan International Airport

Boston Logan International Airport is New England's largest transportation center and generates $7 billion in economic activity each year. It is a city within a city on a 1,700 acre footprint of land. The airport has a fire department, a police department, a power plant, two hotels, a non-denominational chapel and 27 acres of landscaping along the roadways and terminals.

Delta Airlines at Logan flies to over 15 national and international locations throughout the year, including the most popular departing international flight to London's Heathrow Airport. Additionally, Delta offers 73 peak-day departures from Boston.

Liberty Brush Manufacturing, LLC

Liberty Brush Manufacturing offers a full line of quality industrial replacement brushes. The ever expanding product line includes cylindrical scrubbing and sweeping brushes, side brooms, rotary brushes, pad drivers and sand paper drivers. Not only does liberty Brush provide quality brushes they also provide education and information on how to select the right brush and fill section for the right job and how to use them properly.

Liberty Brush has succeeded in becoming a highly respected company in the field of replacement brush manufacturing and distributing. With this reputation in the replacement brush market place and the dedicated staff to ensure this goal, Liberty Brush has grown into a successful operation.

Appendix E- Educational Experience

Faculty Advisor- Dr. Linda Riley

The Airport Cooperative Research Program (ACRP) provides a valuable learning experience for all students that participate. Ryland and Mohamad had a wonderful learning experience associated with this project. It allowed them to significantly improve their communication skills, learn new methods and skills associated with fabrication, and experience the design of a full scale product that is close to ready for commercialization. The nature of the competition allows students such as this team to work on not only the intellectual and research aspects of the project but also to go beyond what they have learned in the classroom. Because of the competition's open ended nature, it provides the opportunity for students to build a technical and expert mentor team that ultimately guides their solution. Ryland and Mohamad excelled in reaching out to airports and airport executives. Their determination to find a baggage cart to test their full scale product was unparalleled. In the end, their perseverance paid off and ultimately the interaction with Delta Airlines and Logan Airport significantly contributed to their success.

The competition provides an excellent platform for the senior engineering capstone design project in that the open-ended nature of the challenge fits perfectly with the learning objectives of the class. The challenge allowed the team an opportunity to study new subject matter and apply their past and new knowledge to solving and addressing an airport challenge.

The students faced several challenges with respect to this project. As engineers, Ryland and Mohamad's exposure to mechanical fabrication in "reality" in contrast to computer models was limited. Not only did they learn from the theoretical and academic perspective of the design process, but they also became quite proficient at welding, metal cutting and bending and other requirements necessary to fabricate their prototype. They sought out a number of experts in industry and were turned down many times with respect to guidance and information. However in the end, this contributed to their better understanding of how the workplace really functions. It also greatly developed their communication skills in having the ability to present their concept, and their need, whatever it might be at the moment, very quickly and succinctly. Overall, the benefits far outweighed the challenges, in fact every challenge they faced contributed to strengthening them as individuals prepared to enter the workplace.

In the future, I see continued participation by RWU in the competition. I feel that this competition is one of the best defined from the perspective of expectations, deliverables and evaluation metrics. In addition, the expert resources made available for students and overall administration of the competition is outstanding. There are no suggestions that I can make with respect to improving the competition. Unfortunately I will be retiring from teaching this year but hopefully my colleagues will continue on with the tradition of RWU's participation.

Undergraduate- Ryland Brickner-McDonald

The FAA Design Competition provided a meaningful learning experience for me. It showed me that my education can be applied to a wide variety of topics, something needed to accomplish this project. I have always liked aviation from a young age from traveling a lot with my family, and aviation has provided me with an in-depth view of a variety of cultures and great memories from many different locations around the world. Having so much previous experience with aviation as a passenger, it was meaningful to get to know the aviation world from an insider; something that this competition encouraged you to do, especially the engineering perspective. One of the major challenges we overcame as a group was gaining an extensive amount of knowledge about foreign object debris (FOD). As a group, we spent months researching and questioning the multiple aspects of FOD; from its sources, to the harm and costs it causes the aviation industry every year, and most importantly, to current tools implemented by the industry to prevent FOD. The knowledge we gained was immense and extremely helpful towards the final design. Based upon the research and information gained, our hypothesis came relatively easily. We knew just about everything there was to know about how FOD can be controlled and we brainstormed an innovative way to develop a new kind of debris removal system. Participation between our group and industry was very meaningful and useful for the project. It provided us with a view from individuals with experience in the field with much more inside knowledge of how an airport operates and the little things that occur in the industry which make a huge difference. This project taught me how to work with others more effectively, how to communicate via email and phone with a wide variety of people with different backgrounds, and how to apply previously learned engineering concepts to the real world.

Undergraduate- Mohamad Ghulam

The FAA competition provided me with a significant educational experience. My knowledge about aviation, and my communication, technical, and research skills have improved greatly over the past year. Since the competition required an extensive amount of research in order to find solutions, our product will make the aviation industry safer. It also provided me the opportunity to face a real world problem because our design project is solving the issues of Foreign Object Debris (FOD), one of the major challenges in the aviation industry. The FAA competition offered me the chance to apply what I have learned from mechanical engineering classes I have taken at Roger Williams University such as: machine design and dynamics because the FRM contains several mechanical components. Building prototypes using circular saws and wielding machines that the school provided have improved my technical skills. Communication with different companies, my group member, and technical advisor played a significant role in improving my communication skills. Overall, I have learned so much about the FAA and airport operations and have added various skills to my knowledge which will benefit me in the future. Finally, the competition has served to enhance my academic experience thus far while attending Roger Williams University.

