2023-2024 ACRP University Design Competition

PuriSky Debris Collector

(August 2023 - December 2023)

Design Challenge: Airport Management and Planning: *Planning and Preparing Airport Infrastructure for the Integration of Commercial Space Operations.*

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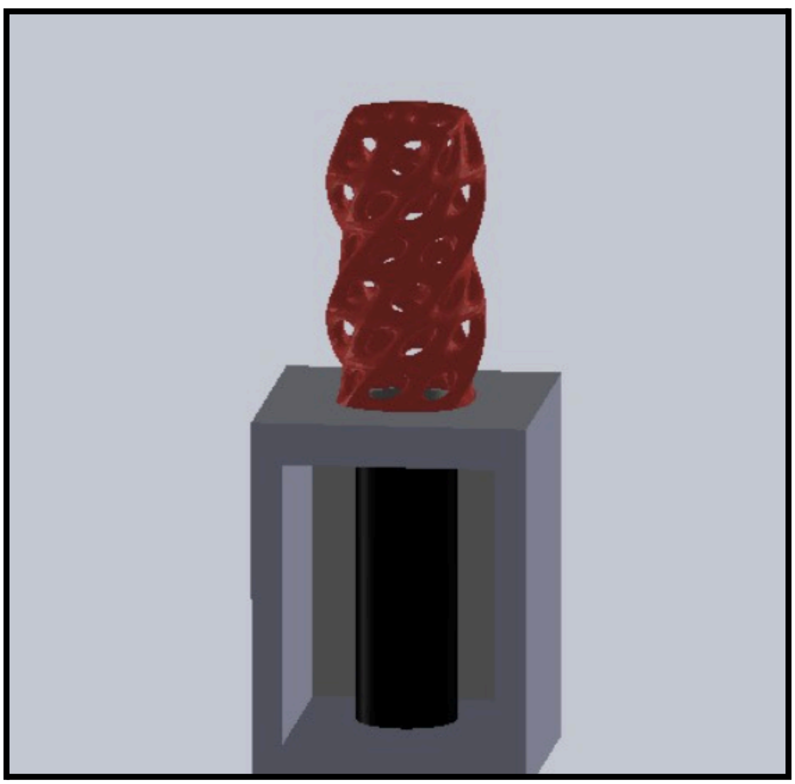


PennState College of Engineering | ENGINEERING DESIGN AND INNOVATION

Executive Summary

A team of four multidisciplinary undergraduate students in The Pennsylvania State University Engineering Leadership Development program is proposing a solution to mitigate the debris clouds generated by continuous space launches. This proposal addresses the ACRP Design Challenge under the Airport Management and Planning: Planning and preparing airport infrastructure for the integration of commercial space operations. This team has designed a field of 24 vacuum filtration towers that will collect the debris particles within these clouds and thus purify the surrounding airspace around the airport, hence the name PuriSky. They have thoroughly researched and analyzed the potential impact that the design has on the air travel industry through a cost-benefit analysis, a risk assessment, and conducting many interviews with experts within the industry as well as pilots. After careful analysis, the team has concluded that the proposed solution is feasible, innovative, and cost-effective, and will subsequently enhance the airport infrastructure in a unique manner. The commercialization of space travel will continue to trend upwards, and the PuriSky debris filtration tower is therefore necessary to ensure that space travel integration with airports comes to fruition. With this solution, airports can reduce the amount of downtime that occurs after spacecraft launches near them. In addition, passengers will have a much better experience at the airport due to the reduced downtime. The resulting projections indicate that they will subsequently be incentivized to spend more money at the airport, which will further improve airport revenue.

Table of Contents

Background

Following recent innovations in the spaceflight industry, it is becoming increasingly evident that commercial spaceflight will become the new standard. While space launches were traditionally conducted exclusively by federal agencies such as NASA and DoD, private companies such as SpaceX and Blue Origin are becoming the primary contractors for both government and commercial missions. As the industry gains new competitors, the frequency of space launches also continues to grow.

In response to the evolving environment of spaceflight, the Federal Aviation Administration (FAA) released a Concept of Operations in 2020 dedicated to addressing the integration of commercial space operations into the National Airspace System (NAS). The document aims to highlight current shortfalls in the NAS in relation to commercial space before identifying stakeholders of the new ConOps (i.e. Safety Organizations, Federal Agencies, and Foreign Entities), outlining the revised operations, and how the operations will accommodate said stakeholders (FAA, 2020). Some of the primary concerns outlined in the document include launch/re-entry sequences and sites, dual-use airports, environmental policies, and risk mitigation for operational scenarios. Overall, the document presents itself as an aggressive approach to ensuring a seamless transition between commercial space and aviation operations; therefore, “As the industry matures and new technologies advancements emerge, the engagement of the FAA and its partnership with industry will also evolve” (FAA, 2020, p. 9).

A notable operational scenario within the document defines the procedures for NAS users (e.g. Air Traffic Control (ATC), airplanes, airports. etc.) in the event of a “Catastrophic Failure on Launch”- the term used for midair spacecraft explosions (FAA, 2020, p. 95). The scenario introduces the danger presented by debris clouds to aviation operations, noting that it is imperative that airplanes are forbidden from flying below certain altitudes or are grounded altogether. The prospect of delaying or canceling flights due to launch failures- though uncommon- further affects the implications of integrating commercial space with aviation.

One key event that supports the need for such alterations in NAS operations is the first-ever SpaceX Starship launch in April of 2023. Equipped with 33 engines- making it the largest and most powerful rocket in history- the Starship produced enough force to decimate the launchpad in Boca Chica, TX before exploding just minutes into the launch. The aftermath of the launch consisted of particulate matter spreading miles away from the launch site, thereby affecting air quality and visibility. Due to the unexpected consequences of the launch, the FAA launched an investigation into the incident with the hopes of solidifying risk mitigation procedures for any subsequent launches (Kolodny, 2023).

Problem Statement

With the impending integration of commercial space with aviation, there is a heightened risk of debris particles from spacecraft launched in close proximity to airports affecting aeronautical operations. The lack of preparation for the first Starship flight test proves that more must be done to diminish the severity of space launches on the environment. According to environmental engineer Eric Roesch, “The possibility of a widely dispersed plume of emissions was not disclosed by the FAA or SpaceX, during the initial environmental and approval process” (Kolodny, 2023). With space launches anticipated to occur frequently on a regular basis, the risk presented by the launch of Starship will only continue to increase. Currently, ATC, airport terminals, and runways are not equipped to handle the visibility issues from debris clouds due to space launches.

The goal of this proposal is to design a system that reduces the debris particles emitted by space launches in order to prevent flights from being grounded due to unsafe visibility conditions. The solution fulfills the requirements of the ACRP Airport Management and Planning Challenge by preparing airport infrastructure for the integration of commercial space operations.

Literature Review

Background, Aftermath, and Implications of the Starship Launch

Only 4 minutes into its mission, the SpaceX Starship spacecraft self-destructed in the early hours of April 20th, 2023. This followed multiple brief launch tests with 3-engine spacecraft, a period of over 500 days in which the company's application for a license for near-orbital launch was under review by the FAA, and a scrubbed launch due to a frozen valve (Malik & Wall, 2023). In addition, SpaceX informed the FAA and other agencies that in the event of an "anomaly," the expected debris would fall within a 700-acre area of the launch site-about one square mile, with the maximum distance being three-quarters of a mile from the launchpad. (Kolodny, 2023)

However, there still were not enough safety measures taken for the launch, namely regarding the launch pad and the ensuing debris cloud from the launch. After a few engines failed to ignite, the spacecraft was idle for several seconds at the start of the launch before finally taking off. The outcome was a crater in the launchpad and debris clouds from the launch site raining down on people in Port Isabel, located 6 miles from Boca Chica (Kolodny, 2023). With the clouds being comprised of concrete particles, the visibility of the surrounding area was massively impacted.

