DOT/FAA/TC-17/47

Federal Aviation Administration
William J. Hughes Technical Center
Aviation Research Division
Atlantic City International Airport
New Jersey 08405

Energy and Financial Viability of Hydronic Heated Pavement Systems

November 2017

Final Report

U.S. Department of Transportation
Federal Aviation Administration

NOTICE

Technical Report Documentation Page

1. Report No.
DOT/FAA/TC-17/47

2. Government Accession No.

3. Recipient's Catalog No.

4. Title and Subtitle
ENERGY AND FINANCIAL VIABLITY OF HYDRONIC HEATED PAVEMENT SYSTEMS

5. Report Date
November 2017

6. Performing Organization Code
ANG-E262

7. Author(s)
Pritha Anand, Ali Nahvi, Halil Ceylan, Vasiliki Dimitra Pyrialakou, Konstantina Gkritza, Kasthurirangan Gopalakrishnan, Sunghwan Kim, and Peter C. Taylor

8. Performing Organization Report No.

9. Performing Organization Name and Address
Department of Civil, Construction and Environmental Engineering
College of Engineering
Program for Sustainable Pavement Engineering & Research (PROSPER)
Institute for Transportation
Iowa State University
813 Bissell Road
Ames, IA 50011-1066

10. Work Unit No. (TRAIS)

11. Contract or Grant No.

12. Sponsoring Agency Name and Address
U.S. Department of Transportation
Federal Aviation Administration
Aviation Research Division
Center of Excellence for General Aviation
Partnership to Enhance General Aviation Safety, Accessibility and Sustainability (PEGASAS)
701 W. Stadium Ave.
West Lafayette, IN 47907-2045

13. Type of Report and Period Covered
Final Report

14. Sponsoring Agency Code

15. Supplementary Notes
The Federal Aviation Administration COR was Mr. Benjamin J. Mahaffay.

16. Abstract

Ice and snow impact transportation infrastructure systems and add significant costs to the United States economy in the form of snow removal, damaged pavement, and lost productivity due to travel delays. As a result of environmental and logistics concerns associated with conventional snow removal systems (CSRS), the use of heated pavements systems (HPS) at airports are continually gaining attention as a desirable alternative. The main objective of this research was to examine the financial viability of installing HPS at airport aprons for different categories of airports. To achieve this, two economic analysis techniques, the Net Present Value and Benefit Cost Ratio, were employed in analyzing a set of case scenarios implementing hydronic heated pavement system (HHPS) as representing HPS. HHPS has been used in practice and familiar to business sectors among different HPS technologies. The required data for economic analysis were collected through airport site visits, email questionnaires, government websites, reports, etc. The costs incurred from melting snow by HHPS and their potential benefits were calculated and compared with the operating costs of CSRS under specific case scenarios. Due to the inherently uncertain nature of weather-related delays, an in-depth sensitivity analysis was conducted to represent contrasting scenarios. It was found that HPS, despite the high installation costs, could be economically viable at commercial airports. The feasibility depends on the size of the airport in terms of operations and area of installation. As HPS technology continues to evolve with time, especially with the use of renewable energy sources and advanced construction methods, the benefits are far likely to outweigh the existing high initial installation costs.

17. Key Words
Airport, Winter maintenance, Heated pavement systems, Hydronic heated pavement systems, Economic analysis, Snow removal

18. Distribution Statement
This document is available to the U.S. public through the National Technical Information Service (NTIS), Springfield, Virginia 22161. This document is also available from the Federal Aviation Administration William J. Hughes Technical Center at actlibrary.tc.faa.gov.

19. Security Classif. (of this report)
Unclassified

20. Security Classif. (of this page)
Unclassified

21. No. of Pages
95

22. Price

ACKNOWLEDGEMENTS

The authors would like to acknowledge the Federal Aviation Administration (FAA) Center of Excellence (COE) for the Partnership to Enhance General Aviation Safety, Accessibility and Sustainability (PEGASAS) for sponsoring this research. The authors thank the following individuals for their support and participation.

