STUDY OF AIRPORT SNOW AND ICE REMOVAL AND ITS ECONOMIC IMPLICATIONS

by

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ABSTRACT

For airports that regularly encounter storms with snow and ice in an average year, removal of this snow and ice is essential for maintaining safe operations. This snow and ice removal must not only ensure safe operations but also must be efficient because efficient removal is crucial to reducing airport delays and the resulting cost and impact that a snow storm has on an airport and its surrounding economy. The purpose of this thesis is to assist airports in determining whether they are appropriately managing their snow and ice removal resources and applying engineering best practices.

Two airports in Europe and two airports in the U.S. that have approximately the same amount of annual snow fall and handle the same mix and volume array of aircraft have been identified for analysis of their snow and ice removal practices. These airports are Frankfurt, Germany and Vienna, Austria in Europe and Philadelphia and Boston in the United States.

Data collection and categorization has been done by means of a Microsoft® Excel workbook, consisting of eight worksheets, to model the characteristics of the airport, the ground equipment, the storm, the aircraft and the time of day. This input information, in turn, generates the output consisting of delays and costs associated with a given scenario and allows for comparison with the other airports being studied. The excel workbook has been run on the four airports and on six snow storms.

The analysis identifies which airports allocated their resources most efficiently and provides a basis for recommendations to the airports. The model may also be replicated for use by other airports.

The thesis concludes that the airports in Europe are more prepared for and have a more efficient snow and ice removal strategy than the airports in the United States. Analysis was done for numerous parameters; the cost per passenger, the cost per metric ton of cargo, and the cost per hour that the pieces of equipment were in use. For most of the analysis parameters, Vienna International Airport was the most efficient.

Chapter 1

INTRODUCTION

1.1 Background

While an airport may be simply defined as a location where aircraft take off and land, modern airports transcend this simple definition. Airports today involve a complex of interconnected activities, services, and functions that have developed to facilitate this basic takeoff and landing purpose. For example, one set of interconnected activities, services, and functions revolve about the impact snow and ice can have on the ability of aircraft to take off and land.

Because airports need to function as safe transfer hubs for passengers and cargo, they can face many problems when it comes to snow and ice. Even the casual traveler recognizes that airports must: 1) observe the weather to ensure safe visibility and conditions, 2) clear the runways and taxi ways to ensure safe, non-slip conditions for vehicles using it, 3) deice aircraft to prevent ice buildup on the craft which would adversely affect its ability to lift off the ground. [1]

It should be noted, however, that even these easily recognizable actions require complex logistics and varied background activities. For example, airports monitor weather conditions to determine the appropriate measures to ensure safely functioning operations. In severe weather conditions at an airport, safe passage of aircraft both on and off the ground may be jeopardized. Even though arriving and departing aircraft may have an Instrument Landing System (ILS) and a Global Positioning System (GPS) to aid them in flight, wind shear and microburst can potentially be fatal for the passengers in the aircraft, if they are not detected and avoided. In the instance of severe weather, at some airports, aircraft on the ground may need to rely on sight to traverse the airport even though ground radar, which would allow the tower to aid aircraft on the ground in poor visibility, is becoming more common. In such a case, where sight must be relied on, the aircraft could potentially steer off the runway or taxiway, collide with another aircraft or airport vehicle, or even possibly collide with the terrain.

In winter it is evident that runways and taxiways cleared from snow are essential to prevent the pilot from losing control of the aircraft due to the lack of friction with the ground. Snowplows, therefore, plow the runway and then use a chemical mixture on the surface to melt the remaining snow and ice that is compacted in the groves in the surface in order to allow for both water drainage and additional friction.

In moist cold weather, it is also clear that deicing an aircraft is essential. While the aircraft is on the ground, water and precipitation accumulate on the wing. The cold fuel of the aircraft, which is stored in the wing, [2] and the cold air around the wing causes the moisture to freeze into a sheet of ice on the surface. When the aircraft attempts to take off, the ice on the surface disrupts the flow of air and prevents the aircraft from getting lift. In such a case, while the aircraft will initially obtain lift, it will then become unstable and uncontrollable and this can ultimately lead to a crash. This was the unfortunate case on January 13, 1982, with Air Florida flight 90, a Boeing 737-200, which took off from Washington National Airport having not been properly deiced, obtained initial lift and became uncontrollable before hitting the 14th Street Bridge and crashing into the frozen Potomac River. [3] Today Type 4 deicing fluid is most commonly used at commercial airports, because this fluid allows for the longest amount of time before needing to be reapplied to the surface and also has the characteristic of shedding off the surface at high speeds to permit the aircraft to safely become airborne. [4]

A cursory review of weather conditions, runway snow removal, and aircraft deicing reveal complex systems engaged in accomplishing the basic airport purpose of facilitating aircraft to take off and land. It also suggests that many more systems must exist and interact at some optimal level for airports to be able to address the challenges of snow and ice.

In December 2010, for example, snow and ice crippled European airports. Heavy wet snow resulted in the closure of numerous airports including London, Paris, and Amsterdam. The snow and ice also revealed an apparent mismanagement of resources at Brussels airport where the airport ran out of deicing fluid and had to cancel flights for several days until supplies could be replenished and aircraft could safely depart. The airport closures in London, Paris, and Amsterdam resulted in passengers being stranded and flights already en route, such as those originating in Asia, being required to divert to open airports such as Frankfurt. [5]

Flight diversions, cancellations, and delays, at a peak holiday travel period, resulted in a large increase in departing and transit passengers, which in turn placed unusually heavy demands on terminal and passenger services and systems in Frankfurt. [6] Wait times to reach the transit desk in order to rebook flights exceeded five hours. Airport seating capacity was insufficient. Food distribution systems were overwhelmed.

To help ease the plight of stranded passengers, the airport provided basic entertainment in the form of a clown and other street performers [7] as well as food and water, in accordance with the European Union law regarding the rights of passengers. [8]

Frankfurt, which was already dealing with its own snow problems, had to adjust for the incoming diverted “heavy” aircraft (long haul flights), which in turn meant that it could not safely accommodate smaller regional flights. In response to the situation, Lufthansa cancelled all domestic flights and with the Deutsche Bahn, the German federal railway, validated and urged use of the airplane tickets on the train. This action successfully reduced the number of passengers in transit who were stranded in Frankfurt but created additional problems for the luggage and cargo systems which were thrown out of synchronization and gradually ground to a halt. [5]

Because certain pieces of luggage were not able to be delivered to their final destination as routed because of cancelled, diverted, or delayed flights, these pieces of luggage were pulled from the luggage delivery system and re-routed. However, by the time that these pieces of luggage were found and re-routed, many of the flights intended to be used for these pieces of luggage had been cancelled, and the entire distribution system had again to be re-searched so that these pieces could be found and pulled out. This led to a downward spiral, which resulted in people’s luggage being laid aside and then being buried by other luggage. The Frankfurt luggage system collapse trickled down to the other airports in Europe. It was reported by airport officials that in Frankfurt there were 20,000 pieces of lost luggage [9] and in Vienna there were 5,000. [10]

Luggage redistribution took a long time, since the airlines had to maintain continuing holiday level baggage handling, find the luggage from cancelled and rerouted flights, and put individual pieces of luggage on flights that would be able to deliver the bags to the appropriate final destinations. This process was further complicated due to different luggage systems between airports and the financial incentives of airlines to fly cargo rather than passengers and luggage. As a result, on one hand, certain flights were flying with space available for additional luggage despite there still being accumulated luggage in the luggage distribution system that could have potentially been on these flights, and, on the other hand, some flights with available space took luggage which was bound for airports near the destination airport so that the luggage ended up leapfrogging to the final destination.

As this simple example of luggage indicates, in today's airport the challenges deriving from snow and ice are quite complex and affect many different systems. The airport systems dealing with weather analysis, runaway snow removal, and aircraft deicing are clearly the primary systems affected but many other airport systems are also involved in meeting the challenges deriving from snow and ice. All must be coordinated in preparation, response, and recovery.

1.2 Problem Statement

The problem, that this thesis investigates, is concerned with the allocation and use of airport resources with respect to the amount of equipment, supplies and personnel that are or should be available to address the impact snow and ice can have on airport systems. Given their limited resources, it is essential that airports appropriately manage these resources, ensure coordination of systems, apply appropriate engineering principles, and prevent a collapse of the expected, if not required, level of service. The cost of being unprepared for a snow and ice storm can be quite high, but judgments must be made with regard to the amount of investment appropriate for an airport to be well equipped for an unusually large snow occurrence.

1.3 Purpose and Objective

The purpose of this thesis is to assist airports in determining whether they are appropriately managing their snow and ice removal resources and applying engineering best practices. To achieve this objective, this purpose will:

- Analyze information from Philadelphia International Airport, Boston Logan International Airport, Frankfurt International Airport, and Vienna International Airport.
- Tabulate average snowfall for the airports with an inventory of equipment and man power available to address the problems generated by the average snowstorm.
- Consider what can or should be done to prepare for exceptional circumstances and analyze whether or not the airports are appropriately, under-, or over-prepared in being able to manage crisis level snow removal.
- Provide a basis that can potentially assist these and other airports in determining whether they are correctly or under managing their winter resources.

1.4 Scope of the Work

This work covers airports that, from the passengers' perspective, have similar levels of service in coping with and maintaining operations when dealing with storms which feature snow and ice. The selected airports regularly experience snow in an average year. The airports are also significant because each plays an important role in contributing to and maintaining the local economy. However, due to the differences in locations different approaches on snow removal are implemented. The analysis is focused from the airport perspective and assumes a constant distribution pattern.

The airports are as follows:

- Philadelphia International Airport (PHL/KPHL)
- Boston Logan International Airport (BOS/KBOS)
- Frankfurt International Airport (FRA/EDDF)
- Vienna International Airport (VIE/LOWW)

The analysis in the thesis does not factor in the implications of wind and its effect on the snow removal effort, as wind has a unique influence on the system and is case specific. The analysis also does not take into account the quantity of wetness in the snow. It assumes that the equipment is run at a constant level of snow removal efficiency and that the experience of the drivers and the efficiency of the equipment, with regards to age and make, do not have an effect on the snow removal effort. It does not differentiate differences in the efficiency of the deicing chemicals. The analysis also does not factor in the cost of diverting an aircraft.

1.5 Organization of Thesis

The thesis is organized as follows:

Chapter 1 consists of an introduction in which the background, problem statement, purpose and objective, scope of the work, and the organization of the thesis is identified. Chapter 1 also provides a definition of the basic terms used in the thesis.

Chapter 2 provides a literature review of the importance of snow and ice removal.

Chapter 3 provides a review of the airports together with some technical and factual information on these airports. In addition, it describes the two different deicing methods that are used and different snow removal vehicles that are employed. The chapter also includes a brief summary of passenger rights in the instance of a delay.

Chapter 4 describes the procedure and methodology used in the data analysis. In particular, it describes the various sheets of the excel model.

Chapter 5 provides the results of the excel worksheet model.

Chapter 6 summarizes the results. It provides a conclusion of the findings and provides recommendations to airports.

1.6 Definition of Terms

Ice is the solid state of water with a density of 913 kg/m^3 (57 lb/ft^3). Compacted snow will turn into ice when the density of compacted snow is about the same as ice.

Snow is a grouping of one or more ice grain crystals.

Dry Snow is snow that has insufficient free water to form cohesive bonding between individual particles.

Wet Snow is snow that has enough free water to permit particles to be cohesive, thus is easy to compact, but where there is no excess of pore water.

Compacted Snow is compressed snow that will hold together when handled.

Slush is snow that has a very high free water content, thus it takes on far more fluid properties and water is observed when handled.

Primary Runway is a runway that is used under existing environmental conditions and handles the majority of aircraft movements.

Secondary runway is a runway that supports the operations of the primary runway, and thus aircraft movements are less.

Aircraft are the mobile part of the mode which traverses the medium of air.

Heavy Aircraft are aircraft capable of takeoff weights of more than 255,000 pounds whether or not they are operating at this weight during a particular phase of flight.

Large Aircraft are aircraft of more than 41,000 pounds, maximum certificated takeoff weight, up to 255,000 pounds.

Small Aircraft are aircraft of 41,000 pounds or less maximum certificated takeoff weight.

[4] [11]

Chapter 2

LITERATURE REVIEW

The need for snow and ice removal during and after a winter storm is absolutely required for safe operations of an airport and the aircraft which it handles. On one hand, airports and airlines follow the business model, which encourages them to operate to generate revenue, and this creates a desire to have the system in operation and not to shut down. On the other hand, airports and airlines must consider the paramount factor of providing safety and not taking unnecessary risks, which indirectly affects the desirability for the air carrier or airport to be used. Air carriers and airports carry the initial costs of snow and ice removal; however, the secondary effects are put on the users.

Research on snow and ice removal has been done in the past, however with different methodology and inputs fields. This paper builds on previous research and includes delay associated with air freight and compares European and American airport snow and ice removal practices. Changes to policies and procedures over the years have altered many of the parameters used in past studies. In addition to the changes of demand and inflation, there are new safety regulations which have been introduced by the FAA to accommodate new types of aircraft. Environmental policies have also been changed by the EPA which have altered the chemicals used for snow and ice removal. [12]

2.1 Cost Reduction

The reduction of delays at the airport and to the air cargo is very important to reduce costs and as the saying goes, “time is money”. Keeping the system going in a winter storm is crucial to reducing costs and prioritization is the key. The total cost of snow removal is ultimately put on to the users. The airport initially caries all the initial costs but factors the costs to the air carriers in the form of landing fees, and they, in turn, integrate the costs in the ticket price to the users. [13]

Airports are encouraged to prioritize which runways, taxiways, and parts of the apron as well as which navigational aids should be cleared. Clearing all the top prioritized ones is required to maintain safe and basic operations. The top priority includes the main runway and the associated taxiway areas, the terminal and cargo areas, the route of the emergency services, and other areas deemed important to maintain airport operations. After the top priority areas are cleared, priority level 2 is dealt with, which includes the secondary/crosswind runways and the taxiways associated with them, commercial parking areas, and airfield facilities not essential for daily flight operations. The remaining areas are categorized as priority 3, and dealt with last. [4] According to FAA standards, airports need to have enough equipment to be able to clear one inch of snow of the highly prioritized areas in a reasonable time frame defined by the size of the airport, which for commercial hubs is within 30 minutes. [4]

Table 2.1: Clearance Time of Airport

Annual Aircraft Operations	Clearance Time (hour)
40,000 or more	½
10,000-39,999	1
6,000-9,999	1 ½
Less than 6,000	2

Airports have available references which aid them on how many pieces of equipment they should have on their premise as suggested by the FAA. [14] However, airport mangers and airlines alike do not want negative publicity so although the minimum specifications are meet, no airport or airlines want to be known for incurring delays.

2.2 Safety

Snow and ice impede the performance of an aircraft and thus jeopardize its safety. Ice on the wings and the control surfaces of an aircraft disrupt the airflow over the wings and prevent lift from being obtained. This causes the aircraft not to be able to climb and easy to stall and thus prone to having the pilots lose control of the aircraft and have the aircraft crash into the terrain. Snow and ice can also impact the performance of the navigational tools and lights on the airports by covering them up and preventing their operational use. Snow and ice can also be thrown up by the wheels of the aircraft and damage components of the aircraft. Snow and ice also impact the coefficient of friction and thus impact the ability of the aircraft to accelerate and decelerate as well as impact the safe maneuverability of the aircraft. [4] In conditions involving ice, pilots are instructed to increase engine thrust to maneuver over the irregularities in the surfaces. [4]

Safety at airports is quintessential. Snow and ice removal is encouraged to take place as quickly as possible and to provide minimal hazards. Irrelevant to the situation, the airport should handle the snow and ice in a similar way as if it were on a wet surface. [4] To provide such standards, airports are encouraged to have a high standard of care by providing state-of-the-art snow and ice removal equipment and techniques and having competent crews. [4] Airports are encouraged to have snow and ice control plans (SICP) which document the procedure to prepare for winter storms before the season, how to deal with the storm when it is at the doorstep, and finally how to deal with the post storm effects, in addition to meetings to assess the storm and the season. [4] [15]

With regards to winter storms, airports need to decide many aspects and ensure former practices are still up to the current standards. They need to designate which areas should be prioritized, and where the snow should be moved to. They also need to decide whether modernization and expansion of the snow and ice removal equipment should be undertaken. Reiterating the training of the personnel in snow and ice removal procedures and with the equipment is also critical. Airports need to understand and know the proper communications methods with the control tower to ensure safe and effective operations. [4] [16] In addition to clearing the runways, taxiways, and apron during a snow storm, airports also need to ensure that the signage of the taxiways is clear to ensure safe operations, and to prevent runway incursions.

In preparing for the winter, air carriers need to review their deicing programs from the previous season and make appropriate changes. They also may need to alter schedules to accommodate for the deicing procedures, and yet generate revenue by keeping the time that the aircraft is on the ground to a minimum. [4]

During winter storms airports need to monitor the surroundings. Attention is paid to the weather radars, to observe location and intensity of precipitations, and to observe the trends over time. [4] Attention is also paid to both the air temperature, to determine whether conditions exist which could yield snow and ice, as well as the ground temperature, to determine the how precipitation would interact with the ground. [2]

Improper snow removal from a runway or taxiway lights would constitute a major safety hazard and thus render the runway or taxiway inoperable. [13] This is because falling snow melts on the warm LED lights, and then freezes creating an ice layer which affects the way the light is emitted. [2] This in turn means that the orientation is affected and safe operations cannot be guaranteed.

2.3 Summary of Chapter 2

Although the clearing and removal of snow and ice is costly and takes time, it is far less expensive than the alternative costs of human lives and loss of air freight. For this reason, having safe operations of airports and air carriers is critical. Although the initial costs of snow and ice removal involve the equipment, the chemicals, and the personnel, there are further costs associated with the delay to the user of the air network; the passenger and the air freight. These costs are ever changing as more and more people and businesses resort to air travel and new technologies are introduced. Thus optimization of snow and ice removal is needed and the values of delays are ever changing.

Chapter 3

DATA COLLECTION AND REDUCTION

This chapter reports on the findings uncovered by research of the relevant airports and their deicing and snow removal methods. To better understand snow and ice removal strategies, data was obtained from the four airports and analyzed. This chapter describes the use of an excel workbook and the inputs to worksheets within the excel workbook which was used to analyze the data. The chapter first describes the airports on which the research is focused. This is followed by a description of the deicing and snow clearing methods. Finally the chapter includes a brief narrative on European and American legislation with regard to delays.

3.1 Introduction to the Airports Studied in this Thesis

Airports are a vital terminal node in the aviation mode of transportation. At the bare minimum they consist of a landing strip, a runway. More complex airports include hangers, communication equipment, a tower to monitor movement in the sky and on the ground, terminals, and pre-flight preparation areas (such as deicing pads). Larger airports can handle large aircraft capable of transporting over 500 passengers and over 600 metric tons of freight.

Maintaining an overall situational awareness is imperative for an operating airport to safely operate. Airport administrators need to exercise oversight over numerous aspects external to the airport property such as the surrounding airspace, landings, and departures, as well as to exercise oversight on aspects located on airport property, such as flight operations and safety. [4] Technologies which include radar (air and ground) contribute to maintaining overall situational awareness and radio communication is mandatory to establish communication between parties on the ground and in the air. In the rare case of emergencies, radio frequencies are reserved, so that all vehicles associated with the recovery can communicate on one channel without excess radio chatter. [2]

3.1.1 Philadelphia

Philadelphia International Airport (PHL, KPHL) is located 11 km (7 miles) southwest of Philadelphia. It can be seen in Figure 3.1. The airport entered operation in 1925. An early highlight in the history of the airport occurred on October 22, 1927, when Charles Lindbergh and the “Spirit of Saint Louis” on a tour of the United States landed at the airport. Construction of the terminal buildings started in 1937 and they opened on June 20, 1940. In the late 1970’s the airport was modernized and the terminal space was expanded. In 1985, a rail line connecting the airport with the city was constructed. In March 2002, Philadelphia airport constructed its new deicing facility that can handle three large jets at a time. The airport also provides an environmentally safe collection and disposal system for the deicing fluid runoff.