Appendix F- References

"AIRPORT BAGGAGE CART 3D MODEL." *formfonts*. Web. 4 Dec. 2014. <http://www.formfonts.com/3D-Model/7138/transportation/i10-aircraft/airport-baggage-cart/>.

"Airport Runway Sweepers." *mascosweepers*. Web. 4 Nov. 2014. <http://www.mascosweepers.com/airportrunway/index.html>.

"Baggage Carts." *Clydemachines*. Web. 4 Dec. 2014. <http://www.clydemachines.com/pdfs/baggage_carts/15F_2800_Baggage_Cart.pdf>.

"Baggage Carts." *clydemachines*. Web. 4 Dec. 2014. <http://www.clydemachines.com/baggage_carts.html>.

Budynas, Richard G. and J. Keith Nisbett. *Mechanical Engineering Design*. Ninth ed. New York: McGraw-Hill, 2008. Print.

Caruso, Lisa. "What Are The Five Most Important Issues Facing The Aviation Industry?" *Transportation national journal*. 30 Nov. 2009. Web. 1 Oct. 2014.

<http://transportation.nationaljournal.com/2009/11/what-are-the-five-most-importa.php>.

"Challenges to Airport Ramp & Runway Debris Control." *Boeing*. N.p., Oct. 2010. Web. 1 Oct. 2014. <http://www.boeing.com/assets/pdf/commercial/airports/misc/asosfodpres.pdf>.

"The economic cost of FOD to airlines." *Fod-detection*. Mar. 2008. Web. 21 Oct. 2014. <http://fod-detection.com/wp-content/uploads/2009/12/the-economic-cost-of-fod.PDF>.

"FAA Air Traffic Organization Safety Management System Manual." *Emerald.ts.odu.edu*. N.p., May 2008. Web. 4 Dec. 2014.

<http://emerald.ts.odu.edu/Apps/FAAUDCA.nsf/SMSManual.pdf>.

"Foreign object damage." *Wikipedia*. Web. 8 Oct. 2014. <http://en.wikipedia.org/wiki/Foreign_object_damage>.

"Foreign Object Debris and Damage Prevention." *Boeing*. Web. 1 Oct. 2014. <http://www.boeing.com/commercial/aeromagazine/aero_01/textonly/s01txt.html>.

"Foreign Object Debris (FOD)." *Aviationknowledge*. Web. 8 Dec. 2014. <http://aviationknowledge.wikidot.com/aviation:fod-under-construction>.

Gupta, Ram S. *Principles of Structural Design: Wood, Steel, and Concrete*. 2nd ed. Boca Raton: CRC, 2011. Print.

"How To Choose Between Solid Rubber, Pneumatic & Polyurethane Forklift Tires." *Theforkliftcenter*. Web. 4 Dec. 2014. <http://www.theforkliftcenter.com/guide/choosing-a-forklift-tire-type.php>.

"MAGNETIC SWEEPER." *uline*. Web. 4 Nov. 2014. <http://www.uline.com/BL_8875/Magnetic-Sweeper>.

"Materials for Bristle Brushes." *Gordonbrush*. Web. 4 Dec. 2014. <http://www.gordonbrush.com/material_descriptions.php>.

"MultiFunctional Solutions - Infants safety at Airside." *Airport Suppliers*. 12 Oct. 2010. Web. 21 Oct. 2014. <http://airport-suppliers.com/supplier/Multifunctional_Solutions_Inc/press_release/Airport_Baggage_Carts_1/>.

"Nylon Brush." *Spiralbrush*. Web. 5 Dec. 2014. <http://www.spiralbrushes.com/nylon.html>.

Osborne, Charlie. "10 challenges for your airline and airport in 2013." *zdnet*. 3 Jan. 2013. Web. 1 Oct. 2014. <http://www.zdnet.com/article/10-challenges-for-your-airline-and-airport-in-2013/>.

"Local pilots: Most mechanical issues accounted for." Democratandchronicle. 18 June 2014. Web. 1 Oct. 2014. <http://www.democratandchronicle.com/story/news/2014/06/17/todd-cameron-small-plane-crashes/10713983/>.>.

"Shields Towable Magnetic Sweeper (60, 72, 84, 96-Inch Lengths)." *aerospecialties*. Web. 4 Nov. 2014. <http://www.aerospecialties.com/aviation-ramp-safety-equipment/fod-magnetic-sweepers/heavy-duty- tow-behind-fod-magnetic-sweeper.html>.

"Starting a Sweeping Business Information." *mascosweepers*. Web. 4 Nov. 2014. <http://mascosweepers.com/pdf/Masco_Starting_Business_Print.pdf>.

"STRATECH LAUNCHES WORLD FIRST INTELLIGENT AIRFIELD/RUNWAY SURVEILLANCE AND FOD (FOREIGN OBJECT & DEBRIS) DETECTION SYSTEM." *Stratechsystems*. Web. 8 Dec. 2014. <http://www.stratechsystems.com/news/p_news72.htm>.

"Sweeper Overview." *FODNews*. 27 Mar. 2013. Web. 21 Oct. 2014. <http://www.fodnews.com/sweeper-overview/>.

"To assist our clients in developing the best possible Safety System to meet their needs." *system-safety*. Web. 8 Dec. 2014. <http://www.system-safety.com/Training_Aids/FOD.htm>.

U.S. Department of Transportation. "Airport Foreign Object Debris (FOD) Management." *Federal Aviation Administration*. Washington DC: 2010. 1-44. Print.