Technical guidance and administrative support:

- Mr. Peter L. Sparacino, FAA
- Mr. Benjamin J. Mahaffay, FAA
- Mr. Jeffrey S. Gagnon, FAA
- Dr. Charles A. Ishee, FAA
- Mr. Donald Barbagallo, FAA
- Dr. William A. Crossley, PEGASAS, Purdue University
- Dr. Richard Wlezien, PEGASAS, Iowa State University
- Dr. Julienne M. Krennrich, PEGASAS, Iowa State University
- Ms. Diane M. Meyer, Engineering Research Institute (ERI), Iowa State University

Commercial and general aviation airports:

- Mr. Paul M. Sichko, Minneapolis-St. Paul International Airport
- Mr. Joshua Burger, John Glenn Columbus International Airport
- Mr. Bryan Belt, Des Moines International Airport
- Mr. Dave Poluga, Kent State University Airport
- Mr. David Sims, Mason City Municipal Airport

PEGASAS industrial advisory board and industry partners:

- Mr. Randy Nelson, Full Nelson Consulting
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- Mr. Rick Crider, Kelly Field at Port San Antonio Airport Authority
- Mr. John Frasca and Mr. Bill Hogate, Frasca International, Inc.
- Mr. Jens Henning, General Aviation Manufacturers Association
- Mr. Scott Meacham and Mr. John Gausch, CAP Aviation Consulting Group, LLC
- Mr. Kevin Ohrenberger, Sikorsky Aircraft Corporation
- Ms. Gloria Liu, Continental Motors, Inc.
- Dr. Bob Tanner, Net Jets, Inc.

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LIST OF SYMBOLS AND ACRONYMS

δ	Stephan-Boltzmann constant
ε_s	Emittance of wet slab
A_r	Ratio of snow-free area to total area
c_1	Conversion factor
C_0	Initial investment
C_i	Cash flow
$c_{p\ snow}$	Specific heat of snow
D	Density of water equivalent of snow
h_c	Convection heat transfer coefficient for turbulent flow
h_f	Heat of fusion for water
h_{fg}	Heat of evaporation at the film temperature at 33°F
h_m	Mass transfer coefficient of concrete slab
P_{dry_air}	Density of dry air
q_e	Heat of evaporation
q_h	Heat transfer by convection
q_m	Heat of fusion
q_o	Heat required in melting snow
q_s	Sensible heat transferred to the snow
r	Discount rate
s	Rate of snowfall
T	Time
t	Temperature
t_a	Ambient temperature
t_m	Average fluid temperature
T_f	Liquid film temperature
T_{MR}	Mean radiant temperature of surroundings
t_s	Melting temperature
t_f	Water film temperature
W_a	Humidity ratio of ambient air at 20°F
W_f	Humidity ratio of saturated air at film surface temperature at 33°F

1G3	Kent State University Airport
ACRP	Airport Cooperative Research Program
AIS	Injury severity levels
ARN	Stockholm-Arlanda Airport
ATES	Aquifer Thermal Energy Storage
BCA	Benefit cost analysis
BCR	Benefit cost ratio
BLS	Bureau of Labor Statistics
BTS	Bureau of Transportation Statistics
Btu	British thermal unit
CMH	John Glenn Columbus International Airport
COD	Chemical oxygen demand
CSRS	Conventional snow removal systems

LIST OF SYMBOLS AND ACRONYMS (Continued)

DOT	Department of Transportation
DSM	Des Moines International Airport
ECAC	Electrically conductive asphalt concrete
ECON	Electrically conductive concrete
EHPS	Electrically heated pavement system(s)
FAA	Federal Aviation Administration
FBO	Fixed-base operator
GA	General Aviation
HPS	Heated pavement system(s)
HHPS	Hydronic heated pavement system(s)
MCS	Monte Carlo simulation
MCW	Mason City Municipal Airport
MSP	Minneapolis-St. Paul International Airport
NPV	Net present value
O&M	Operation & maintenance
ORD	Chicago O’Hare International Airport
OSL	Oslo Airport Gardermoen
PEGASAS	Partnership to Enhance General Aviation Safety, Accessibility and Sustainability
PEX	Cross-linked polyethylene
PV	Present value
R&M	Repair and maintenance
SRE	Snow-removal equipment
U.S.	United States
USD	U.S. dollar
VOT	Value of time
VSL	Value of statistical life

EXECUTIVE SUMMARY

Ice and snow impact transportation infrastructure systems and add significant costs to the United States economy via snow removal, damaged pavement and bridge surfaces, and lost employee time due to travel delay. Conventional snow removal systems (CSRS) for removing ice and snow from paved surfaces include spraying large quantities of anti-ice chemicals on the ground and deploying a great number of snow-removing vehicles. However, these methods are labor intensive and have environmental concerns with possible contamination of nearby bodies of water for highway and airport pavements. Furthermore, CSRS for deicing using road salt and chemicals cause damage to concrete, corrode the reinforcing steel in concrete bridge decks and drainpipes, and destroy the ecological environment.