Figure 3.1: Ariel View of Philadelphia International Airport
(©2012 Google, ©2012 Europa Technologies)

Philadelphia International Airport is the major international hub airport for US Air and a hub for United Parcel Service (UPS). It has seven passenger terminals with a total of 126 boarding gates and is undergoing expansions of the D-E and F terminals as well as rehabilitation of various runways and taxiways. The expansion possibilities of the airport are limited because of the nearby Delaware River. The airport has intermodal connections of automotive vehicles and regional train (South East Pennsylvania Transit Authority--SEPTA) to connect into the city. It possesses wireless, advertised to be free everywhere, although the signal is only found in the food court area. It serves flights to 121 destinations with 30 different passenger airlines and 15 cargo carriers. In 2009 the airport handled 30.8 million passengers and 393,209 metric tons (433,439 U.S. tons) of cargo. The airport has four runways with length and width shown in Table 3.1. It can handle a maximum of about 465,000 flight movements per year. The deicing pads are located on the western side of the airport. [17] [18]

Table 3.1: Runways at Philadelphia International Airport

Runway	Length	Width
Rwy 8/26	1,524m (5,000ft)	46m (150ft)
Rwy 9L/27R	3202m (10,506ft)	61m (200ft)
Rwy 9R/27L	2896m (9,500ft)	46m (150ft)
Rwy 17/35	1664m (5460ft)	46m(150ft)

3.1.2 Boston

Boston Logan International Airport (BOS, KBOS) is located in the east Boston area. It can be seen in Figure 3.2. It was founded in 1922 and on June 13, 1923 the first flight landed at the airport. During the 1930's, despite the great depression, air travel continued to grow, due to the desire of celebrities to enjoy intercontinental flights. In 1949, the airport constructed its first major terminal building, now under the name of terminal B and C. In 1959, Pan Am initiated daily jet service to Europe from Logan. In 1973, Logan airport built its famous twin pylon control tower, which at the time of construction was the tallest in the world. In the 1980s, efforts to develop noise abatement went into effect. In 2006, Terminal A became LEED certified for being a state-of-the-art environmentally friendly building.

Figure 3.2: Ariel View of Boston Logan International Airport (©2012 Google, ©2012 Europa Technologies)

Currently, Boston Logan International Airport does not serve as the hub for any airline. It had, however, been a hub for airlines such as Northeastern Airlines and Pan Am. Logan airport has four passenger terminals and has intermodal connections of automotive vehicles, light rail (subway) and water transportation (although the latter two need a shuttle bus to connect from the terminal to the sites). The expansion possibilities of the airport are limited due to the surrounding bay. Passengers are given good free wireless connections for thirty minutes. Logan serves flights to 72 domestic and 30 international destinations with 35 different passenger airlines and 6 cargo carriers. The airport handled 27,332,000 passengers and 247,833 metric tons (273,190 U.S. tons) of cargo in 2010. The airport has six runways as observed in Table 3.2. It can handle a maximum of about 345,300 flight movements per year. [18] [19]

Table 3.2: Runways at Boston Logan International Airport

Runway	Length	Width
Rwy 4L/22R	2,396m (7,861ft)	46m (150ft)
Rwy 4R/22L	3,050m (10,005ft)	46m (150ft)
Rwy 9/27	2,134m (7,000ft)	46m (150ft)
Rwy 14/32	1,524m (5,000ft)	30m(100ft)
Rwy 15L/33R	779m (2,557ft)	30m(100ft)
Rwy 15R/33L	3,073m (10,083ft)	46m (150ft)

3.1.3 Frankfurt/Main

Frankfurt am Main International Airport (FRA, EDDF) is located 12 km (7.5 miles) southwest of Frankfurt. It can be seen in Figure 3.3. The airport was opened in 1936, and was intended to be the base for airships including the LZ 129 Hindenburg. After World War II, the base served as a major launching point for the Berlin Airlift. In 1955, Lufthansa recommenced its flight service at the airport, when Germany regained sovereignty over the airport. In the early 1970s, the airport was connected to the German rail system. This intermodal connection was further developed in the 1990s and now permits travelers to connect to long distance Inter City Express trains as well as to local trains.

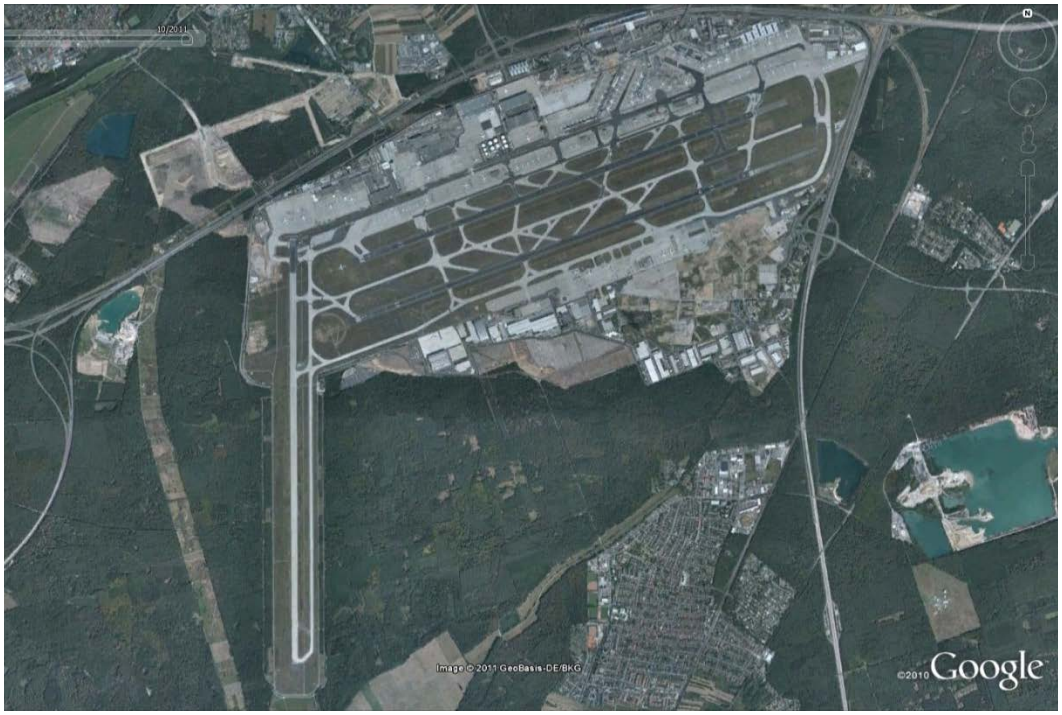


Figure 3.3: Ariel View of Frankfurt International Airport
(©2012 Google, ©2012 GeoBasis-DE/BKG)

Frankfurt am Main International Airport is the busiest airport in Germany and is a major hub airport for Lufthansa. It has five passenger terminals with Terminal A being enlarged (opening 2012) and a new passenger terminal to the south (opening 2015-2018) and a new landing runway to the north which opened in 2011. It has intermodal connections of automotive vehicles, regional and long distance trains, thus allowing a passenger who flies in from overseas to get on a train bound for a wide variety of cities in Germany or elsewhere in Europe. Passengers are unable to obtain free wireless at the airport. Those flying with Lufthansa, however, are able to connect once airborne. Frankfurt am Main serves flights to 266 destinations with 106 different passenger airlines and 30 cargo carriers. The airport handled 53.01 million passengers and 2,231,348 metric tons (2,459,640 U.S. tons) of cargo in 2010. The airport has four runways as seen in

Table 3.3. Under optimal conditions the airport can handle about 464,500 flight movements per year and a maximum of 126 flight movements per hour. There are currently 216 parking locations, however, more spaces are being constructed. [9] [18]

Table 3.3: Runways at Frankfurt International Airport

Runway	Length	Width
Rwy 07C/25C	4,000m (13,123ft)	60m (197ft)
Rwy 07R/25L	4,000m (13,123ft)	45m (148ft) wide with 7.5m (25ft) shoulders
Rwy18	4,000m (13,123ft)	45m (148ft) wide with 7.5m (25ft) shoulders
Rwy 07L/25R	2,800m (9,186ft)	

3.1.4 Vienna

Vienna Schwechert International Airport (VIE, LOWW) is located 18 km (11 miles) southeast of Vienna. It can be seen in Figure 3.4. The airport was built in 1938 and after the war was taken over by the British. In 1954 it replaced the Aspern Airport as the main airport for the city. In the 1960s the airport building was constructed and in the 1970s a second runway was built. The airport received the Olympic teams arriving for the Winter Olympics in 1964 and 1976. In 1992 a shopping mall was constructed between terminal A (renamed D) and terminal C.

Figure 3.4: Ariel View of Vienna International Airport
(©2012 Google, ©2012 DigitalGlobe, ©2012 GeoEye)

Vienna Schwechert International Airport is the busiest airport in Austria and is a major hub airport for Austrian (Airlines and Group), and Fly Niki. It has three passenger terminals with one more under construction expected to open in 2012 which is capable of handling the A-380. An additional runway is also expected to open in 2012. The airport has good free wireless connections located within the terminals. These connections, however, are only available from 7am to 7pm. The airport has intermodal connections of automotive vehicles and a regional train into the city. In the future an intercity rail connection is also envisioned. Vienna Airport serves flights to 260 destinations with about 80 different passenger airlines and 11 cargo carriers. The airport handled 19,691,206 passengers and 295,989 metric tons (326,272 U.S. tons) of cargo in 246,146 flights during the year 2010. The airport has two runways as seen in Table 3.4. Under optimal conditions it can handle a maximum of 68 flight movements per hour, about 246,000 per year. There are 61 commercial parking locations. The deicing pads are located on the eastern side of the apron. [10]

Table 3.4: Runways at Vienna International Airport

Runway	Length	Width
Rwy 16/34	3,600m (11,800ft)	45m (148ft) wide with 7.5m (25ft) shoulders
Rwy 11/29	3,500m (11,500ft)	45m (148ft) wide with 7.5m (25ft) shoulders

3.1.5 Comparison of the four Airports

As observed in Table 3.5 it can be seen how the airports relate with one another. Frankfurt International Airport has the most passengers and cargo volumes. However, Philadelphia International Airport has the most traffic movements. The airports in North America have more snow than the ones in Europe, even though Philadelphia and Frankfurt do not have too much variation. This is because there is a difference in the flow of the artic winds.

Table 3.5: Airport Summary Data

	Philadelphia	**Boston**	**Frankfurt**	**Vienna**
Number of Runways	4	6	4	2
Passengers	30.8 million	27.3 million	53.01 million	19.7 million
Cargo	393,209 metric tons (433,439 U.S. tons)	247,833 metric tons (273,190 U.S. tons)	2,231,348 metric tons (2,459,640 U.S. tons)	295,989 metric tons (326,272 U.S. tons)
Flights	465,000	345,300	464,500	246,000
Average Annual Snowfall	38 cm (15 in)	82 cm (32 in)	31 cm (12 in)	22 cm (8 in)

[20]

3.1.5.1 Runway Dimensions Worksheet

This worksheet is for inputting the dimensions of the runways as shown in Figure 3.5. On the runway dimensions worksheet the user inputs the runway length (in kilometers) and the width (in meters) for the runways at the airport in order of priority. Up to six runways may be included but data is not required for all runways. The program calculates the time to clear the runways (in hours) based on the input dimensions, and the ground equipment data entered in a different worksheet.

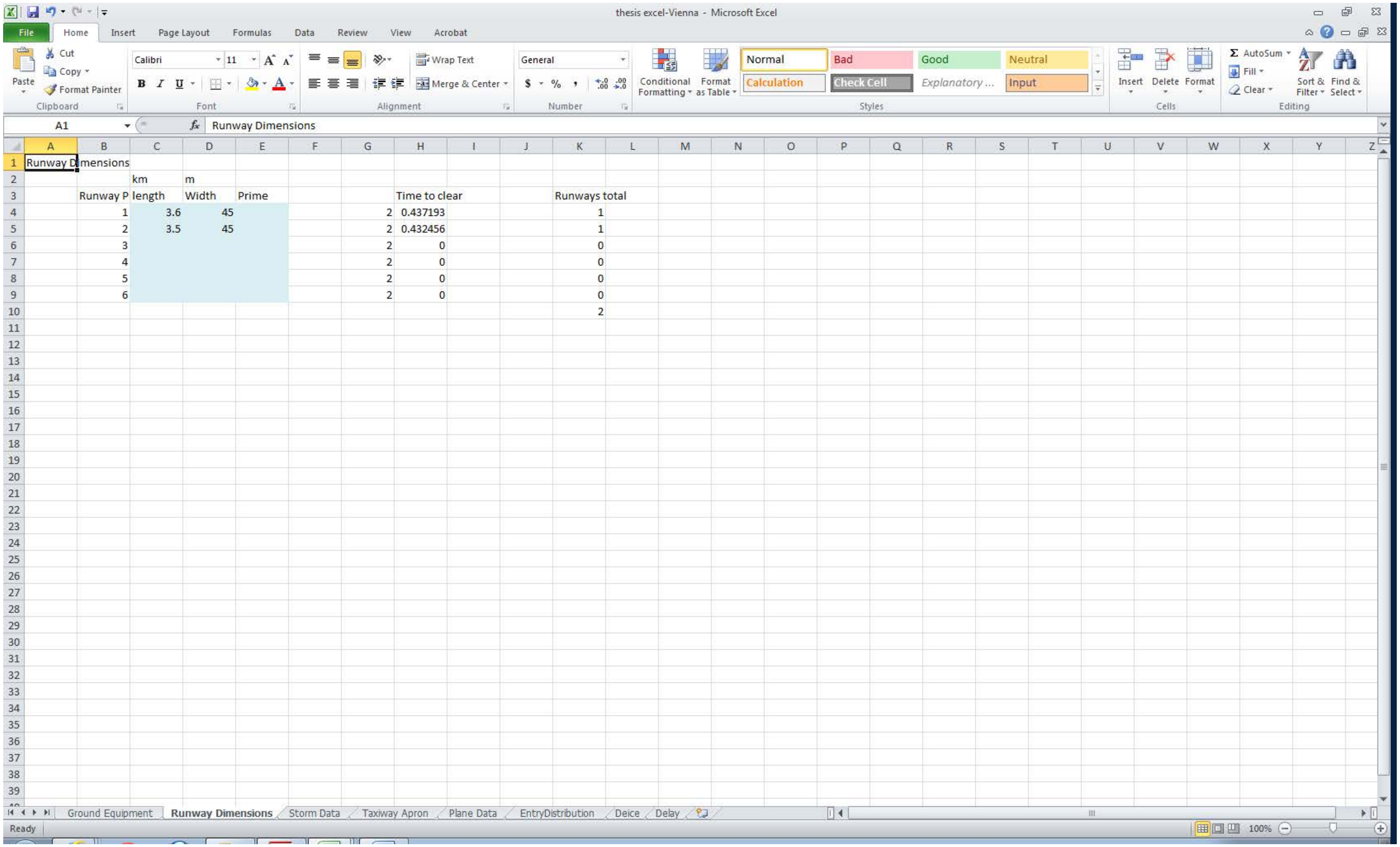
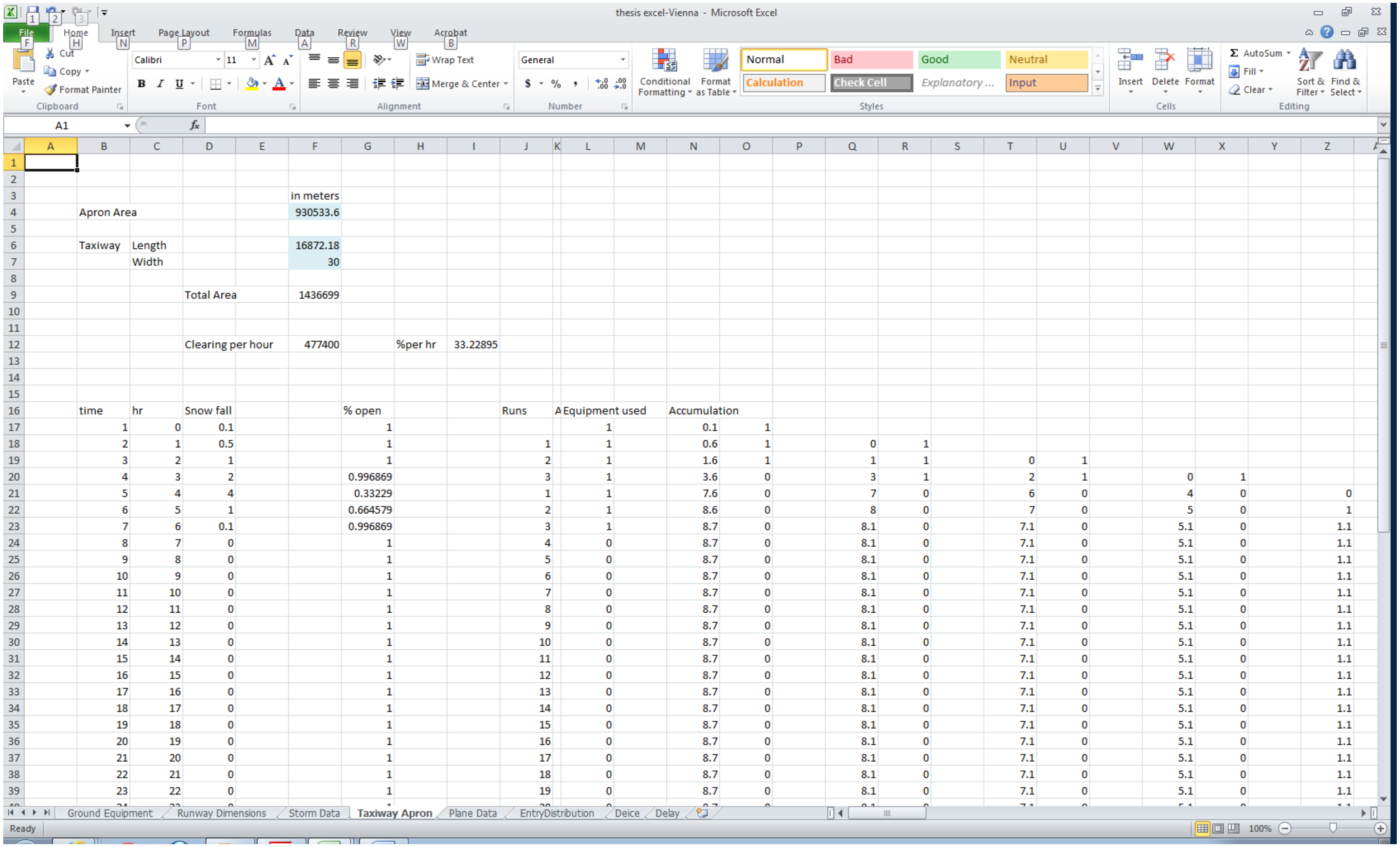


Figure 3.5: Runway Dimension Worksheet

3.1.5.2 Taxiway and Apron Worksheet

This worksheet determines the effects that the clearing of the aprons and taxiways as seen in Figure 3.6. The user inputs the total length and the average width of the taxiways (in meters) and the total area of the apron (in square meters). The worksheet calculates the total area needing to be cleared and based off of the available equipment how much snow is cleared in an hour. This in turn, combined with the snowfall amount determines the cleared area. It also factors in the accumulation to previously cleared areas which may occur in the interim while the equipment is working at a different part of the airport.

It may be noted that this worksheet does not take into effect the snow removed by the snow crews which clear the runway as they get into formation on the runway. However, this benefit is canceled out by the fact that when the crews are clearing the aprons, they may have to swerve and take a longer course to avoid hitting stationary objects.