Following the launch, the FAA launched a mishap investigation into the Starship flight test, ultimately resulting in SpaceX being required to undergo a 75-step plan to subdue the impact of future launches on the surrounding area (TIME, 2023). On November 18th, 2023, SpaceX was finally able to execute a second flight test of Starship, which subsequently exploded nearly 10 minutes into the flight. Although the launchpad withstood the power of the engines, the plume from the rocket still affected the visibility in the area.

Regardless of how sturdy any launchpad is, the sheer power of the rocket engines generates enough force to decimate concrete and generate thick plumes. As demonstrated in the first Starship flight test, these clouds are fully capable of traveling several miles away from the launch site. In addition to devastating the surrounding environment, this could also complicate the integration of commercial space operations with aviation.

Airspace Closures Due to Space Launches

Currently, there are no airports simultaneously servicing commercial aviation and vertical space launches. However, the FAA has outlined standard procedures for the NAS in the event of a space launch, including temporarily grounding flights in a 30-mile radius or diverting them away from the area to account for the spacecraft and ensuing emissions (FAA, 2020). Although it is implied that the FAA may adjust these procedures as space operations are slowly integrated with commercial aviation, there will still be a common understanding that flights must be at least 10 miles away from an ongoing space launch due to federal regulations.

An additional consideration is the duration of airport “downtime” after a launch. While normal rocket launches do not have a significant impact on the number of planes grounded, any Catastrophic Failure on Launch could affect this by a sizable margin. Larger rockets- like Starship- can still cause massive flight delays, even if the launch goes as planned.

One unique aspect of this proposal is that both the problem and the solution are extremely futuristic. Based on current trends, it is reasonable to conclude that commercial space launches will occur more frequently over time, and may eventually happen on a regular basis. This introduces a third and final aspect of the problem: an increase in space launches will result in an increase in the debris clouds that form. With little time between launches- especially if there could be one launch per day- the air quality and visibility will be weakened. In turn, this could result in reduced hours of operation for airports, which would affect the aviation industry financially and reduce the satisfaction of travelers.

Airport Procedures in Response to Environmental Conditions

In the present day, there have not been enough space launches for the environment to have been affected by the launch debris. Therefore, there are no recent examples of airports having to adjust operations as a direct result of low visibility from debris clouds from spacecraft. However, there are several occurrences of airport closures due to low visibility due to environmentally-related factors.

Following a “red alert” issued by the Chinese government in 2016, the Beijing International Airport suffered from low visibility due to thick smog. This resulted in the cancellation of 350 flights, a significant loss for the second-busiest airport in the world. A similar situation occurred 5 years earlier, with several hundreds of flights being canceled as well. The smog affected both airlines and passengers alike, leaving thousands of travelers stranded (South China Morning Post, 2016).

Similarly, the government of the UAE issued a “red alert” in 2022 due to severe sandstorms in and around Dubai. In addition to several flight delays within the two-day span, 44 flights were canceled, with another 12 being diverted to the nearby Dubai World Central Airport.

Again, thousands of passengers were caught up in the disruption, and operations were slow to return to normal (Maszczynski, 2022).

Finally, the 2023 Canadian wildfires disrupted flights to and from the US due to poor air quality and visibility. This prompted the FAA to temporarily halt all inbound flights to Philadelphia and air traffic into LaGuardia. In total, over 4,200 international and domestic flights departing and arriving in US airports were delayed as a direct result of the smoke from the wildfires (Josephs, 2023).

While it may take an extended period of time, an influx of space launches emitting large debris clouds can yield similar impacts on the aviation industry in the future. It is therefore beneficial to identify systems that are designed to combat such situations.

Current Large-Scale Air Filtration Solutions

One particular solution designed to eliminate the impact of smog is located in Xi'an, which houses the world's largest air purification tower. Built-in 2016, the 200-foot tower consists of filters that accounted for a nearly 20% drop in harmful fine particulate matter within a nearly 4 square-mile radius. The tower cost $2 million and has the potential to save tens of thousands of lives in the Chinese city each year (Chow 2018).

In India, an air purification tower was built within the city of Chandigarh, covering a 500-meter radius. Following a similar design to the tower in Xi'an, the structure is the largest in the country and accounted for a 70-80% decrease in air pollution within the area. As such, air temperatures have decreased while visibility has continued to increase (The Tribune, 2021).

A smaller yet effective tower was installed in the Indian capital of New Delhi, standing 18 feet tall and covering a radius of up to 350 meters. Unlike the previous solutions, this tower utilizes electric fans to absorb debris particulates in the surrounding area. This is extremely beneficial for areas with high concentrations of smog and can clean the surrounding air in a short amount of time (Holland, 2023).

While it is possible to prototype hundreds of towers to clear the air within a large area, one key consideration is the manner in which the particulate matter is disposed of. Over a 100-day span, artist “Brother Nut” used an industrial vacuum to collect dust from Beijing’s atmosphere. The end result was a brick made up of the particulates, serving as a symbol of the city’s air quality issues (Buckley & Wu, 2015). In the case of space launches, the majority of the debris clouds will be made up of concrete particles, and using a similar method can result in the creation of concrete as a result of the collection of debris clouds. Therefore, it is entirely possible to not only properly dispose of the air particulates, but also recycle them in an efficient manner.

Cape Canaveral Spaceport and Orlando International Airport

The final portion of the literature review was dedicated to finding a reliable location to implement the team’s solution. While Spaceport America in New Mexico accommodates both aviation and space operations, it only has the capacity for horizontal space launches, which are generally suborbital. In order to properly prepare for the integration of commercial astronautics with aeronautics, it is imperative to identify a site capable of supporting commercial aviation and vertical space launches.

The FAA referred to the Cape Canaveral Spaceport (CCS) as a reference for its revised NAS procedures within the ConOps due to its annual frequency of space launches and proximity to Orlando International Airport (MCO). In addition, Space Florida has outlined expansion plans for CCS that include runways for horizontal launches, transportation to nearby airports, and the integration of all aeronautic and astronautic facilities in the area (Space Florida, 2017).

An additional benefit of integrating CCS with the Orlando International Airport is that it is one of the busiest airports in the country, which could increase the joint revenue of both facilities. Therefore, it would be in the team's best interest to apply the solution to the Orlando area in order for them to properly combat debris clouds while maintaining passenger comfort and regular airport operations.

Interaction with Industry Experts

In order to gain a better background on the requirements for the solution from an aviation industry perspective, three experts were interviewed: John Greaud, Senior Project Manager at Barge Design Solutions, Inc.; Barry Bratton, Associate at ADK Consulting & Executive Search; and Harish Joshi, Aviation Professional (Pilot).

John Greaud

John introduced the concept of Foreign Object Debris (FOD) and how a large cluster of such debris can impede airport operations. Especially if FOD enters an airplane engine, it can cause millions of dollars worth of damage and raise safety concerns. It is crucial to ensure that any sort of debris is accounted for, whether it's on a runway or near the terminal. Airborne FOD is the most difficult to account for, and once spaceports are integrated with airports, accounting for debris particulates in the air is an extremely high priority.

Visibility is not only a crucial factor for airplanes, but for ATC as well. John suggested that if a solution designed to increase visibility were implemented, it would be extremely effective if it were installed on or around a control tower. However, he believed that FOD would mainly impact runways the most, and therefore the solution would have to be implemented in a manner that ensures the entire airspace encompassing the airport is accounted for.

Towards the end of the research period, the team was considering prototyping either a series of small towers near the spaceport or a vacuum unit surrounding the launchpad itself. John suggested that they pursue the vacuum design, as it would attack the problem at the source; in addition, varying wind speeds could affect the small tower design. He also emphasized the function of baghouses and how they could be integrated into the final design. Overall, the group was able to gain a solid background on how a vacuum-based design would benefit the solution.