Heated pavement systems (HPS) have gained attention as desirable alternatives to current ice and snow-removal practices. These systems are practical and economic options for airport pavements that are frequently impacted by snow and ice.

This study focuses on the financial viability of hydronic heated pavement systems (HHPS), representing HPS in current practices, on airport aprons. The apron is the busiest part of the airport where vehicles and airplanes share the same area. Snow-removal operations are challenging and time consuming for the ground staff involved as they are exposed to inclement weather. In addition, due to immense activity and asymmetric (skewed) geometric designs, small snow-removal equipment (SRE) is used in aprons. These factors contribute to flight delays. Also, runways are long, straight strips that are relatively easier and faster to clear with heavy equipment than aprons. Therefore, clearing runways may not be the main contributing factor for flight delays. In this analysis, it is assumed that areas apart from aprons will still be cleared using SRE.

The findings of this study suggest that HPS are financially viable options for clearing pavement surfaces of snow and ice without using mechanical or chemical methods when passenger delay costs, fuel and crew costs, and enhanced safety are considered. HPS may be especially beneficial at aprons because although they are small areas relative to the total paved surfaces of the airport, they are associated with a large portion of winter weather-related delays. In addition, the findings suggest that the feasibility of HPS largely depends on the size of the airport examined, both in terms of aircraft operations and pavement area. Therefore, strategic HPS placement has the potential to reduce the initial construction costs significantly. Throughout this study, several assumptions were made due to incompatibility or lack of data. The costs associated with the CSRS was assumed to be largely dictated by the area considered.

1. INTRODUCTION.

This section provides background information about the background, research objectives, and approach to this report.

1.1 BACKGROUND.

In cold-climate regions, snow- and ice-removal operations are required to ensure the safety, mobility, and efficiency of highways where the driving conditions become hazardous in winter weather. As air travel is an important means of transportation, it is crucial to keep airports functional during severe winter weather. Airports typically use chemical deicers with high-powered snow-removal equipment (SRE), such as snow plows or brooms, to remove snow and ice from aprons, runways, and taxiways. However, snow-removal operations are challenging for the ground crew because of inclement weather exposure. Ground crew require appropriate training to deal with varied level of precipitation and how to react to wind speed and direction [1 and 2].

Many Nordic countries conduct trials during summer to identify the most effective and accelerated way to clear snow [3]. A large fleet of equipment is essential for rapid snow removal, but it is expensive [2]. As time plays a crucial role in clearing airports, the Federal Aviation Administration (FAA) has established guidelines for the amount of time that can be taken to clear snow and ice. According to these guidelines, commercial airports with more than 40,000 annual airline operations are required to clear snow and ice within 30 minutes of 1 inch of snowfall from the Priority 1 areas that directly contribute to safety and the re-establishment of aircraft operations at minimum acceptable level of service [4]. Priority 1 will generally consist of the primary runway(s) with taxiway turnoffs and associated taxiways leading to the terminal , portions of the terminal ramp, portions of the cargo ramp, airport rescue and firefighting (ARFF) station ramps and access roads, mutual aid access points (including gates), emergency service roads, access to essential NAVAID, and centralized deicing facilities [4].

In the aprons, specifically, there is a lot of activity from baggage handlers, ground staff, and oil-refueling operations. Because smaller equipment is used, snow-clearing operations are time consuming and inefficient, and this propagates delays. Additionally, the mix of machinery and human activity at aprons poses safety concerns. These factors motivate the use of heated pavement systems (HPS) at aprons. Heating runways may not be practical, as they are subjected to thrust and high temperature that could damage the heated pavement. Moreover, costs and energy requirements may not be justifiable for such a large area, as pointed out by the Airports Council International [5].

Airports usually have a reduced number of daily operations in winter. If the number of daily operations can be increased, the operating revenue can increase, benefitting the airport. Assuming this reduction is related to the delays caused by snowfalls, alternate snow-removal strategies, such as HPS, have the potential to alleviate the aforementioned problems and keep airports operational during severe winter weather.

1.2 TYPES OF HPS.

HPS can be categorized into two types, hydronic heated pavement systems (HHPS) and electrically heated pavement systems (EHPS). HHPS can be achieved by circulating hot fluid through a series of pipes that run through the pavement. Heated fluid can be supplied from boilers operated by natural gas, geothermal energy, or electricity depending on the airport location. Using HHPS to remove ice and snow has been successful in European airports [6]. EHPS can be achieved by using embedded electrical cables or electrically conductive paving materials for heating.