	B	C	D	F	G	H	I	J	K	L	N	O	Q	R	T	U	W	X	Z
3				in meters															
4	Apron Area			930533.6															
6	Taxiway	Length		16872.18															
7		Width		30															
9			Total Area	1436699															
12			Clearing per hour	477400		%per hr	33.22895												
16	time	hr	Snow fall		% open			Runs	A	Equipment used	Accumulation								
17	1	0	0.1		1					1	0.1	1							
18	2	1	0.5		1			1		1	0.6	1	0	1					
19	3	2	1		1			2		1	1.6	1	1	1	0	1			
20	4	3	2		0.996869			3		1	3.6	0	3	1	2	1	0	1	
21	5	4	4		0.33229			1		1	7.6	0	7	0	6	0	4	0	0
22	6	5	1		0.664579			2		1	8.6	0	8	0	7	0	5	0	1
23	7	6	0.1		0.996869			3		1	8.7	0	8.1	0	7.1	0	5.1	0	1.1
24	8	7	0		1			4		0	8.7	0	8.1	0	7.1	0	5.1	0	1.1
25	9	8	0		1			5		0	8.7	0	8.1	0	7.1	0	5.1	0	1.1
26	10	9	0		1			6		0	8.7	0	8.1	0	7.1	0	5.1	0	1.1
27	11	10	0		1			7		0	8.7	0	8.1	0	7.1	0	5.1	0	1.1
28	12	11	0		1			8		0	8.7	0	8.1	0	7.1	0	5.1	0	1.1
29	13	12	0		1			9		0	8.7	0	8.1	0	7.1	0	5.1	0	1.1
30	14	13	0		1			10		0	8.7	0	8.1	0	7.1	0	5.1	0	1.1
31	15	14	0		1			11		0	8.7	0	8.1	0	7.1	0	5.1	0	1.1
32	16	15	0		1			12		0	8.7	0	8.1	0	7.1	0	5.1	0	1.1
33	17	16	0		1			13		0	8.7	0	8.1	0	7.1	0	5.1	0	1.1
34	18	17	0		1			14		0	8.7	0	8.1	0	7.1	0	5.1	0	1.1
35	19	18	0		1			15		0	8.7	0	8.1	0	7.1	0	5.1	0	1.1
36	20	19	0		1			16		0	8.7	0	8.1	0	7.1	0	5.1	0	1.1
37	21	20	0		1			17		0	8.7	0	8.1	0	7.1	0	5.1	0	1.1
38	22	21	0		1			18		0	8.7	0	8.1	0	7.1	0	5.1	0	1.1
39	23	22	0		1			19		0	8.7	0	8.1	0	7.1	0	5.1	0	1.1

Figure 3.6: Taxiway and Apron Worksheet

3.2 Snow Clearing Equipment

Clearing snow and ice off of a taxiway or runway is essential in permitting an aircraft to safely operate, take off and land. If an aircraft is unable to obtain a safe friction factor with the tarmac the aircraft is prone to slipping off of the contaminated surface, mainly due to the large thrust forces generated by the engines, which are designed to overcome ground friction and air resistance. Without the friction on the ground the aircraft can only rely on its aerodynamic properties for control. However, these properties do not work as efficiently as ground friction when the aircraft is on the tarmac. Thus it is very important for the airport to maintain a high and safe ground friction coefficient to enable safe movements of the aircraft while at the airport.

A runway that is contaminated with snow and ice greatly hinders the safe operations of the aircraft. Most importantly, snow and ice reduce the friction between the craft and the ground, which when an aircraft is trying to land, greatly compromises the effectiveness of the brakes on the tires. A contaminated runway may also result in having the contaminants on the runway being thrown up into the surrounding environment, and potentially into the engines by the massive forces of the engines. This can lead to snow and ice decreasing the performance of the engine, which is critical if an aircraft is departing.

3.2.1 Snow Plow/Blower

Snow plows push the snow and ice with each vehicle pass from the centerline towards the shoulder of the runway or taxiway. A snow plow is shown in Figure 3.7 The snow blower (shown in Figure 3.8), throws the snow and ice from the shoulder away from any used runways or taxiways to help prevent snow from drifting back on the cleared path, due to wind and the thrust force from the jet engines. The distance is determined by the type of aircraft which will be using the facility (the larger the craft, the further the distance). Snow plows and snow blowers are not effective in cleaning the grooves on the runways and taxiways which exist to create friction between the aircraft and ground. Snow plows at airport have an approximate clearing width of 6.4 meters. The shape of the plow and the angle the plow is relative to the direction of motion, influence the clearing efficiency. [14] Snow blowers at airports have approximately a 4 meter effective clearing width. [2]

Figure 3.7: Snow Plow

Figure 3.8: Snow Blower

3.2.2 Snow Broom

The snow broom is part of an airport's snow removal equipment. It works by having a rotating circular broom brush compacted snow and ice from grooves in the taxiways and runways. The cleared grooves increase the friction between the aircraft and the ground and prevent the aircraft from moving on an unintended course. The snow broom is approximately 4 meters wide and attached to the back of the plow. The most popular versions of the snow broom, that combine a unit with a plow, are the Boschung, Vammas, and Hagie multifunctional vehicles. [2] [14]

3.2.3 Chemical Spraying Vehicles

Chemical Spraying vehicles, such as the one shown in Figure 3.9, complete the snow removal order. These vehicles spray an agent which melts the small amount of remaining compacted snow and ice in the grooves, and also helps protects the surface from snow and ice accumulation. The agent can be solid based, mixed with water, or originally be a liquid. Potassium formate is the agent in most common usage at the airports in Sweden. [21] Chemical spraying vehicles have approximately a 20 meter clearing width. [2] [14]

Figure 3.9: Chemical Spraying Vehicle

3.2.4 Friction Testing Vehicle

After the snow and ice clearing vehicles pass, two friction testing vehicles follow in order to check that the coefficient of friction is safe for aircraft operations. The vehicles, essentially a trailer as shown in Figure 3.10, drive five to ten meters from either side of the centerline in order to observe the values where the main landing gear of aircraft will be located. They do not just perform checks in winter but throughout the year to ensure safe operations. If they confirm that the friction values are above 0.40, the surface is cleared for operations. [21]

Figure 3.10: Friction Testing Vehicle

3.2.5 Snow Removal Techniques

Airports usually will split up their snow removal crews into at least two groups such that one group is responsible for clearing the ramp areas and the other the taxiways and runways. The ramp areas that are prioritized are the areas where the gates are located and where aircraft are parked and prepared, as well as the areas and routes that serve the ground vehicles responsible for the array of tasks dealing with the aircraft.

When airports designate the crews to deal with snow and ice removal, the prime objective is to clear the primary runways and supporting taxiways of snow and ice, before dealing with secondary and cross-wind runways. Extra care needs to be taken for high speed taxiways, because at higher speed more friction is required in order for the aircraft to be responsive to the pilot’s commands.

Different airports use different tactics for clearing the runways based on a configuration of equipment. One configuration is show in Figure 3.11. These tactics can vary from doing one half of the runway and then turning around and doing the other half, to doing the entire runway in one sweep. Although it is faster clearing the entire runway all at once, it requires more staff and equipment to perform. Snow clearing tactics involve plows pushing the snow off to the side and snow blowers following behind to blow the snow far away from the runways and taxiways. Fences to prevent the snow from drifting back on to the runway due to the wind may also be constructed. Behind the plows and blowers are the chemical deicing vehicles, which spray the runways to ensure all the snow and ice is melted, and then a friction testing vehicle follows to ensure that a safe level of friction exists. In certain circumstances, such as in freezing rain where it might not be optimal to constantly clear the complete runway to a safe coefficient of friction of 0.4 or greater, sand may be used to increase friction.

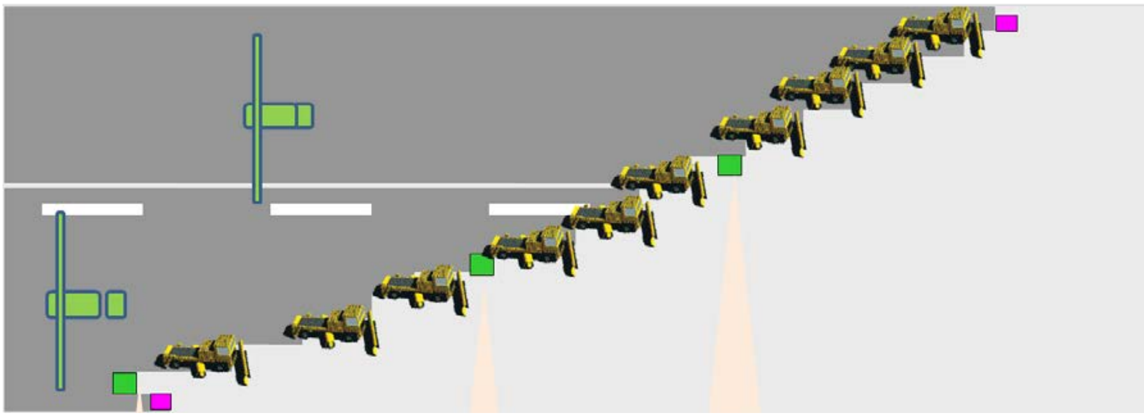


Figure 3.11: Snow clearing tactics at Vienna Airport
Courtesy of Andreas Edelmann

While clearing all surfaces of the airport, the operators of the equipment must be in constant contact with air traffic control and report their locations and their course of movements. This is quintessential as a failure to do so could result in air traffic control giving landing clearance to an aircraft while the equipment is still on the runway or about to intersect the runway. Unless the pilot is able to quickly recognize the threat and respond accordingly, a collision is inevitable. This is less likely for departing aircraft, since the pilots would have more time to follow the course of the equipment and to establish visual contact with them, prior to accelerating past the V1 speed, which is the maximum speed for the pilot to safely abort the takeoff and stop on the runway.

3.2.5.1 Airport Ground Equipment Inventory Worksheet

The Airport Ground Equipment Inventory worksheet is for inputting the characteristics of the ground equipment, such as dimension, operation costs, and inventory amounts. It is shown as Figure 3.12. In the ground equipment worksheet the airport determines the critical snow level, the level at which it deploys the plows (measured in centimeters). According to the FAA this should be 1.5 cm. [4] The airport also has the ability to assign the number of snow clearing crews. From the literature, it was possible to determine the approximate cost of the equipment, the hourly cost, and the effective clearing area. This can be updated as the inventory specifications change. [2] The inventory of the equipment is determined by the airport. The airport also determines the travel speed and the overlap distance of the different pieces of equipment (in meters). At the bottom of the worksheet, the cost of operating all of the equipment is displayed. The cost of operating the equipment is calculated by the amount of fuel that the vehicle consumes and the average price of diesel fuel per liter in the local area. The user also inputs the amount of personnel and their wages. For this analysis the wage was taken to be $20 an hour [22] and fuel prices were an aggregate of the respected regions [23]. The user also inputs the number of passes the equipment does and the distribution of the equipment in the formation.

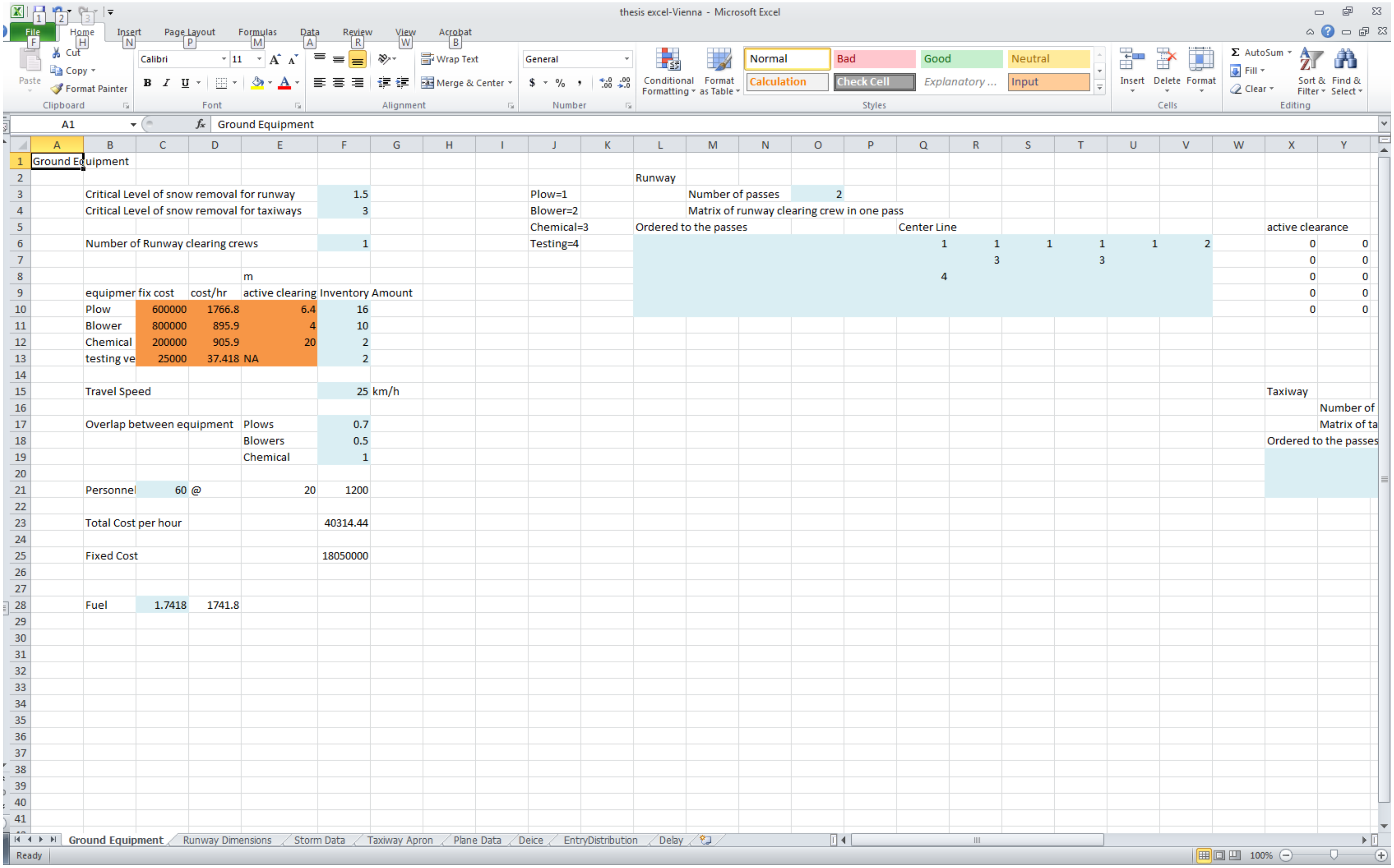


Figure 3.12: Ground Equipment Worksheet

3.3 Deicing Methods

Deicing an aircraft in winter conditions is quintessential to the flight capabilities of the aircraft. If the control surfaces of the aircraft are not properly cleared of snow and ice, then when the aircraft takes off, the snow and ice disrupt the smooth airflow over the wing and prevent it from obtaining lift. This results in the aircraft initially gaining some elevation, but then causes the aircraft to shake violently and descend. It can also be hard for the pilots to control the aircraft before it impacts the terrain.

To prevent such a scenario, aircraft are deiced. There are currently two ways of preparing an aircraft for flight in winter by removing the snow and ice buildup on the wing. The most common is the Glycol based deicing fluid. In recent years, however, airports are adopting infra-red deicing, because it results in less damage to the aircraft and to the environment. [24] Pilots are able to request that the aircraft be deiced if the aircraft still carries fuel from its previous flight in the wing, and if that fuel has not yet reached ambient ground temperature. Airports keep this option open until the temperature reaches about 10C. [2]

3.3.1 Glycol Based

Glycol based deicing consists of a hot fluid combination of glycol and water. Glycol is a deicing chemical which features two hydroxyl (-OH) groups. Glycerol is a similar deicing chemical but feature three hydroxyl groups. The first deicing fluid was Type I, which has a low viscosity and is only effective for short time spans, due to the fact that the deicing fluid would quickly flow off the aircraft. Type II deicing fluid was developed to prevent the fluid from flowing right off. Glycerol only begins to flow off the aircraft once the aircraft obtains a speed of 100 knots. Type III deicing fluid was developed to have the fluid flow off the aircraft at slower speeds, allowing it to be used on smaller and prop aircraft. The newest type of deicing fluid is Type IV. It is the same as Type II, except the fluid is able to remain effective for more time, which is important considering the aircraft may be deiced at the gate and then be required to taxi for some time before it takes off. [24] [25]

The most effective application technique is to apply the deicing fluid on the control surface with the minimum amount of time between application and take off. For this reason many airports have deicing pads located near the ends of runways. Although these pads collect the deicing fluid to be recycled, glycol based deicing fluid still has environmental impacts that occur when it falls off of a departing aircraft.

3.3.2 Infra-Red

Recently some airports such as New York JFK and Munich International are adopting infrared de-icing, which heats the surfaces of the aircraft to melt the snow. The process involves an aircraft taxiing onto an infra-red deicing pad and infra-red waves coming from panels melt the snow and ice. This process does not over heat the surfaces, however, but rather leaves them at the same temperature of a summer day. Infrared de-icing can be performed on any size aircraft up to a Boeing 747-300 by only one operator. Moreover, it does not require special care associated with protecting the environment as is the case of deicing fluid. [24]

3.3.3 Deicing Aircraft and Cost Determination

In order to determine the most appropriate method of deicing, an airport has to consider the volume, distribution, and size of aircraft using the airport. On the basis of this analysis, average deicing requirements can be calculated and costs determined. To obtain this information for the purposes of this thesis, two worksheets were developed. One worksheet focuses on the distribution and size of the aircraft and the other worksheet focuses on the approximate cost of deicing the average aircraft using the airport.