Barry Bratton

At the time of Barry's interview, two types of solutions were being considered; ground-based (i.e. towers, sweepers) and airborne (i.e. blimp, drone). After consulting him, it was best to stick with a ground-based approach as it would allow them to have a centralized power supply and disposal system. In addition, an airborne design would likely raise concerns regarding hindrances for airplanes and may be more of an inconvenience than a viable solution.

Barry also provided extensive insight regarding potential materials to use for the solution, with the primary focus being based around identifying a low-cost and lightweight building material. This would have to be balanced by making sure the structure can withstand any solid debris, indicating that the solution must be sturdy enough to resist FOD of any size. Therefore, it would be advisable to avoid any "bag-like" designs to collect debris and instead opt for solutions made from stronger materials such as steel or ceramic.

When presented with the option between a tower or vacuum design, Barry encouraged the team members to take into account the potential impact the solution could have on birds and other animals. While he did not prefer one approach over another, it became clear that a tower-based design could be easier to prototype to protect wildlife due to its size. His words were therefore taken into consideration when designing safety measures for the final prototype.

Harish Joshi

As an experienced pilot, Harish vocalized his support for the small tower design due to its ability to clean air over a larger surface area rather than focusing on a single area. Commercial pilots are trained to land in near-zero visibility scenarios, however, he told them that dispersed smoke is safer to fly in than a small but dense area of smoke. Because visibility can change drastically over a short distance, it would be best to pursue a solution that eliminates the unpredictability of fog and FOD.

Problem-Solving Approach

Overview

The design process began with understanding the motives and desires of users and stakeholders regarding the implications of commercial space operations with airports. It was deduced that five main stakeholders are involved in the problem to be solved; airport passengers, airport/airline workers, airport managers, commercial airline pilots, and the users of the space sport. Passenger morale was also taken into consideration as it would be affected by delays due to launches in addition to pilots potentially struggling to take off and land due to visibility issues from launch emissions. The amount of money that the airport managers would lose was also taken into account because of the increased amount of shutdowns due to launches. These factors aided in the problem definition; after the problem was identified, the team began to brainstorm ideas for potential solutions. This phase of the project was the most challenging because the team was made up of a diverse range of personalities and backgrounds. However, it allowed them to produce an eclectic assortment of ideas due to each group member's ability to bring new ideas during the idea generation round.

Problem Definition

A side effect of integration of commercial space is a heightened risk of visibility issues affecting airport operations. This issue became apparent during the aftermath of the SpaceX Starship launch failure, which caused massive debris clouds to spread several miles away from the launchpad. Especially with more space launches occurring on a regular basis, this risk will continue to increase over time. Commercial pilots require enough visibility to take off and land, and if this is not an option, flights have to be delayed or canceled, thus losing airports millions of dollars a year. Currently, the airport runway and other surrounding infrastructure are not equipped to handle the visibility issues generated by debris clouds.

The first key insight gained from the literary review is that rocket engines generate enough force to decimate concrete and generate thick plumes. These debris clouds are capable of traveling miles away from the launchpad harming the surrounding environment. In addition, the students found that there have been at least three instances in multiple countries where low visibility has led to flight cancellations and delays. They also learned about how both China and India currently have air filtration towers for air pollution but these towers aren't made for debris particulates. Next, the team was able to cite sources that informed them that it's entirely possible to recycle air particulates like concrete debris. The final product of the review was that they decided to select CCS and MCO as the model ports to integrate together for the solution. This was decided because of the proximity these two ports have to each other and the amount of revenue MCO generates yearly.

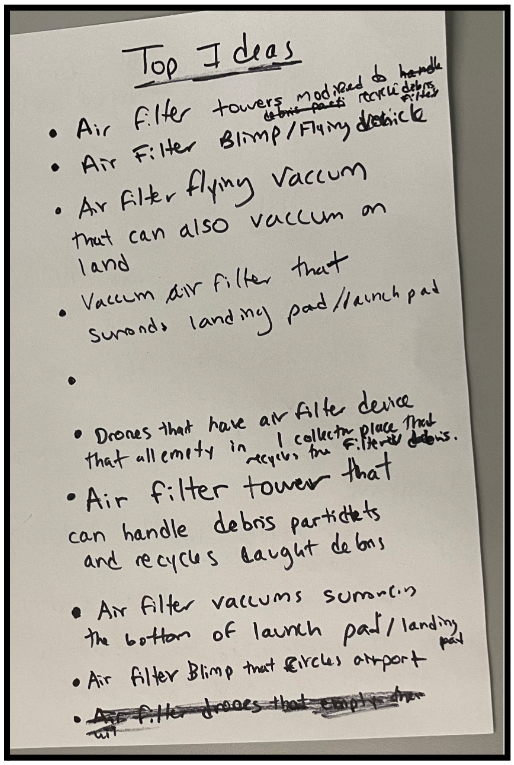
Each person the team interviewed provided valuable expertise to help the team understand the problem and users. An important detail earned from John was that debris would mainly impact runways the most, and therefore the solution would have to be implemented in a manner that ensures the entire airspace encompassing the airport is accounted for, not just one part of the infrastructure. One insight gained from Barry was that it would be best to stick with a ground-based approach, as it would allow them to have a centralized power supply and disposal system; it would also be better because an airborne design would likely be a hindrance for airplanes. Barry also helped them realize the additional environmental impacts the solution could have. Mainly with the potential of wildlife interfering with or getting hurt from the solution. The group learned from Harish Joshi, an experienced commercial pilot, that dispersed smoke is safer to fly in- even if it is spread across a large area- than a small but dense area of smoke.

POV Statement

In the future, airports will require an efficient system to effectively prevent debris clouds generated from launches from affecting the visibility on the runway and surrounding areas. Sufficient visibility is required to ensure that aircraft can take off and land safely. With the addition of commercial space operations, visibility will be reduced every time there is a launch; without an effective solution in place, airports will have no choice but to delay operations or shut down operations completely. It would be game-changing to have a debris collection solution in place that can mitigate visibility issues so that flight timetables can remain unchanged, eliminating the need for delays or cancellations.

Ideation

The ideation process had two phases. The first phase was completed individually, with each team member responsible for coming up with initial solutions to the problem. Then, the team met up as a group for phase two. In this phase, the group utilized the round-robin technique, in which each member of the team shares one idea and then the entire team gives feedback on all the ideas shared. Once the feedback is given, then the group can collectively share their next idea. This method was chosen because the team was determined to primarily have been comprised of introverts who sometimes found it hard to speak up during discussions. With this technique, everyone had the chance to speak and give feedback; after the initial round of ideation, a list of the best ideas was generated. These ideas are reflected in *Figure 1*.



[Figure 1: Top ideas after ideating]

Once the team collectively decided on eight top ideas, the next step was to consult experts to test their ideas so they could narrow down their selection further. They learned from the experts that blimps don't have a very thick membrane, so they may pop if used as a debris collector. Additionally, they learned even the largest drones can't collect as much debris as the tower or vacuum idea. Lastly, they learned that ground-base solutions would eliminate concerns about payloads or retrieval systems. With these key findings, they ultimately decided to move forward with only the ground-based solutions. With further research, the team also decided to split the air filtration tower idea into two different sizes going into the prototyping stage.

Technical Aspects of Design Development

Decision Matrix

Once the group prototyped their top three ideas and tested them with experts it was time to use an unbiased method to select the top idea. They decided to consult a decision matrix, which is referenced in *Figure 2*. In this matrix, the team collectively came up with four main categories to judge each solution on, and through brainstorming, the students came up with many additional criteria to judge the prototypes on. They also included the categories that were important but not as crucial as the top four which were feasibility, efficiency, durability, and cost.