The expected benefits by using an HPS include a reduction in environmental effects of deicers, reduced cost of fuel and energy, fewer labor requirements, and fewer impacts to travelers. To verify and validate such benefits, it is essential to study the cost and energy impacts of such systems.

1.3 RESEARCH OBJECTIVES.

The main objective of this research was to examine the financial viability of installing HPS at airport aprons for different categories of airports. Since runways are long, straight strips, they are relatively easier and faster to clear with heavy equipment than aprons. Therefore, runways may not be the main contributing factor for flight delays during winter weather at a typical airport. Among different HPS technologies, HHPS has been used in practice and familiar to business sectors among different HPS technologies. This study focuses on the financial viability of HHPS, representing HPS in current practices.

The four specific objectives of this research were:

- Assess the amount of energy required to heat a slab to above freezing temperature using an HHPS during a winter precipitation event. Compare the operation cost of using HHPS to the cost of using conventional snow removal systems (CSRS) approaches such as plowing, using chemicals (e.g., potassium acetate), and hauling snow off site.

- Appraise the initial installation costs of an HHPS and ascertain how the cost can be absorbed over a period of time.

- Investigate the economic advantages of an HHPS including operational savings, improved safety, and personnel costs savings for SRE operators.

- Examine differences in HHPS cost and benefits between large, high-traffic airports and small, general aviation (GA) airports.

1.4 ECONOMIC ANALYSES AND APPROACH.

Economic analyses were conducted involving benefit cost analysis (BCA) methods and net present value (NPV), which are discussed in sections 3.4 and 3.5.1, respectively. The purpose of BCA is to compare the benefits and costs associated with a policy or investment; this methodology is commonly used for assessing proposed public projects [7]. NPV is the difference between the present value (PV) of cash inflows and the PV of cash outflows. This study provides a better understanding of the various benefits and costs associated with each strategy and also can serve as a decision-making tool for airport managers to adopt an alternative technology such as HHPS.

2. LITERATURE REVIEW.

2.1 THE CSRS.

CSRS include both mechanical and chemical methods.

2.1.1 Mechanical Methods.

Mechanical methods include the use of SRE such as snow plows, snow blowers, snow brooms, and sweepers. Using mechanical SRE can be time consuming, as they operate at slow speeds, and thus may interfere with aircraft operations. In addition, wet snow and ice can freeze to the pavement, reducing greatly the SRE efficiency. Another major drawback of using mechanical SRE is that they remove snow only from the surface and do not focus at the point of bonding [8]. Mechanical equipment also can damage the pavement and the embedded lighting fixtures.

2.1.2 Chemical Methods.

Chemical methods include using solid chemicals and liquid-spraying equipment with a variety of deicing and anti-icing chemicals. Deicing and anti-icing are two processes used for ice and snow removal from trafficked surfaces at airports. Both processes require expensive machinery, significant personnel time, and detailed planning. Deicing is defined as the process of removing existing snow and ice from a trafficked surface [8]. This process includes mechanical snow-removal methods and the application of ice-melting chemicals after a snow event. Anti-icing is the process of treating the surface with ice-melting chemicals before or during a storm to prevent or delay the formation or adhesion of ice to the surface [8].

The chemicals used most widely at United States (U.S.) airports include potassium acetate, urea, sodium acetate, sodium formate, and propylene glycol. Potassium and sodium acetates are gradually replacing other deicers; however, they can impact aquatic environments through consumption of dissolved oxygen in the water [9]. Acetates do not have widespread effects on plants, but they can be detrimental if used in high concentrations. Acetates, such as potassium acetate (KCH3COO) and calcium magnesium acetate (CMA), are used for anti-icing, and they are generally more expensive than chloride-based products. However, they can be more effective, less corrosive to carbon steel, and not as environmentally harmful as chlorides [10]. Pavement deicers specified by the FAA do not pose environmental hazards and do not require special methods for purification. Therefore, the storm water purification costs have not been considered a part of the analysis. Airport managers usually limit the use of such substances, as they are expensive and can cause tremendous budgetary changes.