3.3.3.1 Aircraft Data Worksheet

The aircraft data worksheet has been developed to input the distribution of the aircraft using the airport as seen in Figure 3.13 (which uses the values for Vienna airport). The user inputs the daily distribution of aircraft types into a matrix. In the matrix the horizontal axis is the functionality of the aircraft (commercial passenger, cargo, and private) and on the vertical axis is the aircraft type (heavy, large, small, and turboprop). The aircraft types were determined based off of the FAA designation of aircraft based off of their weight classes. This matrix is based on the average flights per hour and the passenger and cargo values per aircraft in order to determine the values that should be associated with the average aircraft. The matrix also determines the average passenger and cargo values per aircraft, by taking a weighted average of the different aircraft types. The values of cargo and passengers are based off of the operating capacity of aircraft found in the respective categories based off of FAA and manufacturers websites. However, this does take into account the actual operating capacity of the aircraft. [26] [27] [28] [29]

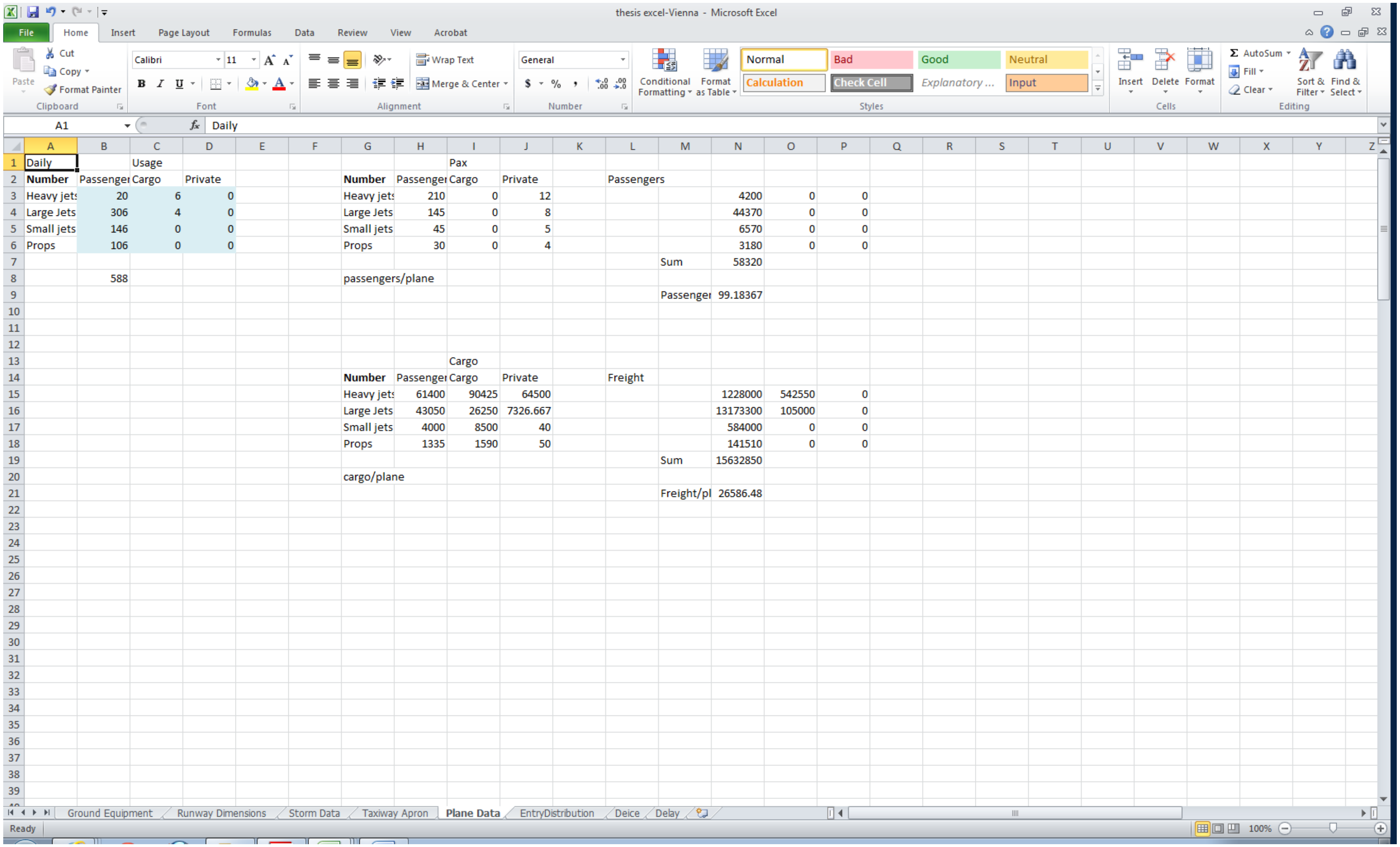


Figure 3.13: Aircraft Data Worksheet

3.3.3.2 Deicing Cost Worksheet

The deicing worksheet, which is seen in Figure 3.14, is to determine the approximate cost of deicing the average aircraft at the airport. It takes into account the size of the aircraft in the calculations, and computes a weighted average based off of the aircraft distribution matrix entered earlier. The costs are indirectly recovered to the airports as the airlines pay for it in the landing fees.

The FAA recommends that holdover time, the time between application of the chemical and the departure of the aircraft is kept as short as possible to keep the probability of ice buildup to a minimum and avoid what occurred to Air Florida Flight 90. Delay with regards to the application of deicing fluid was assumed to be negligible because, as stated by the FAA, under the severe storms the time between application and departure must occur within 5 minutes. Thus from the initiation of applying the deicing fluid until departure, there can be no more than 5 minutes. And thus the driving factor of delay is not the time to apply the deicing fluid but whether the weather conditions provided are safe to fly in. [30]

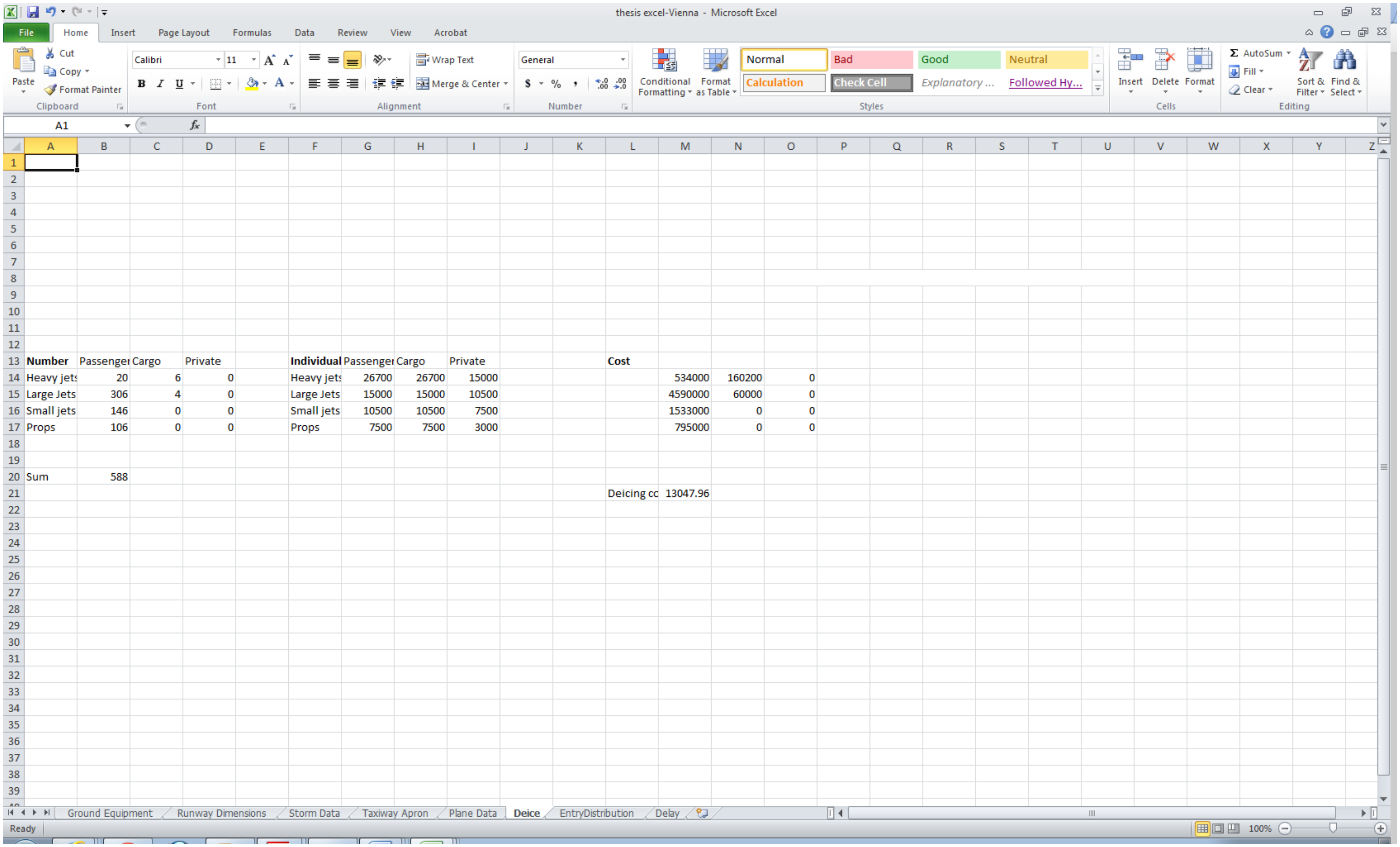


Figure 3.14: Deicing Cost Worksheet

3.4 Legislation

There is different legislation when it comes to the treatment and rights of passengers between Europe and the U.S. It is important to understand the legislation of the country in order to understand the reasoning behind the decision making process for the airports and aircraft in a given situation. Although these laws are frequently being revised, the ones in Europe tend to be more geared to customer satisfaction whereas the ones in the U.S. are more geared to maintaining a safe business operation.

3.4.1 U.S. Passenger Delay

According to United States regulations, when passengers are delayed at an airport due to snow, it is up to the airline and airport to determine what amenities they are to provide. There is new regulation in the process of being passed that would require airlines to provide passengers whose flight has been delayed two or more hours with food and water. [31] According to the Federal Aviation Association (FAA), the cost of delay for passengers is estimated to be at $28.60 per passenger per hour. [32]

This new regulation is more geared to keep the airport in operation and give a two hour buffer before it becomes costly to the airlines. It encourages the delay to be distributed among all the aircraft to reduce the overall costs and does not put as much economic pressure on the airline. The passengers are the ones who unfortunately carry more of the burden and stress.

3.4.2 EU Passenger Delay

According to European Union regulations, airlines and airports must "adequately care" for passengers as defined by EC No 261/2004. Article 9 defines care as:

> "1. Where reference is made to this Article, passengers shall be offered free of charge:
>
> (a) meals and refreshments in a reasonable relation to the waiting time;
>
> (b) hotel accommodation in cases
>
> - where a stay of one or more nights becomes necessary, or
> - where a stay additional to that intended by the passenger becomes necessary" [8]

The law makes the airlines responsible for the care of the passengers, which in a market driven environment, encourages airlines to pressure airports to remain open, to reduce excess costs related to delays. This in turn may increase the risks taken. In the event of an airport closure, in theory, the passenger should be well treated.

3.5 Summary of Chapter 3

Understanding the characteristics of the location with respect to the airport dimensions and applicable laws is important in grasping the situation at hand with regards to the flexibility of the airport actions that can be undertaken. The geometry determines the amount of snow clearing inventory and the laws determine how soon the clearing needs to be done.

Deicing methods and equipment choices are important in allowing for fine tuning tactics to suit the airport geometry. It should be recognized, however, that certain nearby objects may prevent pieces of equipment from being most effectively used. Nevertheless, inputting the data into the excel workbook provides an understanding of the effectiveness.

Chapter 4

DATA ANALYSIS AND METHODOLOGY

This chapter describes the steps which were implemented and the decisions employed in the research. It also describes the procedures used for this thesis with regard to the collection and analysis of the data. A description of the storms which provided the basis of the analysis is also included.

In order to be able to categorize the data appropriately and to model how the various alternative snow and ice removal techniques compare with each other, an excel workbook was constructed. This chapter describes the use of an excel workbook and the outputs of the worksheets within the excel workbook which was used to analyze the data.

4.1 Procedure

Two airports in Europe and two airports in the U.S. that have approximately the same amount of annual snow fall and handle the same mix and volume array of aircraft were identified. Background research into the airports was conducted to determine characteristics related to the airports, such as the geometry of the airport, the aircraft and type handled at the airport. The airports were contacted to obtain data, with regards to the inventory of snow equipment and number of personnel responsible for snow removal, as well as financial pieces of data, which subsequently all the airports would not provide.

Further data was researched which would be held as constants in the research. These included the operating speed and effective clearing width of the snow removal equipment and the salaries of the people who clear snow and ice. Also the number of passengers, the amount of cargo, and the cost of deicing an aircraft based off of its size and functionality type were researched. In addition, airports were observed for a day with regards to the aircraft which they handled, and the aircraft were counted and sorted into categories.

To analyze this data, an excel data analysis tool was constructed, which is described later. The worksheets are designed to determine the cost of various sample snow storms with regard to snow removal and delays to passengers and to freight. Information with regards to runway geometry, ground equipment characteristics, the distribution of the type of aircraft present at the airport, and storm details was input into various fields in the excel worksheet and the outputs of the worksheet is the cost of the delay of the snow and ice storm. The excel workbook was run on the four airports and on six snow storms.

Finally, a cost-effectiveness analysis based on the total cost of the storm and the inventory amount of the equipment and the hours during which the equipment was in use, the cost of the storm per passenger, and the cost of the storm per unit of cargo were conducted. This allowed the airports to be able to be compared with one another on the same denomination.

4.2 Data Collection Methodology

The methodology used is as follows:

- Two EU airports and two US airports were chosen, which regularly have snow and ice.

- Airport administrators were contacted for details regarding the manpower allocated to snow removal and the number and type of equipment that they use for snow removal.

- Sample snow storms were used to determine hourly snow fall accumulation rates.

- The exchange rate between Euro and US dollars is from January 23, 2012 and is $1.31 to €1.00. All figures in the tables are expressed in US dollars.

- The total cost over the number of hours the equipment was implemented, the cost per passenger, and the cost per unit of air freight were all analyzed.

4.3 Overview of the Data and Analysis

The data was obtained from each airport. The data includes:

- The snow accumulations for each hour of observation
- Specific parameters of the airport, such as runways dimensions and flight operation capacity
- The equipment in the snow and ice removal fleet, including dimensions
- The distribution of the type of aircraft

In addition, the cost of delay to passengers is based on the standard FAA value of delay per person per hour, determined to be $28.60. [32] The delay of the cargo was assumed to be valued at $0.10 per kilogram per hour. The cost of snow removal labor was determined as $20 per hour. [22]

The output, measured as delay, identifies the impact that the accumulation of the snow and the efforts to have it removed have on facility operations. The relationships among the inputs and the outputs are shown in Figure 4.1. Each of the inputs and outputs is represented as a worksheet in Microsoft® Excel. Each of the areas shown in blue at the top are inputs. The grey areas on the next level are calculations, and the green on the bottom is the result. Each worksheet is described in the following subsections.

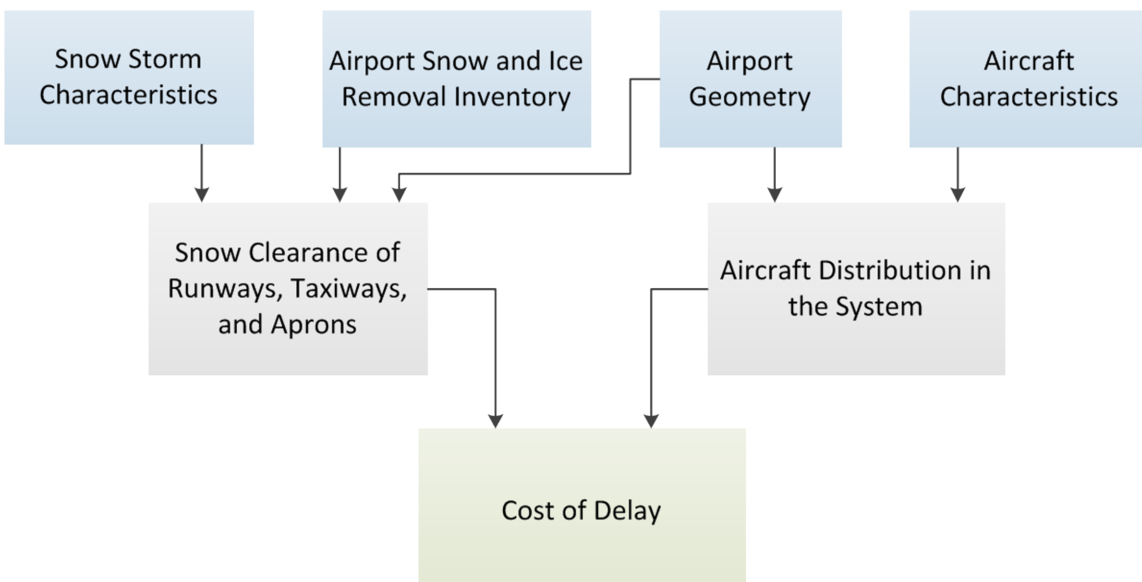


Figure 4.1: Flow Chart of the Excel Worksheets

As observed in Figure 4.1, “Snow Storm Characteristics” is comprised of the intensity and the time of day during which the storm occurs. “Airport Snow and Ice Removal Inventory” details the snow removal equipment at the airport and the costs associated with them. “Airport Geometry” describes the dimensions of the runway, the taxiway, and the aprons. “Aircraft Characteristics” describes the type and size of aircraft that are at the airport and allows for the determination of the average aircraft. “Snow Clearance of Runways, Taxiways, and Aprons” calculates the amount of time needed to clear the surface and combined with the snow fall intensity and, clearing equipment, how operational the airport is. “Aircraft Distribution in the System” calculates the amount of aircraft entering the system based off of the airport and time of day. “Cost of Delay” includes the costs related to equipment deployment, the number of passengers and amount of cargo, as well as the deicing of aircraft.

4.4 Data Analysis Methodology

For analysis of the data, the thesis developed six scenarios, which featured three different storms, in pairs, one starting in the morning hours and the other starting in the evening. This pairing is designed so that the peak of the storm affects the morning and evening aircraft movement peak hours and one can determine how time of the day of the storm influences the delay at the airport. The three storms chosen include one which has the majority of snow at the beginning and then trickles off; the second storm starts off slow and then peaks and ends suddenly; and the third storm is an 18 hour storm. These storms are used in the model, which were run for Philadelphia, Boston, Frankfurt, and Vienna airports. From the model it was possible to estimate approximately how much these storms cost and it is then possible to compare and analyze how effective these different airports are with regards to these storms, based off of the cost per piece of equipment per hour, the cost per passenger, and the cost per metric ton of freight.

4.4.1 Description of the Storms

For the analysis, six different storms were considered. The six different storm scenarios consisted of three pairs of storms. Within each pair, the storms were the same with respect to intensity but differed in so far as one started in the morning and the other in the afternoon. This was intended to observe the effect of the storm on the morning flights and the effect the delay may have created trickle down throughout the day and on the evening flights and the effect the delay may have created trickle down throughout the night. The snow fall rates for each storm are summarized in Table 4.1.

Table 4.1: Snow Storms

	Storm 1	Storm 2	Storm 3	Storm 4	Storm 5	Storm 6
Length	7hr	7hr	5hr	5hr	18hr	18hr
	start at 0600	start at 1500	start at 0900	start at 1200	start at 0000	start at 1200
Hourly Snow Fall (cm)	0.1	0.1	0.1	0.1	0.01	0.01
	0.5	0.5	5	5	0.1	0.1
	1	1	2	2	0.23	0.23
	2	2	0.7	0.7	0.6	0.6
	4	4	0.1	0.1	0.6	0.6
	1	1			0.7	0.7
	0.1	0.1			1	1
					3	3
					2.7	2.7
					2.2	2.2
					2	2
					2.3	2.3
					1.6	1.6
					1.5	1.5
					1.4	1.4
					1	1
					0.7	0.7
					0.15	0.15
Total Snow Fall (cm)	8.7	8.7	7.9	7.9	21.79	21.79

Storms 1 and 2, as seen in Figure 4.2, are 7-hour storms that first have a low snowfall rate and have their peak snow fall at 4 cm per hour in the storm's fifth hour. Two hours later the storm subsides. Storm 1 starts at 6 a.m. and storm 2 starts at 3 p.m.

The peak snowfall, therefore, occurs at 10 a.m. and 7 p.m. respectively. The total accumulation is 8.7 cm.

Storms 3 and 4, as seen in Figure 4.2, are 5-hour storms that start off with their snow fall peak early on, with 5 cm falling in the storm's second hour. The storm subsides 3 hours later. Storm 3 starts at 9 a.m. and storm 4 starts at 12 p.m. The peak snowfall, therefore, occurs at 10 a.m. and 1 p.m. respectively. The total accumulation is 7.9 cm.

Storms 5 and 6, as seen in Figure 4.2, are 18-hour storms that are intended to present an example of a worst case scenario. Although the snow fall peak is 3 cm an hour in the storm's eighth hour, roughly at the center, the storm continues on and thus recovery from delays is prolonged. Storm 5 starts at 12 a.m. and storm 6 starts at 12 p.m. The peak snowfall occurs at 7 a.m. and 7 p.m. respectively. The total accumulation is 21.79 cm.