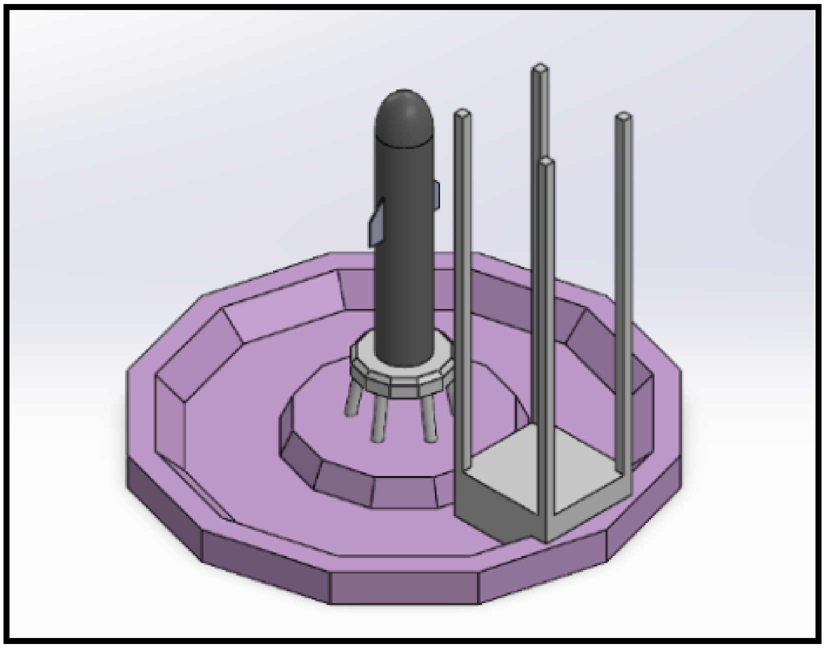
		PRIMARY				SECONDARY						
	Criteria Weight	Feasibility 10	Efficiency 10	Durability 8	Cost 7	Maintenance 5	Environmental Impact 4	Easy to Use 3	Build Time 2	Materials 1	**TOTAL** 50	**SCORE (PERCENT)**
Big Tower	Score out of 10	8	5	8	7	8	6	8	5	8		
	Weighted Score (DO NOT EDIT)	*8*	*5*	*6.4*	*4.9*	*4*	*2.4*	*2.4*	*1*	*0.8*	34.9	**69.80%**
Small Tower	Score out of 10	9	8	6	7	7	8	8	6	8		
	Weighted Score (DO NOT EDIT)	*9*	*8*	*4.8*	*4.9*	*3.5*	*3.2*	*2.4*	*1.2*	*0.8*	37.8	**75.60%**
Launchpad Vacuum	Score out of 10	7	8	9	6	5	8	8	4	8		
	Weighted Score (DO NOT EDIT)	*7*	*8*	*7.2*	*4.2*	*2.5*	*3.2*	*2.4*	*0.8*	*0.8*	36.1	**72.20%**

[Figure 2: Evaluation of the top three solutions through a Decision Matrix]

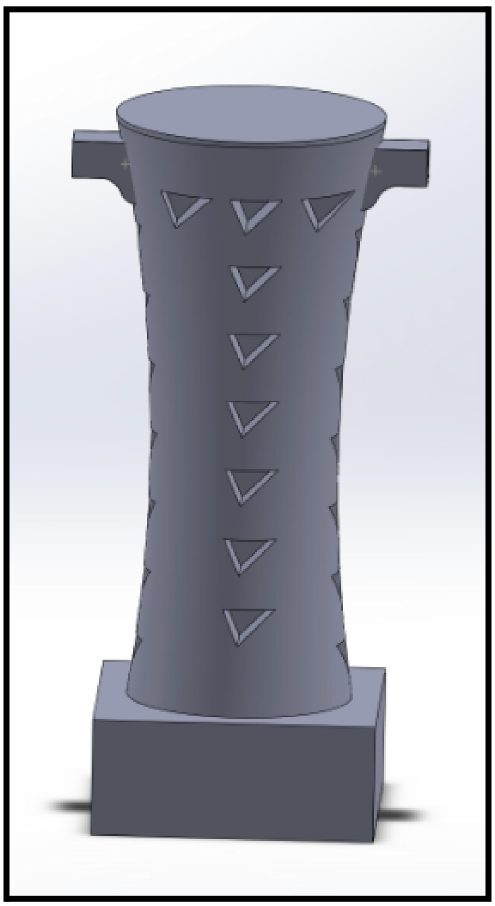
With those nine categories selected, the team referred to the expert interviews and literary review to score each top solution. The big filtration tower scored 69.80%, which was the lowest score; the small filtration tower scored 75.60%, thus scoring the highest. The launchpad vacuum scored 72.20%, placing its score between those of the other two solutions. Ultimately, the small tower was selected as the best solution as a result of the matrix. However, because the launchpad vacuum also scored highly, it was determined that combining those two ideas by integrating the best aspects of each idea into a uniform solution would be the optimal course of action.

Rapid Prototyping

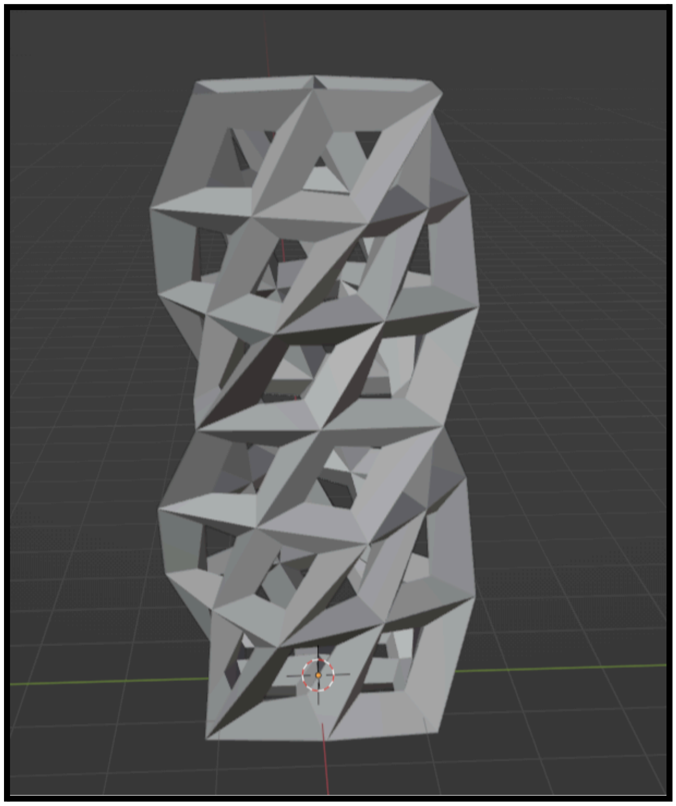
In order to receive the best possible feedback from stakeholders/experts, the team created CAD models of each top idea; *Figure 3* through *Figure 5* illustrate the visuals and descriptions of the prototypes. The first idea the team modeled was the launchpad vacuum idea: the motivation behind this idea was that the best way to solve the problem would be to tackle it at its source. This solution would surround the launch pad and absorb all debris generated during launches. The second prototype constructed was a big air filtration tower. With this concept, there would be triangular holes on each side of the tower through which debris clouds would pass through. Within the big tower, there would be a filtration system and a mist system to purify the air as well. At the top of the tower are spouts that would blow out the purified filtered air back into the environment. The final prototype is the small filtration tower, in which there would be several more openings to allow larger portions of the clouds to be filtered through the tower. This spans over 360 degrees as well and would act as an advanced air filter. After testing these three ideas, the group would then be able to pick one of them to move forward with.