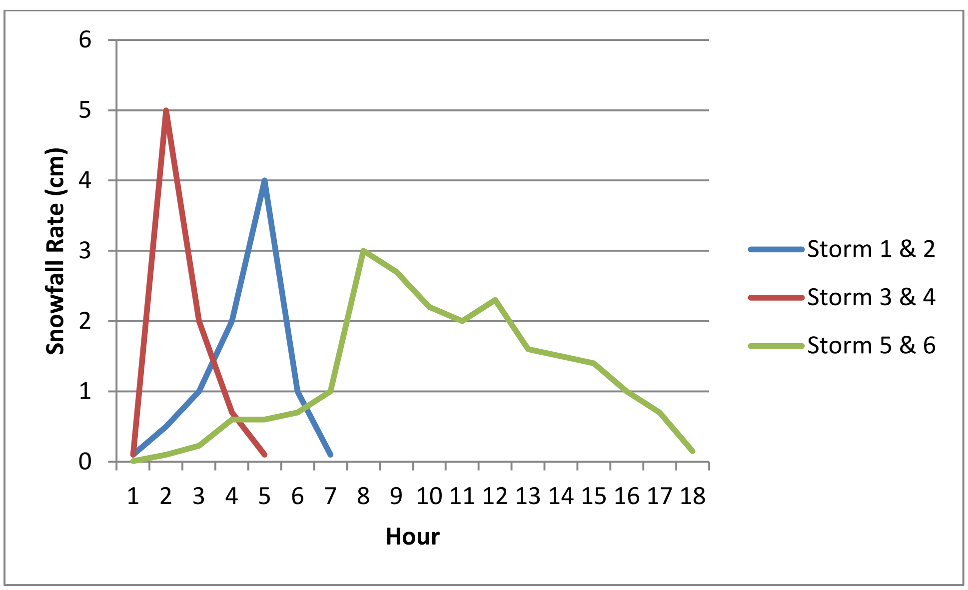
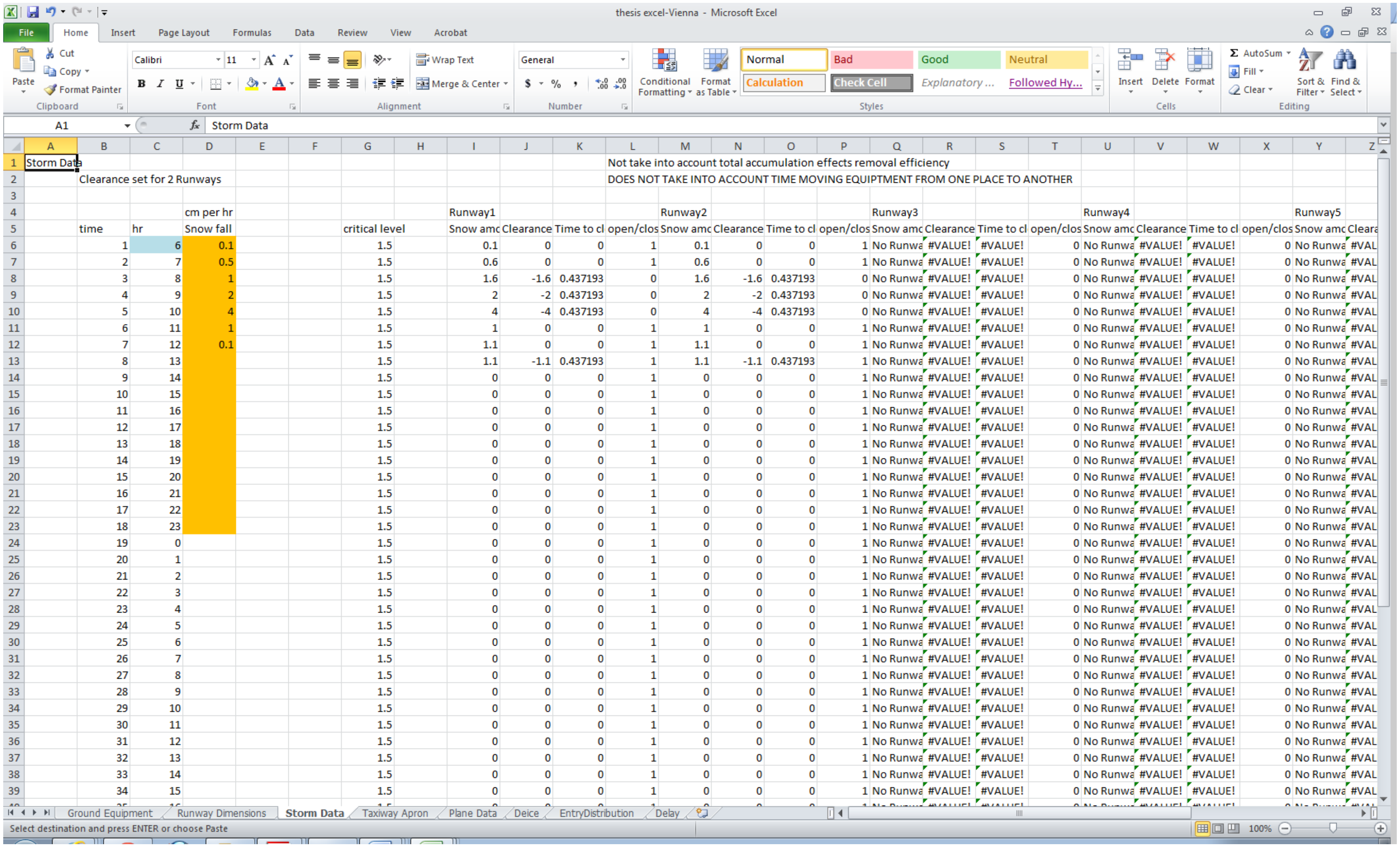


Figure 4.2: Graphs of Snow Storms

4.4.2 Storm Data Worksheet

This worksheet is for inputting the characteristics of the snow storm and is shown in Figure 4.3. In the storm data worksheet the user inputs the starting hour of the storm and the hourly accumulations of snow. The critical level of snow removal is obtained from the inputs on the ground equipment spread sheet. The snow accumulation column is the amount of snow on the ground, a combination of the current hourly snow amount combined with the amount that was on the ground the hour before. When the snow is cleared, the amount in the column returns to zero. The clearance column displays the amount of snow cleared. If the snow amount is larger than the critical level, it is that amount; otherwise, when the snow is cleared it becomes zero. On less prioritized runways, this snow amount factors into whether crews are available for these runways or must remain occupied with the primary runways and are not able to serve the secondary runways at least in an adequate manner. The time to clear is based off of the clearance time of the runway, presuming that it is getting cleared. The open/closed column displays whether or not the runway is open, based on whether it is cleared, or whether it remains closed either because of snow accumulations or because it is being cleared. At the far end of the worksheet there are two columns that state the total number of runways, and the number of runways that are open during that hour.



thesis excel-Vienna - Microsoft Excel

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z
1	Storm Data											Not take into account total accumulation effects removal efficiency														
2		Clearance set for 2 Runways										DOES NOT TAKE INTO ACCOUNT TIME MOVING EQUIPTMENT FROM ONE PLACE TO ANOTHER														
3																										
4				cm per hr					Runway1				Runway2				Runway3				Runway4				Runway5	
5		time	hr	Snow fall			critical level		Snow amc	Clearance	Time to cl	open/clos	Snow amc	Clearance	Time to cl	open/clos	Snow amc	Clearance	Time to cl	open/clos	Snow amc	Clearance	Time to cl	open/clos	Snow amc	Cleara
6		1	6	0.1			1.5		0.1	0	0	1	0.1	0	0	1	No Runwa	#VALUE!	#VALUE!	0	No Runwa	#VALUE!	#VALUE!	0	No Runwa	#VAL
7		2	7	0.5			1.5		0.6	0	0	1	0.6	0	0	1	No Runwa	#VALUE!	#VALUE!	0	No Runwa	#VALUE!	#VALUE!	0	No Runwa	#VAL
8		3	8	1			1.5		1.6	-1.6	0.437193	0	1.6	-1.6	0.437193	0	No Runwa	#VALUE!	#VALUE!	0	No Runwa	#VALUE!	#VALUE!	0	No Runwa	#VAL
9		4	9	2			1.5		2	-2	0.437193	0	2	-2	0.437193	0	No Runwa	#VALUE!	#VALUE!	0	No Runwa	#VALUE!	#VALUE!	0	No Runwa	#VAL
10		5	10	4			1.5		4	-4	0.437193	0	4	-4	0.437193	0	No Runwa	#VALUE!	#VALUE!	0	No Runwa	#VALUE!	#VALUE!	0	No Runwa	#VAL
11		6	11	1			1.5		1	0	0	1	1	0	0	1	No Runwa	#VALUE!	#VALUE!	0	No Runwa	#VALUE!	#VALUE!	0	No Runwa	#VAL
12		7	12	0.1			1.5		1.1	0	0	1	1.1	0	0	1	No Runwa	#VALUE!	#VALUE!	0	No Runwa	#VALUE!	#VALUE!	0	No Runwa	#VAL
13		8	13				1.5		1.1	-1.1	0.437193	1	1.1	-1.1	0.437193	1	No Runwa	#VALUE!	#VALUE!	0	No Runwa	#VALUE!	#VALUE!	0	No Runwa	#VAL
14		9	14				1.5		0	0	0	1	0	0	0	1	No Runwa	#VALUE!	#VALUE!	0	No Runwa	#VALUE!	#VALUE!	0	No Runwa	#VAL
15		10	15				1.5		0	0	0	1	0	0	0	1	No Runwa	#VALUE!	#VALUE!	0	No Runwa	#VALUE!	#VALUE!	0	No Runwa	#VAL
16		11	16				1.5		0	0	0	1	0	0	0	1	No Runwa	#VALUE!	#VALUE!	0	No Runwa	#VALUE!	#VALUE!	0	No Runwa	#VAL
17		12	17				1.5		0	0	0	1	0	0	0	1	No Runwa	#VALUE!	#VALUE!	0	No Runwa	#VALUE!	#VALUE!	0	No Runwa	#VAL
18		13	18				1.5		0	0	0	1	0	0	0	1	No Runwa	#VALUE!	#VALUE!	0	No Runwa	#VALUE!	#VALUE!	0	No Runwa	#VAL
19		14	19				1.5		0	0	0	1	0	0	0	1	No Runwa	#VALUE!	#VALUE!	0	No Runwa	#VALUE!	#VALUE!	0	No Runwa	#VAL
20		15	20				1.5		0	0	0	1	0	0	0	1	No Runwa	#VALUE!	#VALUE!	0	No Runwa	#VALUE!	#VALUE!	0	No Runwa	#VAL
21		16	21				1.5		0	0	0	1	0	0	0	1	No Runwa	#VALUE!	#VALUE!	0	No Runwa	#VALUE!	#VALUE!	0	No Runwa	#VAL
22		17	22				1.5		0	0	0	1	0	0	0	1	No Runwa	#VALUE!	#VALUE!	0	No Runwa	#VALUE!	#VALUE!	0	No Runwa	#VAL
23		18	23				1.5		0	0	0	1	0	0	0	1	No Runwa	#VALUE!	#VALUE!	0	No Runwa	#VALUE!	#VALUE!	0	No Runwa	#VAL
24		19	0				1.5		0	0	0	1	0	0	0	1	No Runwa	#VALUE!	#VALUE!	0	No Runwa	#VALUE!	#VALUE!	0	No Runwa	#VAL
25		20	1				1.5		0	0	0	1	0	0	0	1	No Runwa	#VALUE!	#VALUE!	0	No Runwa	#VALUE!	#VALUE!	0	No Runwa	#VAL
26		21	2				1.5		0	0	0	1	0	0	0	1	No Runwa	#VALUE!	#VALUE!	0	No Runwa	#VALUE!	#VALUE!	0	No Runwa	#VAL
27		22	3				1.5		0	0	0	1	0	0	0	1	No Runwa	#VALUE!	#VALUE!	0	No Runwa	#VALUE!	#VALUE!	0	No Runwa	#VAL
28		23	4				1.5		0	0	0	1	0	0	0	1	No Runwa	#VALUE!	#VALUE!	0	No Runwa	#VALUE!	#VALUE!	0	No Runwa	#VAL
29		24	5				1.5		0	0	0	1	0	0	0	1	No Runwa	#VALUE!	#VALUE!	0	No Runwa	#VALUE!	#VALUE!	0	No Runwa	#VAL
30		25	6				1.5		0	0	0	1	0	0	0	1	No Runwa	#VALUE!	#VALUE!	0	No Runwa	#VALUE!	#VALUE!	0	No Runwa	#VAL
31		26	7				1.5		0	0	0	1	0	0	0	1	No Runwa	#VALUE!	#VALUE!	0	No Runwa	#VALUE!	#VALUE!	0	No Runwa	#VAL
32		27	8				1.5		0	0	0	1	0	0	0	1	No Runwa	#VALUE!	#VALUE!	0	No Runwa	#VALUE!	#VALUE!	0	No Runwa	#VAL
33		28	9				1.5		0	0	0	1	0	0	0	1	No Runwa	#VALUE!	#VALUE!	0	No Runwa	#VALUE!	#VALUE!	0	No Runwa	#VAL
34		29	10				1.5		0	0	0	1	0	0	0	1	No Runwa	#VALUE!	#VALUE!	0	No Runwa	#VALUE!	#VALUE!	0	No Runwa	#VAL
35		30	11				1.5		0	0	0	1	0	0	0	1	No Runwa	#VALUE!	#VALUE!	0	No Runwa	#VALUE!	#VALUE!	0	No Runwa	#VAL
36		31	12				1.5		0	0	0	1	0	0	0	1	No Runwa	#VALUE!	#VALUE!	0	No Runwa	#VALUE!	#VALUE!	0	No Runwa	#VAL
37		32	13				1.5		0	0	0	1	0	0	0	1	No Runwa	#VALUE!	#VALUE!	0	No Runwa	#VALUE!	#VALUE!	0	No Runwa	#VAL
38		33	14				1.5		0	0	0	1	0	0	0	1	No Runwa	#VALUE!	#VALUE!	0	No Runwa	#VALUE!	#VALUE!	0	No Runwa	#VAL
39		34	15				1.5		0	0	0	1	0	0	0	1	No Runwa	#VALUE!	#VALUE!	0	No Runwa	#VALUE!	#VALUE!	0	No Runwa	#VAL

Ground Equipment | Runway Dimensions | Storm Data | Taxiway Apron | Plane Data | Deice | EntryDistribution | Delay

Select destination and press ENTER or choose Paste

Figure 4.3: Storm Data Worksheet

4.4.3 Distribution Worksheet

The entry distribution worksheet is for the distribution of aircraft into the system as seen in Figure 4.5. It has a function (Figure 4.4) which takes into account the peak hours of 09:30 and 18:00 and a curve which values most traffic at the hours of light in the day. The function is scaled to the curve based on the maximum amount of traffic that can be handled per day and is input from the aircraft data worksheet. This is to ensure that the distribution of air traffic is reasonable, with the majority existing in the hours when society is awake and that it quiets down during the night. There is also a field which takes into account an adjustment factor, to adjust to the value to a certain traffic volume.

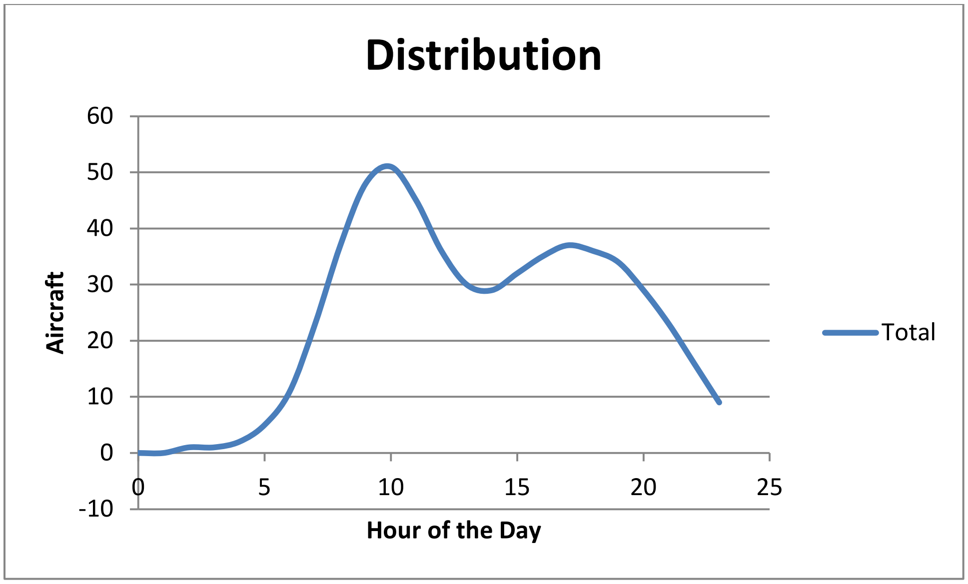
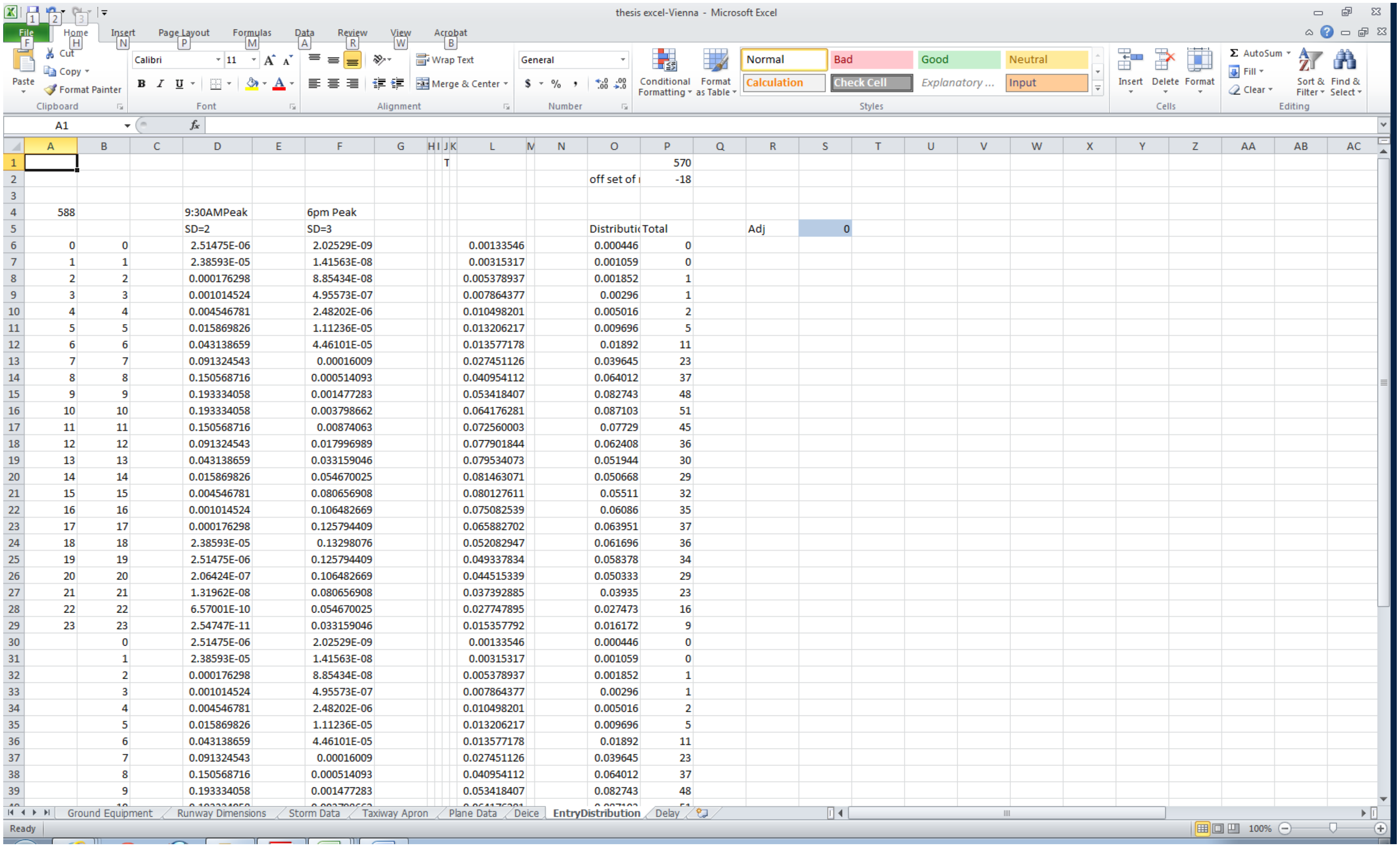


Figure 4.4: Aircraft Distribution

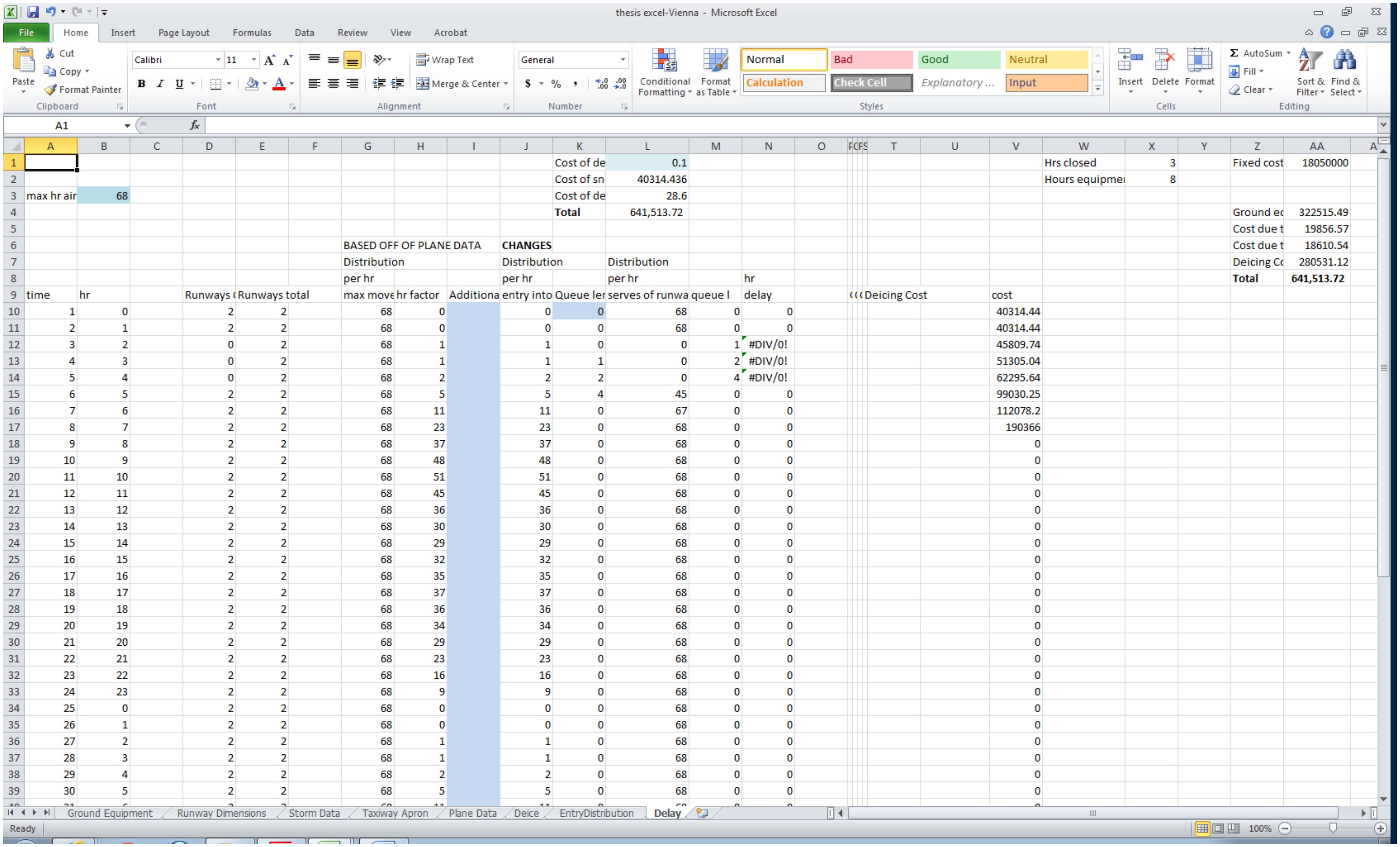


	A	B	D	F	K	L	O	P	R	S
1					T			570		
2							off set of i	-18		
3										
4	588		9:30AMPeak	6pm Peak						
5			SD=2	SD=3			Distributi	Total	Adj	0
6	0	0	2.51475E-06	2.02529E-09		0.00133546	0.000446	0		
7	1	1	2.38593E-05	1.41563E-08		0.00315317	0.001059	0		
8	2	2	0.000176298	8.85434E-08		0.005378937	0.001852	1		
9	3	3	0.001014524	4.95573E-07		0.007864377	0.00296	1		
10	4	4	0.004546781	2.48202E-06		0.010498201	0.005016	2		
11	5	5	0.015869826	1.11236E-05		0.013206217	0.009696	5		
12	6	6	0.043138659	4.46101E-05		0.013577178	0.01892	11		
13	7	7	0.091324543	0.00016009		0.027451126	0.039645	23		
14	8	8	0.150568716	0.000514093		0.040954112	0.064012	37		
15	9	9	0.193334058	0.001477283		0.053418407	0.082743	48		
16	10	10	0.193334058	0.003798662		0.064176281	0.087103	51		
17	11	11	0.150568716	0.00874063		0.072560003	0.07729	45		
18	12	12	0.091324543	0.017996989		0.077901844	0.062408	36		
19	13	13	0.043138659	0.033159046		0.079534073	0.051944	30		
20	14	14	0.015869826	0.054670025		0.081463071	0.050668	29		
21	15	15	0.004546781	0.080656908		0.080127611	0.05511	32		
22	16	16	0.001014524	0.106482669		0.075082539	0.06086	35		
23	17	17	0.000176298	0.125794409		0.065882702	0.063951	37		
24	18	18	2.38593E-05	0.13298076		0.052082947	0.061696	36		
25	19	19	2.51475E-06	0.125794409		0.049337834	0.058378	34		
26	20	20	2.06424E-07	0.106482669		0.044515339	0.050333	29		
27	21	21	1.31962E-08	0.080656908		0.037392885	0.03935	23		
28	22	22	6.57001E-10	0.054670025		0.027747895	0.027473	16		
29	23	23	2.54747E-11	0.033159046		0.015357792	0.016172	9		
30		0	2.51475E-06	2.02529E-09		0.00133546	0.000446	0		
31		1	2.38593E-05	1.41563E-08		0.00315317	0.001059	0		
32		2	0.000176298	8.85434E-08		0.005378937	0.001852	1		
33		3	0.001014524	4.95573E-07		0.007864377	0.00296	1		
34		4	0.004546781	2.48202E-06		0.010498201	0.005016	2		
35		5	0.015869826	1.11236E-05		0.013206217	0.009696	5		
36		6	0.043138659	4.46101E-05		0.013577178	0.01892	11		
37		7	0.091324543	0.00016009		0.027451126	0.039645	23		
38		8	0.150568716	0.000514093		0.040954112	0.064012	37		
39		9	0.193334058	0.001477283		0.053418407	0.082743	48		

Figure 4.5: Distribution Worksheet

4.4.4 Delay Worksheet

This worksheet is for calculating the delays as seen in Figure 4.6. The delay worksheet displays the result of cost and queuing for a given snow storm. The maximum distribution per hour is a set parameter based on the geometry of the airport -- it is the maximum amount of aircraft movements that can occur within a given hour, and is determined by the airport. The entry into the system distribution per hour is the amount of movement that occurs per hour. The queue length is the amount of congestion that has occurred prior to the period of analysis. The delay is based off of the ratio of runways open and the available cleared space on the taxiways and aprons, the maximum distribution of the system and the queue length. The cost is based on the snow equipment in use based off of the fuel usage of the vehicle, the cost of labor, the cost of passenger delay (determined to be $28.60 per passenger per hour [32]), and the cost of cargo was assumed to be $0.10 per kilogram of cargo per hour, however the real value is dependent on the actually cargo the airport handles, and thus the airport can adjust the value. The aircraft deicing costs are set up such that only when there is a delay or the equipment being used, is it calculated into the costs, because deicing occurs constantly in cold weather conditions. The values to the various fields are determined by inputs on previous worksheets. Additionally, the airport can include adjustments for aircraft amount at the various hours analyzed. The airport may also observe the average hours of delay per aircraft, the total hours the equipment is in use, the total ground equipment cost, total passenger cost, total cargo cost and the deicing costs in the upper right hand corner.



	A	B	D	E	G	H	I	J	K	L	M	N	T	V	W	X	Z	AA
1									Cost of de	0.1					Hrs closed	3	Fixed cost	18050000
2									Cost of sn	40314.436					Hours equipmei	8		
3	max hr air	68							Cost of de	28.6								
4									**Total**	641,513.72							Ground ec	322515.49
5																	Cost due t	19856.57
6					BASED OFF OF PLANE DATA			**CHANGES**									Cost due t	18610.54
7					Distribution			Distribution		Distribution							Deicing Cc	280531.12
8					per hr			per hr		per hr		hr					**Total**	**641,513.72**
9	time	hr	Runways (	Runways total	max move	hr factor	Additiona	entry into	Queue ler	serves of runwa	queue l	delay	(((Deicing Cost	cost				
10	1	0	2	2	68	0		0	0	68	0	0		40314.44				
11	2	1	2	2	68	0		0	0	68	0	0		40314.44				
12	3	2	0	2	68	1		1	0	0	1	#DIV/0!		45809.74				
13	4	3	0	2	68	1		1	1	0	2	#DIV/0!		51305.04				
14	5	4	0	2	68	2		2	2	0	4	#DIV/0!		62295.64				
15	6	5	2	2	68	5		5	4	45	0	0		99030.25				
16	7	6	2	2	68	11		11	0	67	0	0		112078.2				
17	8	7	2	2	68	23		23	0	68	0	0		190366				
18	9	8	2	2	68	37		37	0	68	0	0		0				
19	10	9	2	2	68	48		48	0	68	0	0		0				
20	11	10	2	2	68	51		51	0	68	0	0		0				
21	12	11	2	2	68	45		45	0	68	0	0		0				
22	13	12	2	2	68	36		36	0	68	0	0		0				
23	14	13	2	2	68	30		30	0	68	0	0		0				
24	15	14	2	2	68	29		29	0	68	0	0		0				
25	16	15	2	2	68	32		32	0	68	0	0		0				
26	17	16	2	2	68	35		35	0	68	0	0		0				
27	18	17	2	2	68	37		37	0	68	0	0		0				
28	19	18	2	2	68	36		36	0	68	0	0		0				
29	20	19	2	2	68	34		34	0	68	0	0		0				
30	21	20	2	2	68	29		29	0	68	0	0		0				
31	22	21	2	2	68	23		23	0	68	0	0		0				
32	23	22	2	2	68	16		16	0	68	0	0		0				
33	24	23	2	2	68	9		9	0	68	0	0		0				
34	25	0	2	2	68	0		0	0	68	0	0		0				
35	26	1	2	2	68	0		0	0	68	0	0		0				
36	27	2	2	2	68	1		1	0	68	0	0		0				
37	28	3	2	2	68	1		1	0	68	0	0		0				
38	29	4	2	2	68	2		2	0	68	0	0		0				
39	30	5	2	2	68	5		5	0	68	0	0		0				

Figure 4.6: Delay Worksheet

4.5 Summary of Chapter 4

Systematic and uniform collection of data from the airports was important for consistency and comparison. Putting the various airports under three different snow storm scenarios and altering the time during which the storms occurred allowed for comparison and trends to become visible at the various airports.

Data collection and categorization was done by means of an excel workbook, consisting of eight worksheets, to model the characteristics of the airport, the ground equipment, the storm, the aircraft and the time of day. This information, in turn, generates the costs associated with the given scenario and allows for comparison with the other airports being studied. It is important to observe and compare the efficiency of the airports, in order to determine which airport has the most efficient usage of its inventory for snow and ice removal.

Chapter 5

RESULTS

This chapter describes the snow and ice removal equipment inventories and provides a table of results of the costs of the storms analyzed for each of the airports. A cost effectiveness analysis was performed to evaluate which airports were best able to handle the various storms.

5.1 Philadelphia

Philadelphia International Airport winter storm management includes having two teams of 90 people working in eight hour shifts to achieve the snow removal. When there is a severe snow storm, the teams will have their shifts extended to sixteen hours. They use glycerol to deice the aircraft and use liquid chemicals for the runways and taxiways; a pellet form of the deicing chemical is used on the apron. Philadelphia International Airport's equipment includes two chemical trucks, four multifunctional Oshkosh vehicles, eight brooms, six plows, twelve snow blowers, three loaders, six snow hogs, six snow melters. The specific equipment is listed in the Appendix. The airport also will be getting two Boschung multifunctional vehicles. [33] The estimated costs are shown in Table 5.1 and Figure 5.1.

Table 5.1: Cost at Philadelphia (in thousand $)

	Storm 1	Storm 2	Storm 3	Storm 4	Storm 5	Storm 6
Expected Delay Per Aircraft	5.13	1.72	2.65	1.56	9.8	1.41
Hours Equipment Deployed	14	14	11	11	24	24
Ground equipment cost	243.7	213.2	191.5	191.5	417.8	417.8
Cost due to Passengers	8,015.4	1,389.6	4,140.6	2,445.0	15,252.0	2,197.8
Cost due to Freight	7,617.8	1,365.2	3,935.2	2,323.7	14,495.6	2,088.8
Deicing Costs	25,992.9	6,859.3	15,643.5	10,220.3	43,573.3	12,602.6
Total	41,869.8	9,827.3	23,910.8	15,180.5	73,738.7	17,307.1

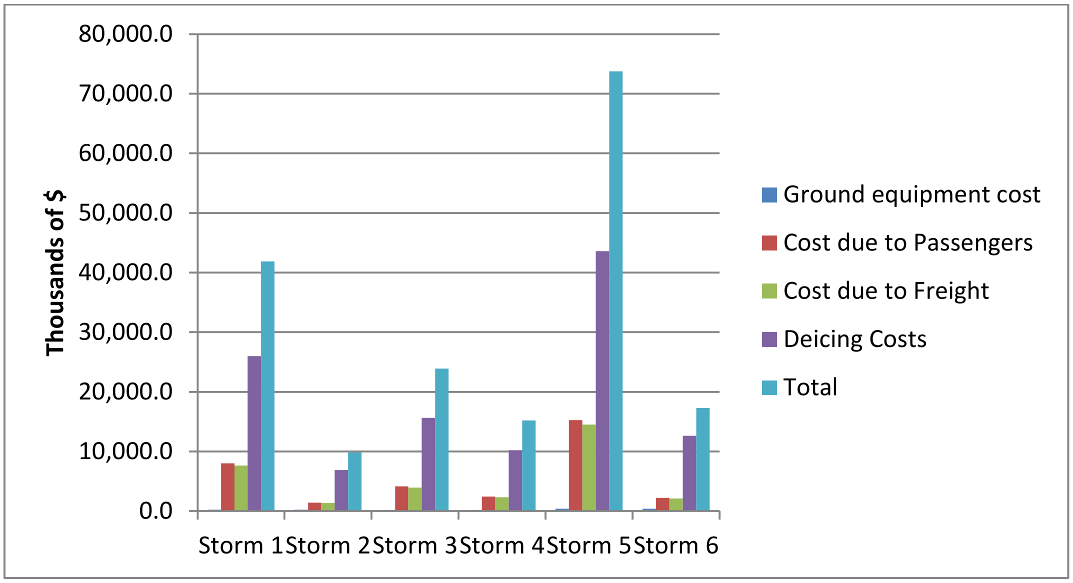


Figure 5.1: Graph of Cost at Philadelphia (in thousand $)

5.2 Boston

Boston Logan International Airport has 88 employees, allocated to snow and ice removal. Aircraft are deiced with Glycol and the runways are deiced with potassium acetate. Although not much inventory is stockpiled at the airport, Logan has the ability to replenish its supplies daily. The equipment that Boston Logan International Airport has includes eleven Vammas multifunctional vehicles, one Hagie multifunctional vehicle, six plows, two Rolba snow blowers, four Oshkosh snow blowers, three front end loaders, and three liquid chemical trucks. The specific equipment is listed in the Appendix. [34] The estimated costs are shown in Table 5.2 and Figure 5.2.

Table 5.2: Cost at Boston (in thousand $)

	Storm 1	Storm 2	Storm 3	Storm 4	Storm 5	Storm 6
Expected Delay Per Aircraft	1.415	0.735	0.702	0.316	5.497	1.872
Hours Equipment Deployed	9	9	7	7	20	20
Ground equipment cost	213.2	213.2	165.8	165.8	473.8	473.8
Cost due to Passengers	2,676.3	1389.6	1,328.5	598.3	10,396.6	3,541.7
Cost due to Freight	2,629.2	1365.2	1,305.1	587.8	10,213.6	3,479.3
Deicing Costs	9,394.3	6859.3	6,628.9	4,968.3	27,688.0	13,345.8
Total	14,913.1	9827.3	9,428.3	6,320.2	48,772.0	20,840.6

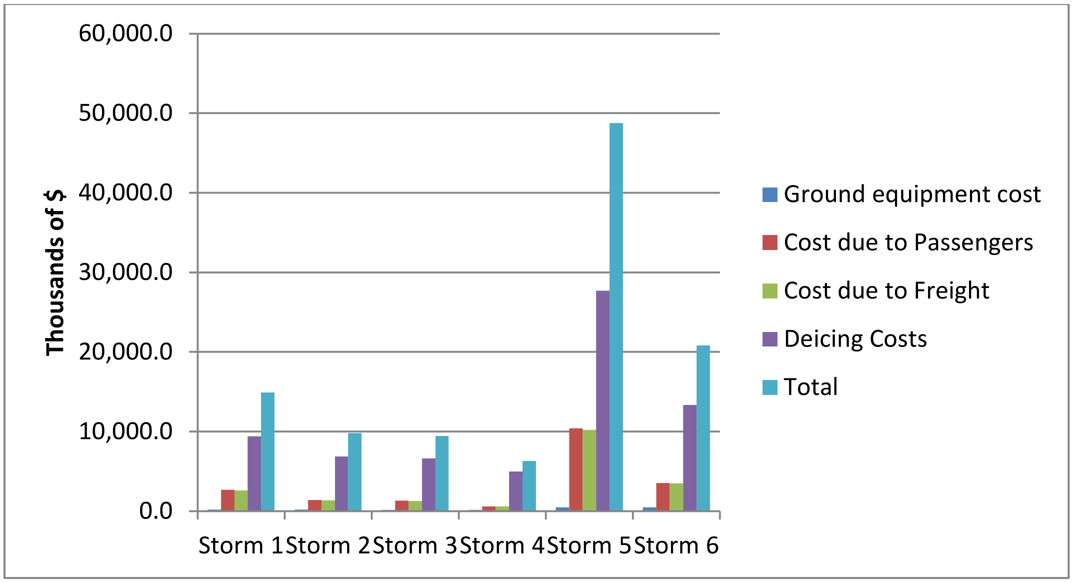


Figure 5.2: Graph of Cost at Boston (in thousand $)

5.3 Frankfurt

Frankfurt International Airport has 450 staff members allocated to the removal of snow and ice. Both solid and liquid forms of Aviform deicing agent are used at the airport to deice tarmac and aircraft. Frankfurt airport inventory can handle ten 24hr periods of heavy snow. The equipment available to Frankfurt International Airport includes sixty-five Boschung Jetbroom multifunction vehicles, which feature a plow and a broom, eighteen chemical spraying vehicles, fourteen snow blowers in addition to three special snow blowers for the taxiways to the new northwest runway, and one inspection vehicle. The specific equipment is listed in the Appendix. [35] [36] The estimated costs are shown in Table 5.3 and Figure 5.3.