[Figure 3: Launchpad Vacuum Debris Collector]



[Figure 4: Big filtration tower]



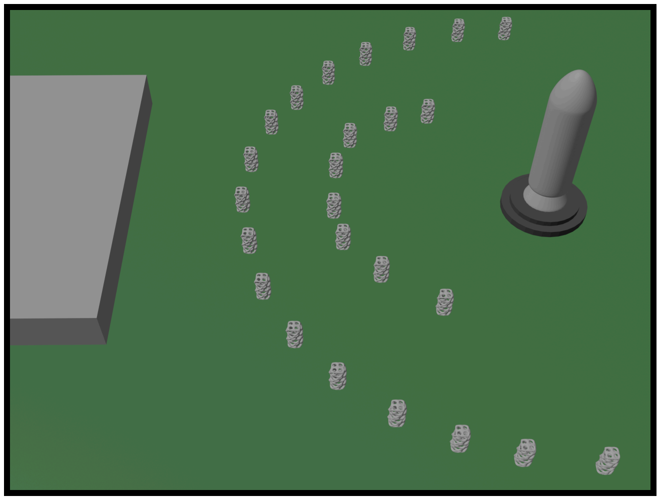
[Figure 5: Small filtration tower]

Stakeholder Feedback

The last task required from the rapid prototyping phase was testing the top ideas with experts or stakeholders. For this phase, the team referred back to John Greaud, Harish Joshi, and Barry Bratton. John suggested that they should pursue the Vacuum design due to it attacking the problem at the source while introducing the concept of Baghouses to the group; the students could then integrate the baghouse’s function and effectiveness into the final solution. Harish preferred the Small Tower design, emphasizing how covering a large surface area is more beneficial to pilots’ ability to fly in addition to the safety of all passengers and crew due to the unpredictability of fog. He also stated how as a pilot, he is trained to land in near-zero visibility scenarios, and that dispersed smoke is safer to fly in than a small but dense area of smoke. Barry was conflicted between the Vacuum and Small Tower designs, and he brought up that either solution could harm the bird population and may be something to consider further. John also prompted the team to consider how varying wind intensities and directions could affect the placement of the Small Towers if they chose that solution.

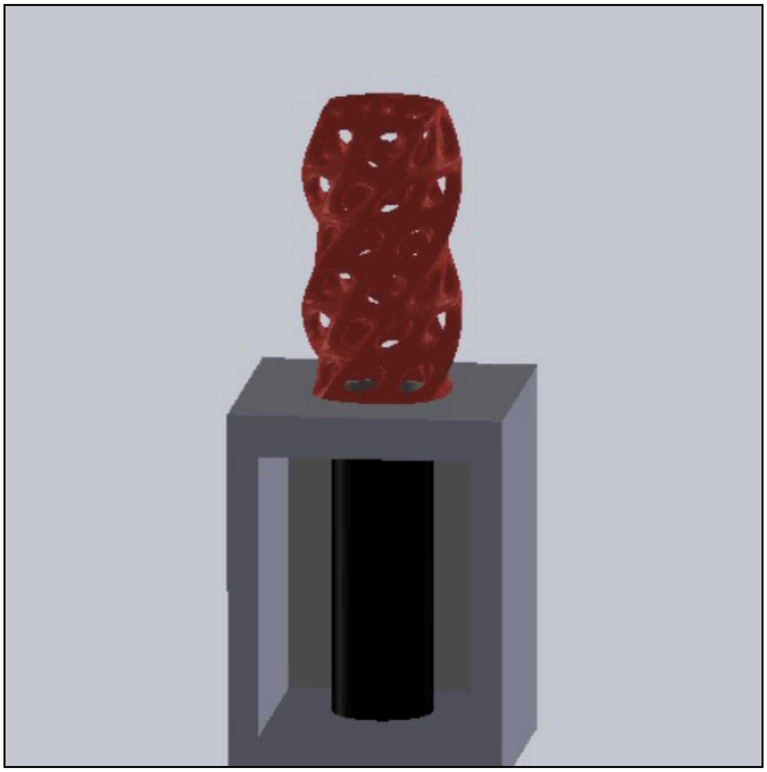
Final Prototype

After speaking to the experts and designing the decision matrix, the group ultimately decided to go with a field of small filtration towers. After further discussions with John, the team realized having the tower use a normal air filter was not going to work for preventing airport operation shutdowns. This is because it sometimes takes up to a whole day with a normal air filter tower to effectively clean the surrounding environment. They decided that for the final solution, aspects of the vacuum launch pad idea would be incorporated into the filtration tower. With a vacuum installed in the tower, the debris clouds would be collected and purified at a much faster rate necessary, thus enhancing the efficacy of the solution. After fine-tuning the proposed solution, the students decided to test the idea again with John. John described further how the wind direction and speeds could cause the clouds to miss the solution. From this interview, the team decided to change the amount of towers from 6 to 24 towers and alter the orientation of the towers. The orientation changed from a square formation to a semi-circle formation with two rows, as shown in *Figure 6*.



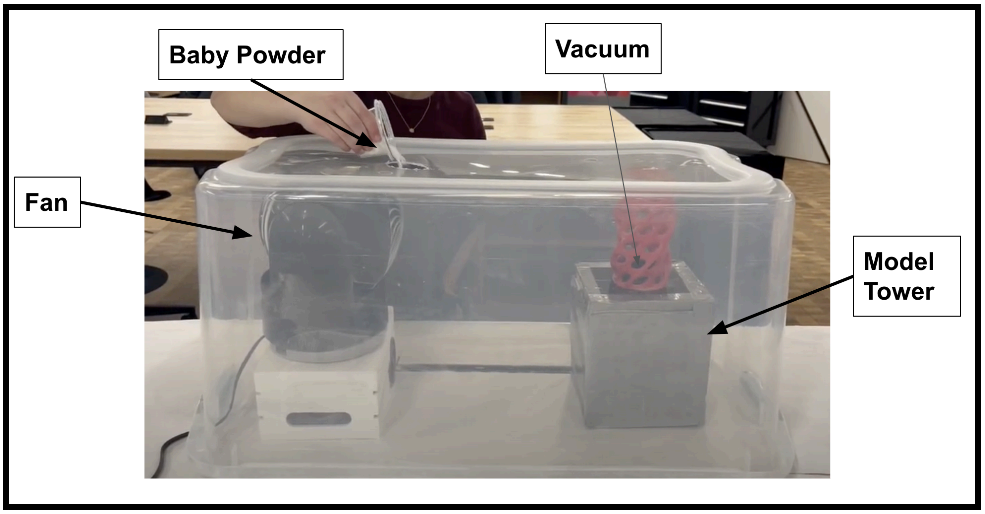
[Figure 6: CAD rendering of final solution]

The area reflected in the leftmost part of the diagram represents the airport, while the model furthest to the right is a structure that symbolizes the rocket; in the middle are the towers in their improved formation. The final solution is called the PuriSky debris collector, consisting of a field of 24 vacuum filtration towers, as referenced in *Figure 7.* Each tower has a building that houses an advanced vacuum, which feeds into the innovative suction tower design that consists of circular openings designed to absorb debris clouds from every direction. How the tower works is the debris clouds will drift through it and as the clouds go through the tower the vacuum will be able to absorb the debris particles embedded in the clouds. By the time the clouds leave the tower, they will have little to no debris particles left within them and therefore won't affect the visibility at the airport. The tower has a dual function of being able to clean the surrounding air in all directions as well based on prototype testing. Eventually, the vacuum storage unit will fill up with debris particulates. When this happens, a built-in hatch has been installed to drop the stored debris into a truck that can park itself under the vacuum storage unit. The concept of trucks being able to run through every tower came about after one of the experts suggested that the group should find a way to link the storage collection to all 24 towers.

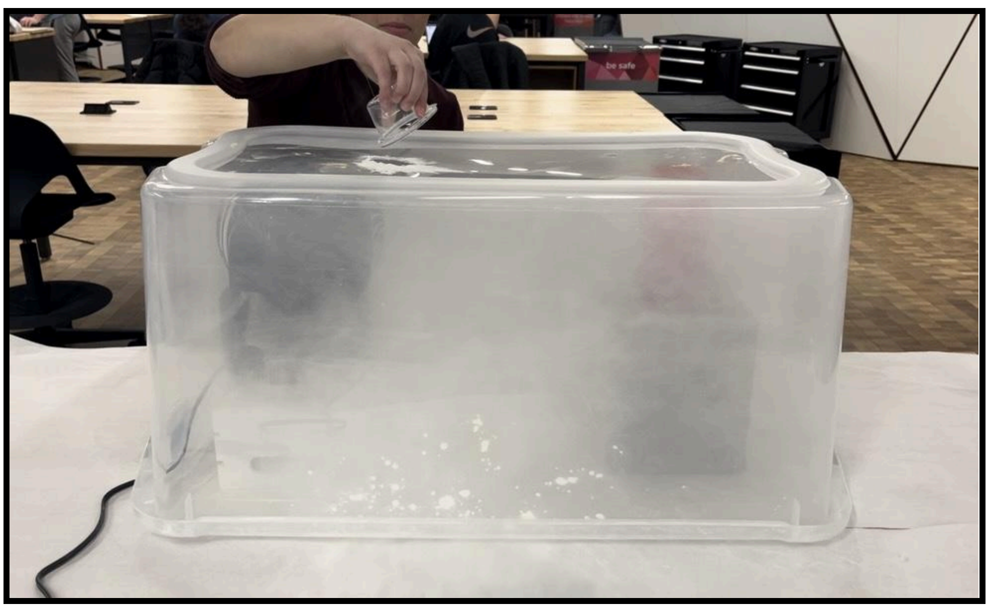


[Figure 7: Solidworks model of Final Vacuum Filtration Tower Solution]

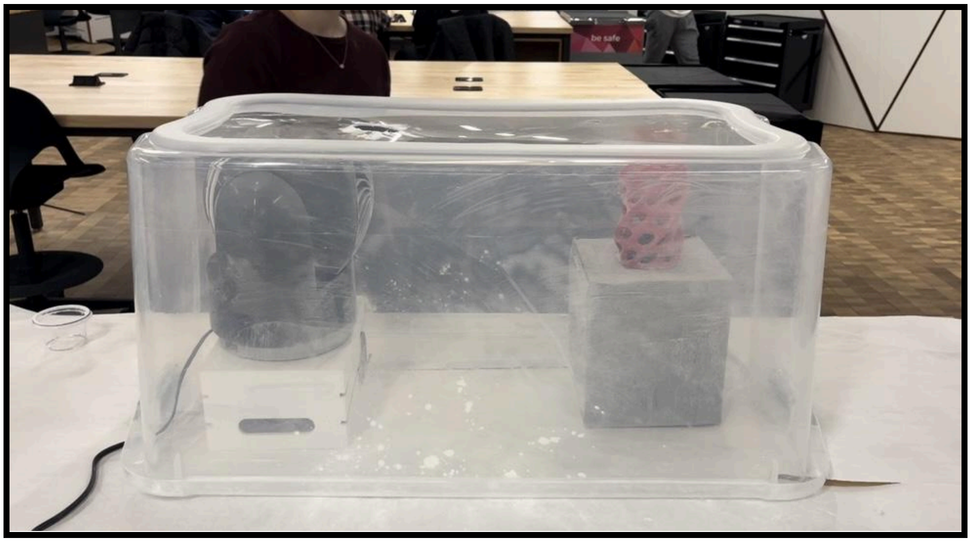
The final prototype is demonstrated in *Figure 8*. The team opted to buy a fan that would simulate the natural wind flow that would carry these debris clouds from the launch to the airport. They also used a box to elevate the fan to the correct height, built a model tower using additive manufacturing and cardboard, and cut holes in the box for the vacuum hose to fit through and insert into the tower on top of the model building. Baby powder was utilized as well in order to simulate the debris clouds. A plastic bin was put over the prototype to create a more isolated environment to better illustrate how the solution would work in the real world. For the demonstration of how the prototype works, a team member turned on the fan at the lowest setting, poured the baby powder into the bin, and finally turned on the vacuum solution. Within very little time, a sufficient proportion of the original visibility level was restored to the bin. Please refer to *Figures 9* and *10* to view the clarity of the bin during the demonstration.



[Figure 8: Diagram of final prototype]



[Figure 9: Visibility without using the solution]



[Figure 10: Visibility after using the solution]

Figure 11 outlines the data collected in the initial trials of the prototype. One team member tested the final prototype individually in order to collect information on how the design can be further optimized. Originally, the students bought a mini vacuum to put into the tower. This mini vacuum was intended to be the main focus of the prototype testing, but the team also wanted to test it to see how effective the solution would be if it utilized a much larger vacuum. The testing phase involved releasing 4 grams of baby powder into the modulus and keeping time for how long it took for the baby powder to disperse enough to ensure sufficient visibility. This would be repeated for a total of 5 trials per round for the three vacuum types (None, Big, and Small), with two different rounds measuring the variability in data as a result of the tower's distance from the fan. When tested with a distance of 2 feet between the tower and each fan in the first round, the mini fan cleaned the air 1.4 times faster than the control (no vacuum), while the bigger vacuum cleaned the air 2 times faster than the control. When the distance was changed in the second round, the mini vacuum cleaned its surroundings 1.5 times faster than the control while the bigger vacuum recorded values averaging 2.4 times faster. From this testing, the team concluded that the larger the vacuum, the more effective the solution will be in relation to the price points for both vacuums. In addition, the closer each vacuum would be in proximity to the launch pad, more debris would be absorbed. The team's estimations indicate that due to these debris clouds, airports would be shut down for an average of 2 hours. Because the solution cleans the air 2 times faster than the control, it was concluded that there would be virtually no shutdown time if the solution was enacted, with an upper bound of 1 hour of downtime if necessary.

Vaccum Type	Trial Number	Tower Distance from Fan [ft]	Baby Powder Used [g]	Dissipation Time [s]
No vaccum (Control)	1	2	4	24.18
No vaccum (Control)	2	2	4	22.43
No vaccum (Control)	3	2	4	24.28
No vaccum (Control)	4	2	4	23.41
No vaccum (Control)	5	2	4	26.77
Big Vaccum	1	2	4	11.37
Big Vaccum	2	2	4	11.87
Big Vaccum	3	2	4	13.18
Big Vaccum	4	2	4	11.85
Big Vaccum	5	2	4	11.18
Mini Vaccum	1	2	4	14.3
Mini Vaccum	2	2	4	18.94
Mini Vaccum	3	2	4	15.91
Mini Vaccum	4	2	4	19.43
Mini Vaccum	5	2	4	17.44
No vaccum (Control)	1	1.5	4	32.32
No vaccum (Control)	2	1.5	4	26.09
No vaccum (Control)	3	1.5	4	25.41
No vaccum (Control)	4	1.5	4	17.45
No vaccum (Control)	5	1.5	4	36.59
Big Vaccum	1	1.5	4	7.75
Big Vaccum	2	1.5	4	9.65
Big Vaccum	3	1.5	4	11.55
Big Vaccum	4	1.5	4	13.47
Big Vaccum	5	1.5	4	14.87
Mini Vaccum	1	1.5	4	19.76
Mini Vaccum	2	1.5	4	15.73
Mini Vaccum	3	1.5	4	18.95
Mini Vaccum	4	1.5	4	18.37
Mini Vaccum	5	1.5	4	18.46