Table 5.3: Cost at Frankfurt (in thousand $)

	Storm 1	Storm 2	Storm 3	Storm 4	Storm 5	Storm 6
Expected Delay Per Aircraft	1.269	0.689	0.612	0.231	5.719	1.954
Hours Equipment Deployed	8	8	6	6	19	19
Ground equipment cost	1,380.5	1,380.5	1,035.4	1,035.4	3,278.6	3,278.6
Cost due to Passengers	3,023.2	1,641.3	1,458.9	551.1	13,628.5	4,656.3
Cost due to Freight	3,169.7	1,720.8	1,529.6	577.9	14,289.3	4,882.1
Deicing Costs	10,471.5	7,435.4	7,008.9	4,483.0	37,193.7	15,774.1
Total	18,044.8	12,178.0	11,032.7	6,647.3	68,390.1	28,591.1

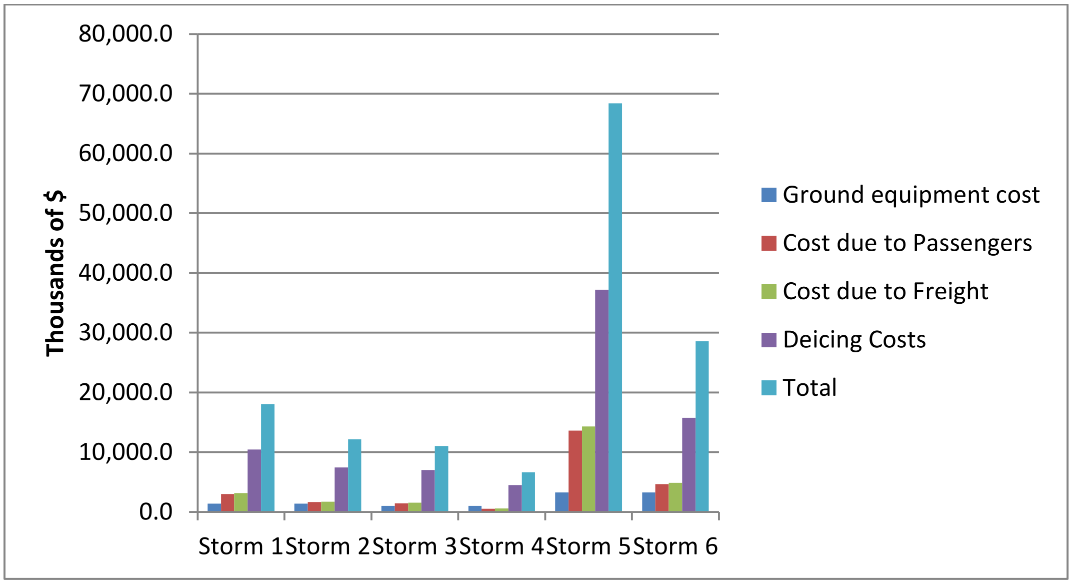


Figure 5.3: Graph of Cost at Frankfurt (in thousand $)

5.4 Vienna

Vienna International Airport relies on approximately 60 people who work in other parts of the airport and who are not on duty to be involved with the snow clearing effort. They start mobilizing the snow removal effort when the first signs of accumulation are visible and it usually takes about 90 minutes before they deploy. The airport uses a solid deicing material which is diluted with a liquid and is sprayed on to the surfaces. The equipment that Vienna International Airport has includes sixteen Boschung Jetbroom multifunctional vehicles, ten snow plows, ten snow blowers, two chemical vehicles, and two skiddometer friction testing trailers. The specific equipment is listed in the Appendix. [2] [37] The estimated costs are shown in Table 5.4 and Figure 5.4.

Table 5.4: Costs at Vienna (in thousand $)

	Storm 1	Storm 2	Storm 3	Storm 4	Storm 5	Storm 6
Expected Delay Per Aircraft	0.38	0.175	0.170	0.037	1.08	0.24
Hours Equipment Deployed	8	8	6	6	19	19
Ground equipment cost	322.5	322.5	241.9	241.9	766.0	766.0
Cost due to Passengers	641.1	292.2	283.7	62.4	1,804.1	400.0
Cost due to Freight	600.9	273.8	265.9	58.5	1,690.9	374.9
Deicing Costs	3,307.7	2,250.8	2,211.6	1,441.8	7,143.8	3,307.7
Total	4,872.1	3,139.3	3,003.0	1,804.6	11,404.7	4,848.5

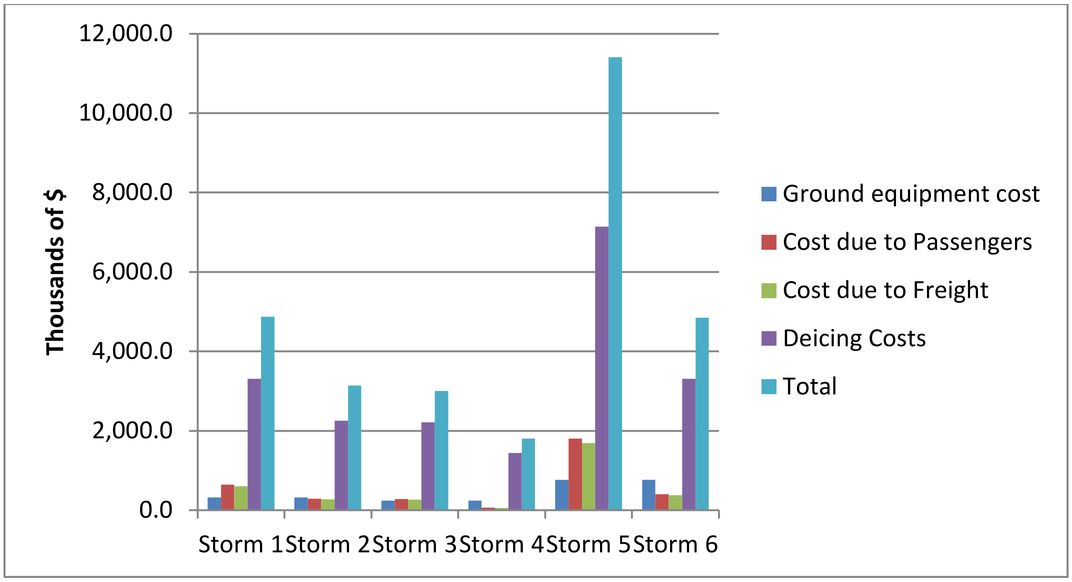


Figure 5.4: Graph of Costs at Vienna (in thousand $)

5.5 Cost Effectiveness Analysis

A cost effectiveness analysis was performed in order to compare the airports with each other. The factor used to determine the efficiency is the total cost of the storm divided by the number of passengers and also by the amount of cargo. A further analysis was done to determine the cost per hour that the presence of a piece of snow removal equipment has on the airport.

The major driving forces to the snow removal costs are the number of passengers and the amount of cargo, and inversely the amount of equipment and the hours it is in use. Thus further analysis was conducted to determine the efficiency of the snow and ice removal relative to the annual number of passengers and the annual amount of cargo that the airport handles.

$$\frac{\sum Total\ Storm\ Cost}{\sum Annual\ Passengers}$$

Table 5.5: Cost per Passenger ($)

	Storm 1	Storm 2	Storm 3	Storm 4	Storm 5	Storm 6
Philadelphia	1.36	0.32	0.78	0.49	2.39	0.56
Boston	0.55	0.36	0.35	0.23	1.79	0.76
Frankfurt	0.34	0.23	0.21	0.13	1.29	0.54
Vienna	0.25	0.16	0.15	0.09	0.58	0.25

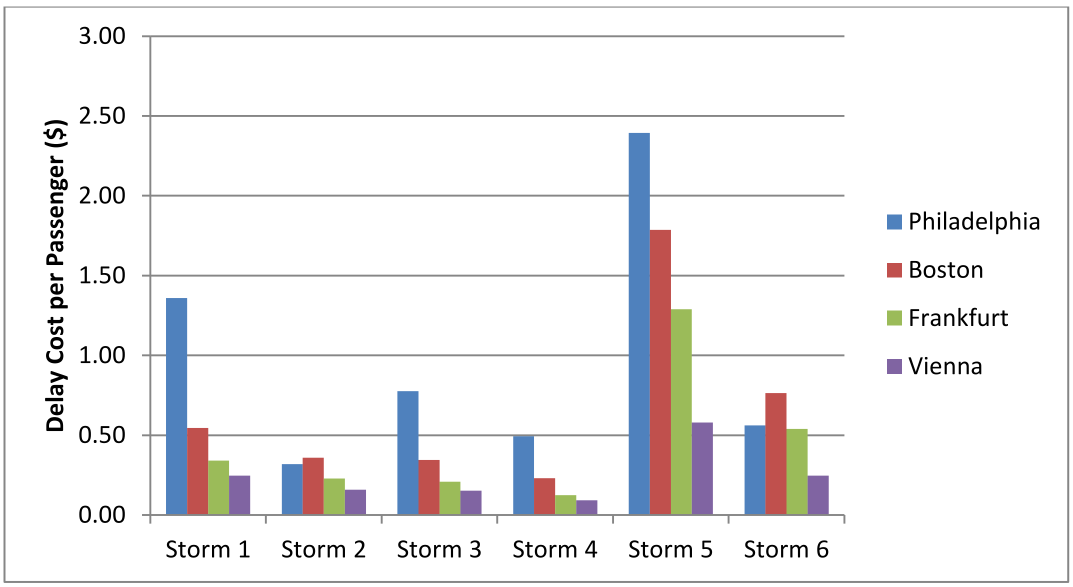


Figure 5.5: Graph of Delay Cost per Passenger of the Storms

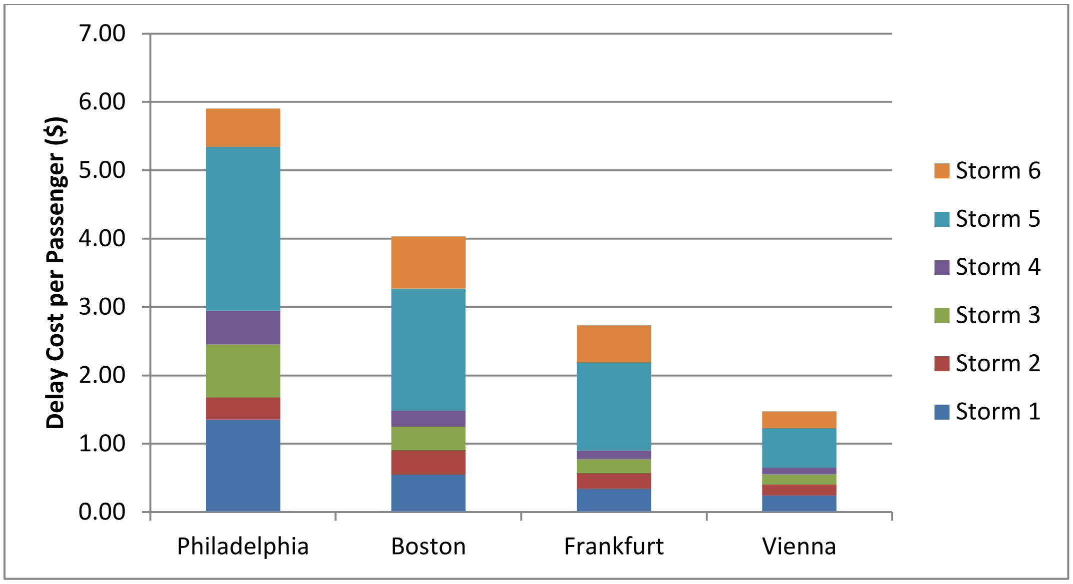


Figure 5.6: Culmination of Cost per Passenger per Airport

As seen in Table 5.5 and Figure 5.5 and Figure 5.6, the cost per passenger is least expensive overall in Vienna. Although among the airports analyzed, Vienna handles the fewest number of passengers and according to the formula should have the largest cost per passenger; the costs are mitigated as delays are kept to a minimum and the inventory of the equipment is at an appropriate level. Storm 1 demonstrates well the effect that the ratio of passengers per pieces of equipment has on the costs. Frankfurt airport has approximately the same efficiency as Vienna airport on a cost per passenger basis, but as the storm increases in length and delays are accumulated it becomes noticeable that Frankfurt airport has a significantly larger inventory despite having more passengers.

$$\frac{\sum Total\ Storm\ Cost}{\sum Annual\ Metric\ Tons\ of\ Freight}$$

Table 5.6: Cost per Metric Ton of Freight ($)

	Storm 1	Storm 2	Storm 3	Storm 4	Storm 5	Storm 6
Philadelphia	106.48	24.99	60.81	38.61	187.53	44.02
Boston	60.17	39.65	38.04	25.50	196.79	84.09
Frankfurt	8.09	5.46	4.94	2.98	30.65	12.81
Vienna	16.46	10.61	10.15	6.10	38.53	16.38

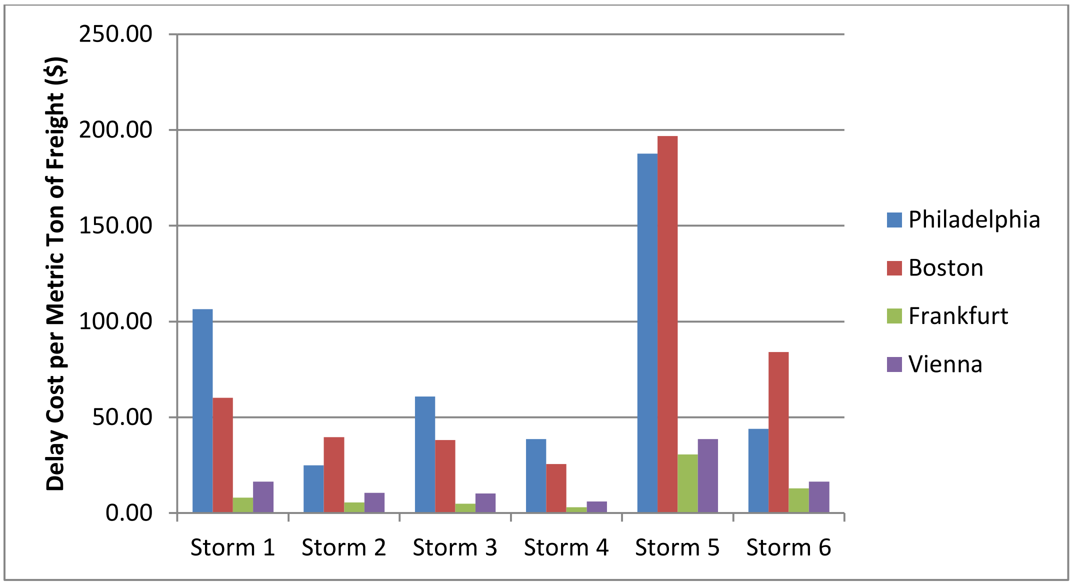


Figure 5.7: Graph of Delay Cost per Metric Ton of the Storms

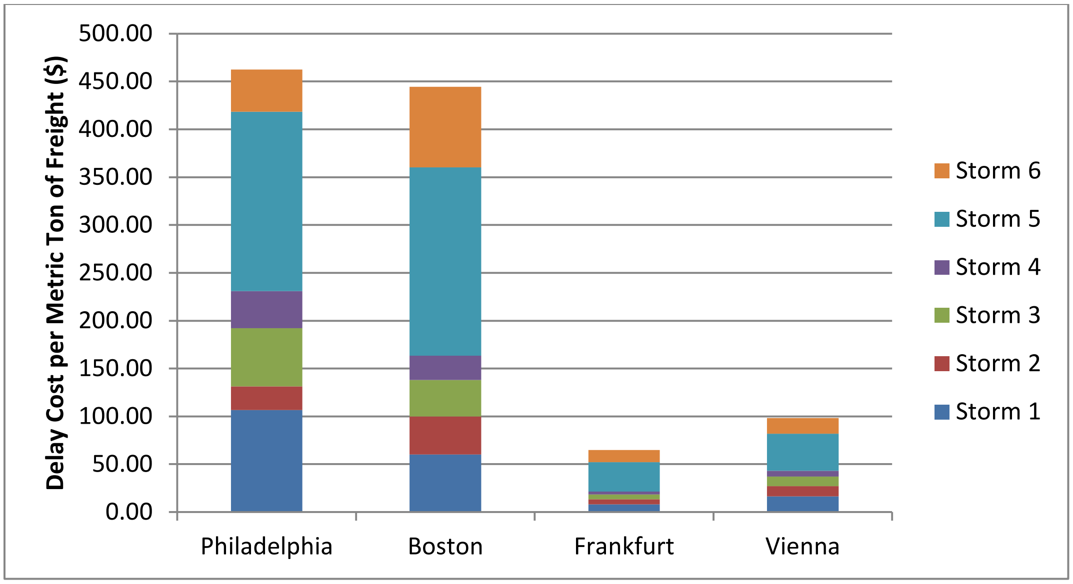


Figure 5.8: Culmination of Cost per Metric Ton per Airport

It can be observed, in Table 5.6 and Figure 5.7 and Figure 5.8, that Frankfurt has the least cost per metric ton of cargo. This is because Frankfurt handles a significantly larger amount of freight relative to the other airports and thus costs are spread over a larger denominator.

The number of pieces of equipment and the number of hours these pieces of equipment were in use during the storm has also been analyzed as it has a major effect on how effective the snow clearing is performed as seen in Table 5.7 and Figure 5.9. The airport with the least number of U.S. dollars per hours that the equipment was in use is the best, because the equipment is most efficiently used and thus has the least costs as seen in Figure 5.10. Too few pieces of equipment have a larger cost per vehicle. In addition it would drive the cost up as the snow and ice removal would not be met adequately and further delays would occur increasing the cost. Too many pieces of equipment would increase the cost of hourly usage, although decrease the time needed to remove the snow.

$$\frac{\sum Total\ Cost}{\sum Pieces\ of\ Equipment \sum Hours\ Used}$$

Table 5.7: Cost of Snow Removal per unit per hour (thousands of $)

	Storm 1	Storm 2	Storm 3	Storm 4	Storm 5	Storm 6
Philadelphia	119.6	28.1	86.9	55.2	122.9	28.8
Boston	57.1	37.7	46.4	31.1	84.1	35.9
Frankfurt	23.0	15.5	18.8	11.3	36.7	15.4
Vienna	20.3	13.1	16.7	10.0	20.0	8.5

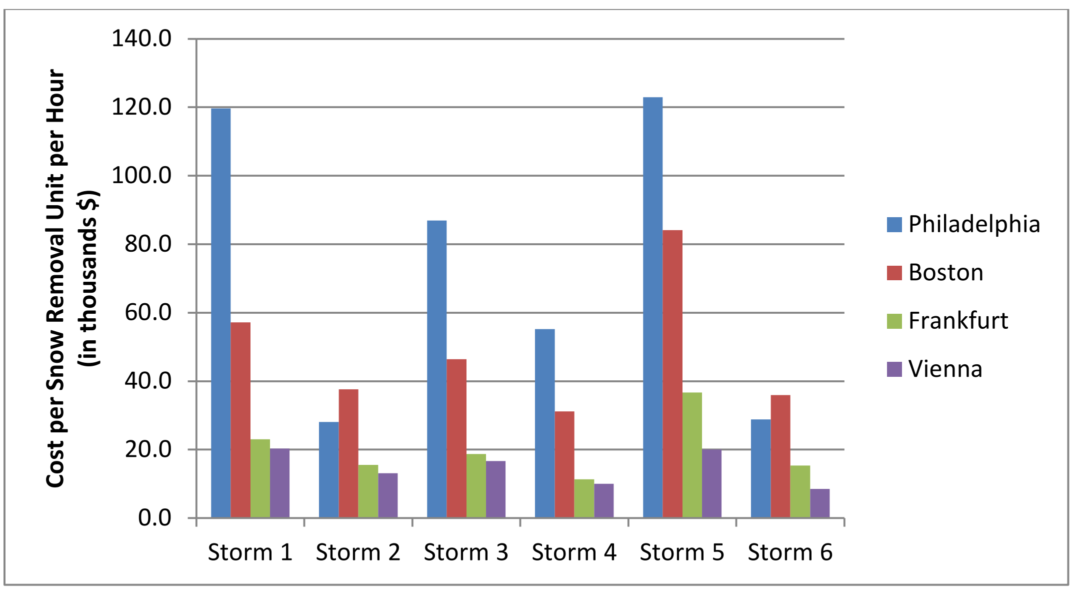


Figure 5.9: Graph of Cost of Snow Removal per unit per hour

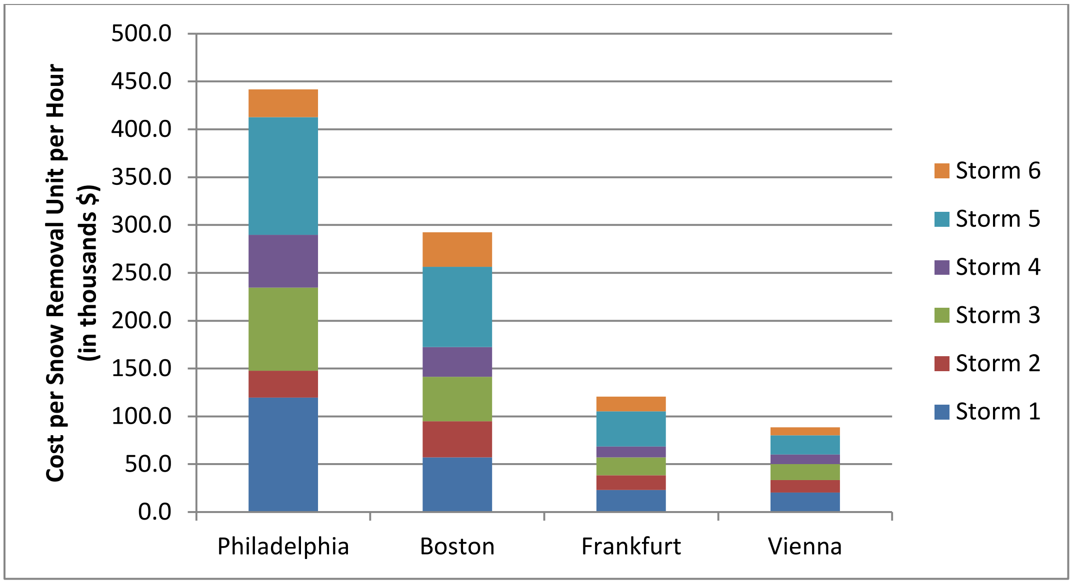


Figure 5.10: Culmination of Cost of Snow Removal per unit per hour

It is observed that Vienna airport has over all the storms the least cost of snow removal per unit of equipment per hour. This is mainly due to the number in the inventory relative to the size which results in its effective usage. Although having a large inventory such as in Frankfurt airport may be costly, the costs of a delay to the air traffic, which it handles is significantly more costly.