Vaccum Type	Tower Distance from Fan [ft]	Baby Powder Used [g]	Average Time [s]	Speed Percentage	Efficiency
No vaccum	2	4	24.214	--	--
Big vaccum	2	4	11.89	203.65%	2 times faster
Mini Vaccum	2	4	17.204	140.75%	1.4 times faster
No vaccum	1.5	4	27.572	--	--
Big vaccum	1.5	4	11.458	240.64%	2.4 times faster
Mini Vaccum	1.5	4	18.254	151.05%	1.5 times faster
Concluson: Use big vaccum in final prototype					

[Figure 11: Results and analysis from final prototype testing]

Future Modifications & Improvements

Based on the feedback the team received from multiple design showcases, the group is intent on implementing a few recommendations into a potential future solution. The first modification will be to implement a cleaning system within the building that houses the vacuum. It was brought to the group's attention that the geographic location where they planned to implement their final solution has an extremely humid environment. With the debris being mainly concrete this humid environment could liquify the concrete and then it could get onto the fan blades and solidify again and cause malfunctions. To rectify this in the future the team wants to build a cleaning system that will clear off the fan blades in the vacuum when buildup is detected.

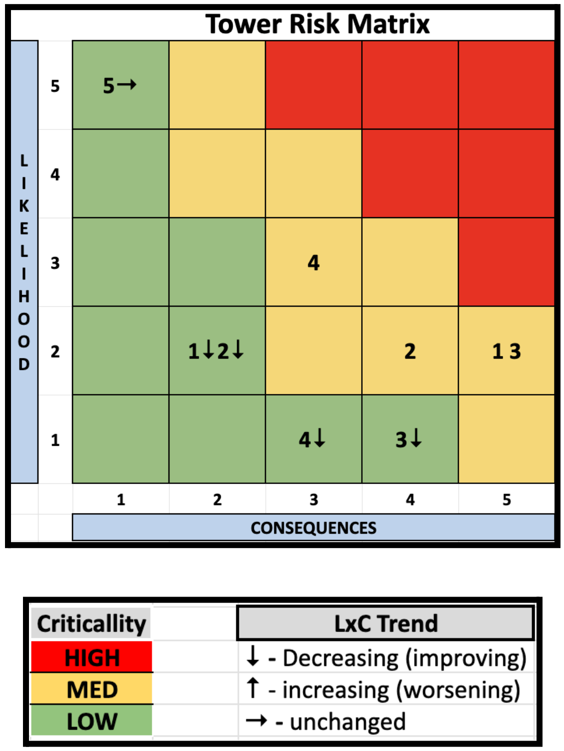
One detail the team was unable to include in the project due to time constraints was a recycling system. In the future, one potential addition to be made to the prototype would be the inclusion of a system within the tower to capture and recycle the concrete debris into improved roadways and other similar projects. The students learned from John that airports already recycle broken-down concrete into worn runways and roads, so the solution could solve two problems simultaneously by introducing a recycling system to the tower. Another piece of feedback the group received was centered around the disposal of the debris from the storage unit. It was mentioned that if the concrete is still in powdered form, it may be difficult for it to drop out of a hatch into a truck without it dispersing and causing a larger mess. In the future, the team intends to install a moisturizing system for the storage unit of the vacuum with the purpose of hydrating the debris mixture. If the debris particles are watered down and therefore closely packed together, they can then more easily fall into the trucks that cycle through each tower.

Risk Analysis

In order for the solution to be viable in a commercial environment, the team must make sure that any risks from unexpected circumstances are minimized or entirely eliminated. To account for these possibilities, the group conducted an in-depth risk analysis. This assessment involved research, testing, and group brainstorming of possible solutions. As a result, this analysis allowed the group to develop many reduction strategies for what could have been detrimental circumstances for the tower designs.

Below, in *Figure 12,* the team constructed a risk matrix along with a table that explains the risks they were addressing. As reflected, the towers didn't face many high-likelihood risks. Instead, there were many high-consequence but low-likelihood risks to address. In tandem with the previous *"Future Modifications & Improvements"* section, the group has been able to lower the consequences of a high percentage of these risks. Two of the must-solve risks were the chances that people or wildlife, such as birds, would get near the towers and find themselves inside the dower due to the holes. This was addressed by placing a simple metal mesh or guard on the inner circumference of each tower. The mesh still allows for the collection of fine debris particles but also prevents anything from people to wildlife from reaching or flying inside.

Multiple other mitigation strategies that arose from the risk analysis were addressed in the previous section, as mentioned before. With all these strategies implemented, the physical development of the tower system will be plausible, but accounting for risks is a perpetual activity. In order to keep the system up to date with safety measures, regular discussion must be had to consider any unsuspected or newly developed risks that could factor into the project.



ID	Risk	Mitigation ↓→
1	Tower may cause harm to nearby wildlife due to suction from high-powered vacuums.	Wire mesh around the inner circumference of each tower
2	Tower storage systems may fill up too quickly or overflow with debris.	Storage system with roadway infrastructure for truck collection
3	People may try and mess with the tower and get injured	Fencing and security cameras will be installed around the tower
4	Due to wind direction the debris cloud could miss the towers entirely	Semi-circle tower layout
5	Noise of tower may be disruptive to the surrounding environment	Only running towers during rocket launch period

[Figure 12: Risk Analysis charts]

Projected Impacts

Cost-Benefit Analysis

This section will focus on a summary of all of the costs and benefits associated with the project by using a Cost-Benefit Analysis (CBA). The CBA is a systematic approach to analyzing the projected total costs and benefits associated with a project. This is important because it helps to find out if the benefits will outweigh the costs. The total cost to bring the solution to life is summarized in the table below. The next table will summarize the potential benefits that the solution will bring to the airport. Based on this information, the team was able to find out the payback period for this design.

Figure 13 outlines the total costs that would be associated with this project in a condensed form. There are three sections: construction materials/installation, cost of labor for production, and maintenance labor and repair costs. The construction materials/installation cost is the largest cost associated with the design because of the technology that is required for the turbines within the towers. The team's reference for this technology is an airplane engine, as they provide the amount of power and suction needed for their solution. These engines currently run on gasoline, but the team believes that electricity would be a more efficient and eco-friendly source. They anticipate $2,500,000 per turbine for the design. The next highest cost within the construction materials/installation section is the cost of the tower design. The towers are made out of concrete and reinforced with steel inside. They also anticipate that the cost of concrete for one tower will be $62,500 and the cost of steel to be about $44,000. The rest of the costs are dwarfed by these items but include items such as a debris screen to keep some of the larger debris as well as wildlife from getting inside the tower and damaging the turbine.

The next section of the costs is the cost of labor. This includes the construction workers, architects, and managerial staff. Estimates show that the construction workers will cost around $150 per hour, and it is anticipated that they will take about ten hours, or just about two months to complete construction on the towers. The team expects that the architect will take about 3 weeks to complete the design, and the management to work alongside the construction workers.

Finally, the cost of maintenance and repair. This includes costs such as electricity and the cost to maintain the turbines. The largest contributor to this cost is the cost of electricity. Due to the amount of power being pulled by the turbines, roughly 300kW for two hours, the group estimates that the cost for electricity yearly would be around $840,960. The team does not anticipate too much maintenance to be done as the turbines are dealing with a fairly fine powder that should not hinder their performance. Approximately $11,000 for maintenance labor and $4,000 for maintenance tools and supplies is expected to be accounted for in the budget.

Type	Phase	Item	Year 0	Year 1	Year 2	Year 3	Year 1-3 Subtotal
Orlando International Airport costs							
Cost	Installation/Production	Construction Materials/Installation	$ 72,359,951				
Cost	Installation/Production	Labor Cost	$311,400				
Cost	Operation/Maintence	Maintenance labor and repair		$855,915	$855,915	$855,915	$2,567,746
Total Cost							$75,239,097

[Figure 13: Condensed CBA]

Figure 14 expands upon the benefits associated with the design. The benefits only begin in Year 1 as opposed to Year 0 because it is anticipated that Year 0 will be spent getting the entire system up and running. The two benefits that were identified with the solution were the reduction of downtime within the airport and the increase in customer satisfaction due to the reduced downtime. Currently, customers who are satisfied with their experience at airports are willing to spend $44 more each time that they are there. This coupled with a growing airline industry of about 300,000 people gives the airport a benefit of $12,100,000 annually. As a result of the prototype testing, the team identified that they would save two hours with the solution. This is two more hours that the airport can spend running every day. The students calculated the amount of money that the Orlando International Airport makes per hour using the budget set by the airport in 2021. This figure was multiplied by two hours and then again by 365 days. From this, calculations indicate that this solution would save the airport $33,333,333 per year.

Greater Orlando Aviation Authority benefits						
Benefit, tangible	Airport operations	reduced downtime	$ -	$33,333,333	$ 33,333,333	$ 33,333,333	$ 100,000,000
Benefit, intangible	Airport Operations	Increased happiness of passengers	$ -	$ 12,100,00(	$ 12,100,000	$ 12,100,000	$ 36,300,000
Total Benefits							$ 136,300,000

[Figure 14: Benefits portion of CBA]

After analyzing the costs and benefits associated with the design, it was concluded that the payback period would be about sixty-two weeks, or just about one year and three months.

Future Implications

The cost-benefit analysis proves that the solution is incredibly viable, and will help facilitate a safer future for the commercial spaceflight and aviation industries. However, the solution is not only limited to space launch debris that hangs in the air. Some aspects of the solution are applicable to current issues affecting airports, such as wildfires and sandstorms.

Wildfire Smoke Reduction

In the summer of 2023, Canada experienced a set of wildfires that affected not only Canada but the eastern side of the United States as well. The smoke from the wildfires was so significant that it grounded flights in the United States. If this solution had been implemented, the amount of downtime that occurred because of the smoke could have been greatly reduced. The amount of wildfires is predicted to continue to increase as a result of global warming; therefore, this solution is more relevant than ever to help keep the airspace unpolluted.

Sandstorm Visibility Improvement

Another use for this solution is improving visibility within sandstorms. While sandstorms are not a major issue within the United States, places such as Dubai frequently get sandstorms, especially in the summer months. In 2022, 45 flights were delayed or grounded due to sandstorms around the Dubai International Airport (DXB). The visibility dropped to 500 meters in certain areas. Had this solution been implemented, the team could have improved the visibility around the airport such that the flights would not need to be grounded for such an extended period of time. With the reduction of flight delays and cancellations, the airport would then be able to resume normal operations within a shorter period of time.

Appendix A - Contact Information

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Appendix B - University Description

Penn State University is an institution of higher education in Pennsylvania. It houses the College of Engineering which includes numerous engineering degrees at both the undergraduate and graduate levels. The College of Engineering supports an undergraduate minor in engineering leadership in which undergraduate engineers can build the non-technical skills to support the great technical skills they are developing through their engineering curriculum. The engineering leadership development program offers students classes in project management, leadership education and development, business basics, and cross-cultural teaming. Students in the minor are dedicated to building these skills in addition to the technical workload required of their discipline's curriculum. The engineering leadership program also offers a graduate program in the form of a master of engineering and an online graduate certificate in Engineering Leadership and Innovation Management.

Appendix C - Industry Experts

John Greaud

Senior Project Manager at Barge Design Solutions, Inc.

Barry Bratton

Associate at ADK Consulting & Executive Search

Harish Joshi

Aviation Professional (Pilot)

Appendix E - Evaluation of Educational Experience

Student Perspective

1. *Did the Airport Cooperative Research Program (ACRP) University Design Competition for Addressing Airports Needs provide a meaningful learning experience for you? Why or why not?*

   The ACRP Design competition provided our team with a very valuable learning experience. For the first time in any of our classes, we had the opportunity to interview industry experts in order to enhance our project. This provided the team with practice in speaking to professionals and asking the right questions. The competition also helped us learn more about product development and leadership.

2. *What challenges did you and/or your team encounter in undertaking the competition? How did you overcome them?*

   Our team decided to pick the integration of commercial space with the airport operations challenge. This prompt in itself led to many challenges for our group because a lot of the research was hard to find due to it being only a future problem. We overcame this by talking with professionals and using research estimated from current problems today. We also lost a group member halfway through the competition. To overcome this we had to distribute the workload between the remaining team members. Lastly, during the project, our group kept pivoting to entirely new problems and solutions. This led our team to be behind multiple times throughout. To overcome this our group met and worked extra every week until we were caught up with our class.

3. *Describe the process you or your team used for developing your hypothesis.*

Our team had several different variations on potential solutions for the topic that we selected, yet none of them were similar. We started by trying to tackle a noise pollution issue, then moved on to repairing damage to launch pads, and finally settled on the vacuum debris filtration tower with many mini changes going on between the major ones. The reason for this many pivots was that every time we talked to an expert they had something to say about the feasibility of our solution. Seeing as the problem is so futuristic and given our limited knowledge of airport operations, the team decided that if the expert didn't agree with the feasibility we had to change it. Finally, we landed on the vacuum debris filtration tower as our most feasible solution.

4. *Was participation by industry in the project appropriate, meaningful and useful? Why or why not?*

   Participation by the industry was extremely important as we did not have much knowledge of airports and their operations. Only by interviewing industry experts were we able to understand the different edge cases that would come with our topic. In addition, talking to a pilot was very helpful for us to gain insight into a pilot's view on our solution. Since our solution was so futuristic the knowledge we gained from experts was essential to our project.

5. *What did you learn? Did this project help you with skills and knowledge you need to be successful for entry in the workforce or to pursue further study? Why or why not?*

   Our team learned valuable insight into what leading a team is like. Throughout this project, each team member was the designated leader for a specific part of the project. This gave each team member the experience of leading a team. Along with this, we learned problem-solving skills in an industry context as well as communication skills and time management. This project definitely gave us knowledge that will help us be successful in entering the workforce.

Faculty perspective

1. *Describe the value of the educational experience for your student(s) participating in this competition submission.*

   Students in our leadership course are learning how to lead within the engineering context. This project provides an exceptional and organized experience for our engineering students to apply the knowledge and their personal leadership style as they lead their teams throughout the semester. The challenges provided mimic a real-world experience giving students an opportunity to practice both technical and non-technical problem-solving skills.

2. *Was the learning experience appropriate to the course level or context in which the competition was undertaken?*

   Yes, the learning experience was appropriate for the level of our students and fit within the context of our learning environment, per the note above.

3. *What challenges did the students face and overcome?*

   Students faced some challenges getting in touch with experts and through that learned how important it is to talk with the "user" in order to come up with the best solution. Some students tried to jump ahead to the solution and not work through the design process to use all the information gathered in order to come up with a creative solution. They learned that user-centered research is important when coming up with solutions to challenges.

4. *Would you use this competition as an educational vehicle in the future? Why or why not?*

We have used this competition as an educational vehicle for the past several years. The competition structure allows us to combine innovative project development via the 5-stage design process while giving student teams opportunities to learn about leadership.

5. *Are there changes to the competition that you would suggest for future years?*

   Yes. We plan to continue to use it based on the organization, the well thought out options for projects, the support, and the industry contacts. Making some of the appendices into an online form would be helpful, and perhaps allowing for one submission of some appendices if a group is turning in multiple projects.

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