Table 5.8: Cost Benefit of Changing the Snow Removal Inventory

	Original	Increase of 1			Increase of 2			Increase of 3			Team
		Plow	Blower	Chemical	Plow	Blower	Chemical	Plow	Blower	Chemical	
Plow	16	17	16	16	18	16	16	19	16	16	19
Blower	10	10	11	10	10	12	10	10	13	10	11
Chemical	2	2	2	3	2	2	4	2	2	5	2
Testing	2	2	2	2	2	2	2	2	2	2	2
Person	60	61	61	61	62	62	62	63	63	63	64
Fixed	18,050,000	18,650,000	18,850,000	18,250,000	19,250,000	19,650,000	18,450,000	19,850,000	20,450,000	18,650,000	20,650,000
Average fix per storm	90,250.00	93,250.00	94,250.00	91,250.00	96,250.00	98,250.00	92,250.00	99,250.00	102,250.00	93,250.00	103,250.00
Total storm costs	4,872,111.17	4,742,174.20	4,879,438.37	4,879,518.37	4,660,314.36	4,886,765.57	4,886,925.57	4,578,454.51	4,894,092.77	4,894,332.77	4,585,781.71
Total cost	4,962,361.17	4,835,424.20	4,973,688.37	4,970,768.37	4,756,564.36	4,985,015.57	4,979,175.57	4,677,704.51	4,996,342.77	4,987,582.77	4,689,031.71
Average per increase	4,962,361.17	4,926,626.98			4,906,918.50			4,887,210.02			4,689,031.71
Expected Delay (hr) Per Aircraft	0.384	0.364	0.384	0.384	0.350	0.384	0.384	0.337	0.384	0.384	0.337
Average per increase	0.384	0.378			0.373			0.368			0.337

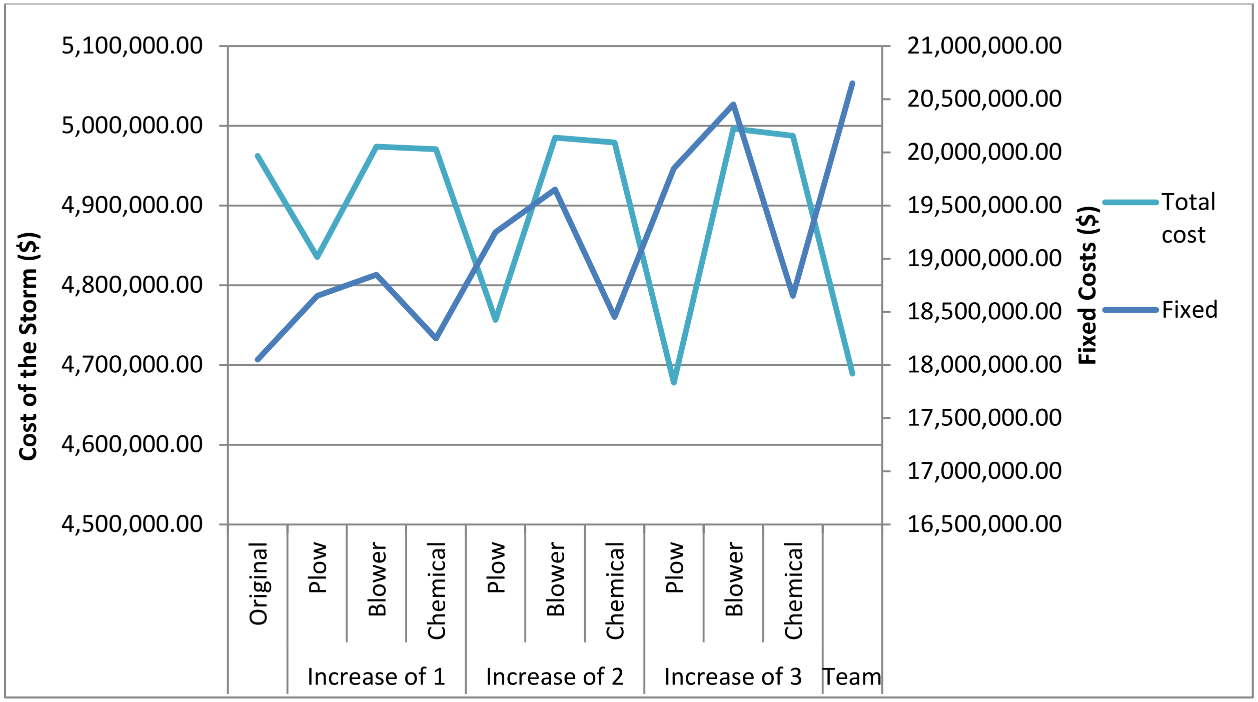


Figure 5.11: Cost of Changing Equipment Inventory

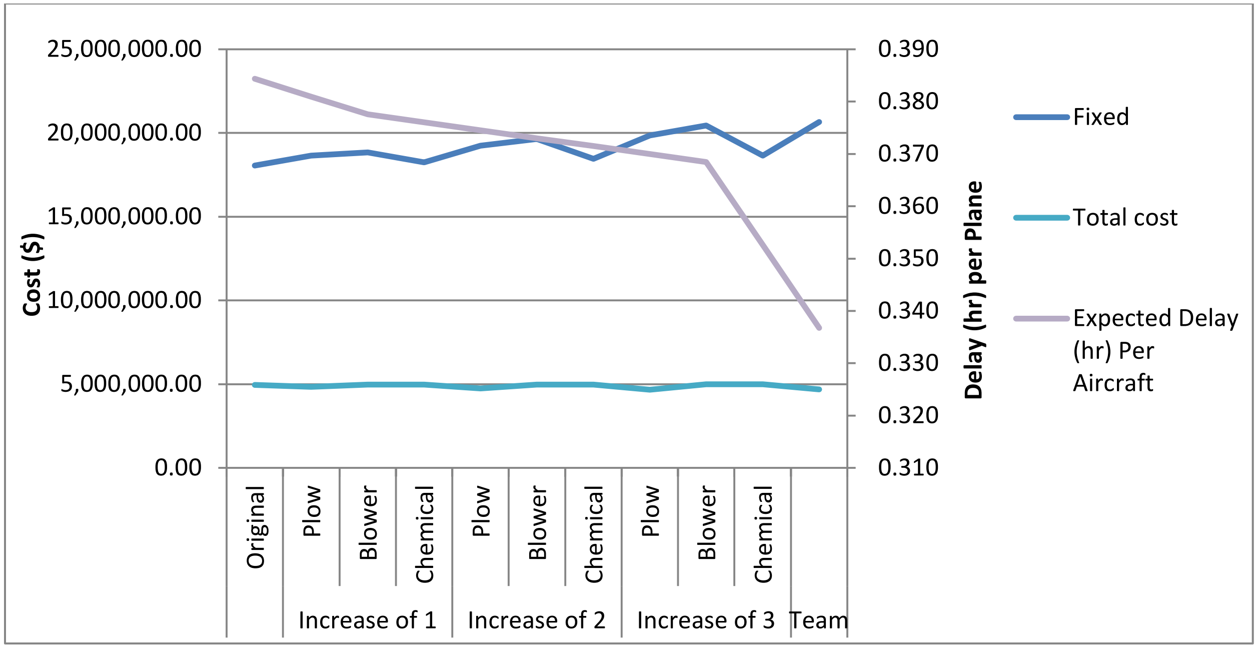


Figure 5.12: Cost and Delay of Changing Equipment Inventory

Increasing the inventory can have positive or negative effects. As observed in Table 5.8, gaining a single piece of equipment will increase the cost; however, when there are enough diverse pieces they can work together and form a group. This can decrease the delays and thus the costs are reduced as observed in Figure 5.11. However, having too few pieces of equipment would have a larger cost per vehicle and would further drive the cost up as the snow and ice removal would not be met as quickly. In turn, delays would form and thus cost, due to these delays, as seen in Figure 5.12. Having too many pieces of equipment would increase the cost of hourly usage. Although it may appear it would decrease the time needed to remove the snow, it would not, as the storms occur at a given rate and cannot be expedited.

5.6 Analysis of Results

Although the average aircraft may not be delayed the exact number of hours calculated, the measure provides a good basis to reference the relative amount of delay that the storm may have. A smaller delay would mean the impact is minimal and similar to normal daily operations. However, a larger expected delay is likely to create much delay and aggregation in the system. This is what happened in December 2010. Given the number of hours of expected delay identified in this model, one can conclude that Vienna has the most efficient snow clearing procedure as they have the least number of expected delay per aircraft (Table 5.4). However, when one looks at the cost of snow removal on an equipment-hour basis, it also appears that Vienna (Figure 5.10), with the least cost of snow removal for per unit of equipment per hour it was used, has the most efficient snow removal, followed closely by Vienna. The airports in the U.S. have a larger spread of cost, as well as an obvious gap between them and the ones in Europe. In part, this is driven by local legislation, where Europe is more geared to customer delay being costly to the industry, whereas in the US there is more of a focus on having the cost be accumulated by the passengers. There is also influence with regards to the trickledown effect. [8] [31]

Table 5.9: Average Storm with Regards to Time of Day

	Average AM Storm Cost	Average PM Storm Cost
Philadelphia	23,253,215	7,964,653
Boston	12,185,562	6,164,685
Frankfurt	16,244,611	7,902,732
Vienna	3,213,317	1,632,059

The time of the day has an influence on the cost to the airports as it has a major role in the delay factor as seen in Table 5.9. The costs of the morning storms and evening storms were compared amongst the airports and it was observed that the evening storms cost approximately 45% of their morning counterparts. This is primarily due to the trickledown effect of delays, which is when an airport shuts down and a backlog occurs. It takes longer for this to dissipate when there is less of a margin between the operations and the maximum.

The trickledown effect takes longer to dissipate at the airports in the US where normal operations are closer to their maximum operating capacity, which is driven by the fact that the airports are private entities and that the federal government is less involved with them. The trickledown effect of delays in turn greatly influences the costs at the airports.

The total cost of large volume airports such as Frankfurt is high due to the great equipment inventory combined with the large number of passengers and freight, thus when snow and delay are involved, the effect can be colossal. To mitigate this, having a large inventory is necessary to keep costs related to delays from growing exponentially quicker than the costs of the equipment. For smaller airports, costs related to an hour of delay may be small, and thus having a large array of inventory is not justified as the cost of the equipment is so great. It is then more cost efficient having less equipment and doing more passes.

Although snow clearing equipment is purchased at a per unit basis and cost variations exist due to what each piece of equipment can do and how effectively it can do it, one must recognize that it is necessary to have the proper combination of people and equipment to clear the runways and taxiways most effectively. Thus having excess pieces of equipment and not having a complete team is counterproductive to having an efficient snow clearing solution. Eventually, more equipment allows airports to clear runways in fewer passes, thus quicker, however the cost associated with a single pass is larger. So if the cost of an additional pass is less than the cost related to the delay of the additional pass, then it is worth purchasing more equipment to reduce the number of passes. However, if the opposite is true, then additional equipment is not needed or possibly even a reduction of equipment involved in a pass is recommended.

The costs are driven by the amount of cargo and the number of passengers, and inversely the total amount of hours the equipment is used. Thus the efficiency of the snow and ice removal is proportionate to the amount of passengers and cargo that the airport handles. As mentioned above, gaining a single piece of equipment will increase the cost; however, when pieces work together and form a group, the delays are reduced and thus the costs go down.

5.7 Summary of Chapter 5

The variations of the snow storms are important to allow for comparison between the airports. It was observed that although the airports are different from one another, trends between the airports became obvious, relative to the airport's experience with snow and ice and local legislation. It was also interesting to observe the efficiency of the different airports when the ratio of total delay was compared to the number of pieces of equipment and the hours they were in action, such that airports with significantly greater numbers of passengers had more equipment than airports with a lesser number passengers.

Chapter 6

CONCLUSIONS & RECOMMENDATIONS

This chapter describes the results and draws conclusions from the findings. It provides recommendations to airports and suggests where this research is applicable. It also points out where further development and research can and should be done.

6.1 Summary

The results show that the efficiency and effectiveness of the snow removal effort depends on the amount of equipment/staff at the airport, the amount of air traffic at the airport, the geometry of the airport, and finally the specifics of the storm. The geometry of the airport can be an important factor in determining the efficiency of snow removal as well as the amount of time and distribution of equipment needed to do the job. Airport geometry affects the way the equipment can be implemented as well as determining the time the equipment is commuting between two areas on the airport grounds. This is related to the amount of time that the equipment is required to be used to remove snow and thus how long it is in use. The distribution of the inventory of the equipment allows for effective snow removal teams to be established.

In a given storm, the time of day influences the cost of the storm as the amount of traffic varies with respect to the time of day. This can mean that a lot of snow for an hour in the middle of the night may be far less costly than half the amount of snow in the middle of the day. The amount of snow also influences snow clearance and its efficiency as the amount determines how close together the snow removal runs should be.

The airport that has the least total cost is Vienna International Airport because it has the least amount of people and cargo which pass through it. Vienna International Airport was the only airport which had the least hours of delay per aircraft, due to having an optimized snow and ice removal effort. The airport with the lowest cost per hour of equipment usage is Vienna International Airport because it has the lowest ratio of passenger and freight costs to the number of pieces of equipment.

6.2 Conclusions

In conclusion, the paper identifies a variety of factors involved in the implementation of successful snow removal efforts. The amount of snow, the type of snow, the wind direction, all factor into the efficiency of the snow removal effort. The tactic used to remove the snow also has an effect. These variables, in turn, combined with the aircraft traffic at the specific hour, allow for the amount of snow related delay to be determined.

In order for airport management to be sufficiently prepared for winter storms, it needs to have an overall grasp of the situation and an understanding of how systems are interconnected. This is critical as one system failure can lead to another system being strained and eventually also failing. This process of system failures can occur within an airport and also between airports as was observed in December 2010 when the closure of airports such as London and Paris resulted in long haul flights, which were already en-route, being diverted to airports such as Frankfurt and Munich and, although they did not fail, the added traffic combined with on-going snow removal activities resulted in additional chaos, as the airports could no longer deal with some of their own scheduled flights. This initiated a domino effect among many airports in Europe.

Through the analysis, Frankfurt airport has the most effective snow and ice removal effort. Despite the large number of passengers and the large amount of freight which it handles, it is able to keep the delays to a minimum and thus have low costs. This also is important in promoting the economic desirability of the regional economy.

With regard to winter storms, having measures related to mitigating their effect is important in reducing the overall cost to the economy. Although it may appear expensive for an airport to have an efficient but safe snow and ice removal strategy in place, such a strategy works to reduce delays of goods and services, and passengers. This is a particularly sensitive issue for business travelers where trip delays can have a significantly adverse impact on their contribution to the economy.

Each airport should justify its snow and ice removal strategy based on determination of the amount of snow and ice that the airport typically receives on an annual basis and the number of passengers and amount of freight that it handles. If an airport annually receives a significant amount of snow and ice, having a large inventory may be desired; but a large inventory may also be desired if the airport handles many passengers or freight, where a small delay due to snow and ice can create a costly back up. In any case, no airport that has a possibility of receiving snow or ice can afford the risks associated with operating without adequate snow and ice counter measures. Therefore, even these airports with the only the occasional chance of snow and ice must at the bare minimum maintain some snow and ice removal equipment.

6.3 Recommendations

This research is intended to be able to be used as an example both for further research in the field and for implementation of best practices by airport facilities. As noted earlier, more research needs to be done in areas where snow is common throughout most of the year, as well as at airports where snow rarely occurs. In the meantime, other airports may be able to adapt the methodology and worksheets to input their own data, determine their needs, and gauge their standards, based on the relative amount of snow that they receive.

Based on the findings in this study, Philadelphia International Airport should and Boston Logan International Airport could consider an increase in their inventory. Frankfurt International Airport should consider maintaining its current inventory, and potentially decreasing it by several units as they age. Vienna International Airport should maintain its current inventory until its new construction is completed or current inventory needs to be replaced**.**

6.4 Application

This research is applicable to airports that experience snow every year, but where snow storms are an “event” and snow does not cover the terrain for significant periods of the year, as is the case in certain airports in Russia or Scandinavia.

The research contributes to academia by providing methodology and analysis of ways and factors that snow and ice storms influence airports. It demonstrates that many factors influence the removal of snow and ice at airports.

With additional research from the academic world, it will hopefully be possible to distinguish cost effective measures of preparedness that different airports, in different climate zones, that receive different amounts of snow, may take to ensure minimal disruption deriving from their snow management and make guidelines available to airport management.

6.5 Summary of Chapter 6

It is important to understand that although the research focused only on two American and two European airports, it can be extended to other airports and be adapted for other situations that might arise with changes in the airports over time. The research has been able to determine the importance of snow and ice removal and has been able to compare the efficiency of the airports studied and to suggest whether some changes should occur. Hopefully, further research can be done which in turn will improve and expand the current research.

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Appendix

EQUIPMENT DATA INFORMATION

Equipment Data from Philadelphia

Staff 90

Number	Equipment
4	Multifunctional Oshkosh Vehicle
8	Snow Broom
6	Snow Plow
12	Snow Blower
3	Loaders
3	Snow hogs
6	Snow melters
2	Chemical Trucks
2	Boschung Multifuctional (ordered)

Equipment Data from Boston

Staff 88

Number	Equipment	Type
11	Vammas	Multifunctional Vehicles
1	Hagie	Multifunctional Vehicles
6		Plows
2	Rolba	Snow Blower
4	Oshkosh	Multifunctional Vehicles
3		Front end loaders
3		Liquid Chemical Trucks

Equipment Data from Frankfurt

Staff	450	
Number	Equipment	Type
65	Boschung Jetbroom	Multifunctional Vehicles
18		Chemical Spraying vehicles
14		Snow blower
3		Special snow blower for taxiway bridge
1		Inspection Vehicle

Equipment Data from Vienna

Staff	60	
Number	Equipment	Type
16	Boschung Jetbroom	Multifunctional Vehicles
10		Snow Plows
10		Snow Blowers
2		Chemical trucks
2	Skiddometer	Friction Testing Vehicles