2.2 CURRENT STATE OF PRACTICE—HPS.

2.2.1 The HHPS.

In 1948, the first application of heated pavement in the U.S. resulted in a hydronic heating system constructed into a 137-m long (450-ft) bridge deck in Klamath Falls, Oregon. A solution made of half ethylene glycol and half water circulated through 19 mm-diameter (3/4-in.) iron pipes located 7.5 cm (3 in.) below the pavement, surface as shown in figure 1, and 45 cm (18 in.) on center. The ethylene glycol acted as antifreeze for the fluid. The solution was heated by a 62°C (143°F) geothermal well through a heat exchanger before being pumped through the deck. The pump, which required electricity to run, was the only operation cost of the heated pavement. The Klamath Falls hydronic system initially had the heating capacity to keep the bridge clear for a snowfall intensity of 76 mm per hour at an air temperature of -23°C (3 in. per hour at -10°F). In 1992, the temperature of the geothermal well dropped from 62°C to 37°C (143°F to 98°F), and the well was rehabilitated. In 1997, the hydronic system failed from leaks in the iron pipes caused by corrosion. A replacement geothermal-powered hydronic system was installed into the bridge after the failure. The new system used 19-mm (3/4-in.) diameter cross-linked polyethylene (PEX) tubes imbedded 7.6 cm (3 in.) deep in an 18-cm (7-in.) thick concrete layer. The PEX tubes were placed 36 cm (14 in.) on center in a double-overlap pattern. In 1999, the total cost of the reconstruction project was approximately 430,000 USD and the annual operation and maintenance cost was 3,000 USD and 500 USD respectively [11].

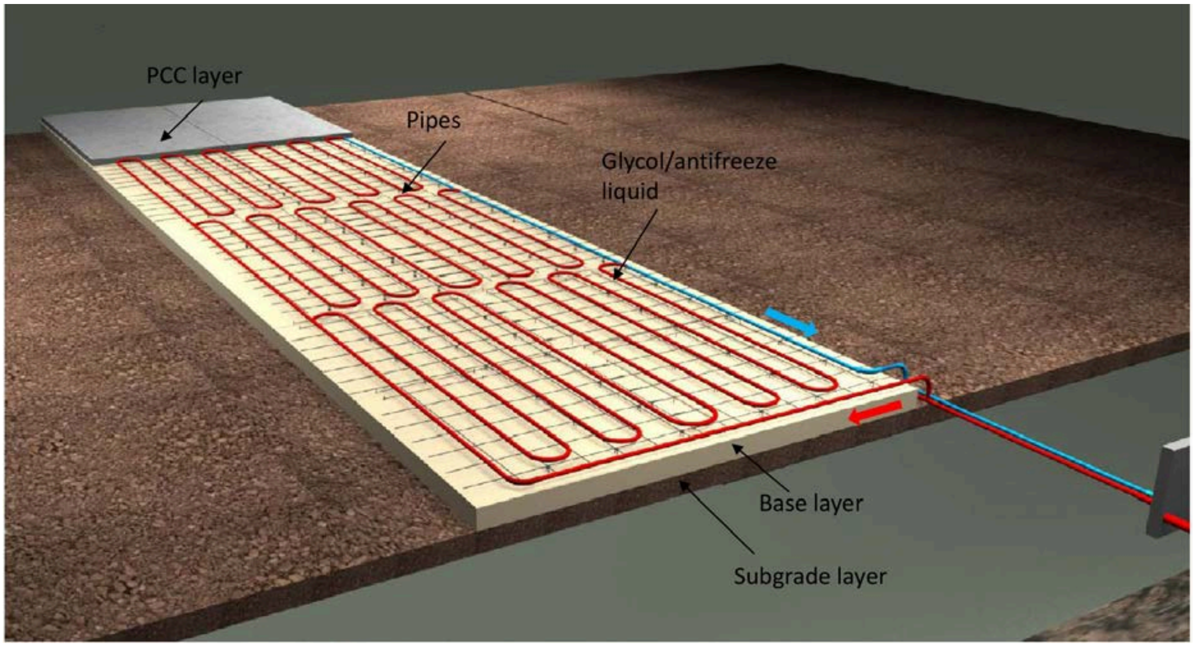

Figure 1. Hydronic Heated Slabs

Hydronic heated pavement has since spread globally with high concentration of use in Nordic countries and Japan. Hydronic heated pavement is primarily used in bridges, but it has been used recently to heat aircraft parking stands in Nordic countries [12]. Today, the U.S. has hydronic and heat pipe bridges in operation in Oregon, Nebraska, Texas, Virginia, Wyoming, and New Jersey.

The hydronic system is geothermally heated through Aquifer Thermal Energy Storage (ATES), as shown in figure 2 [6]. The Oslo Airport Gardermoen (OSL) contains 35 hydronic heated aircraft parking stands ranging from 600 to 780 m^2 (6,500 to 8,400 ft^2) in size. The hydronic system is also supplemented by one electric and four oil-fired boilers to reach the design-heating performance of 248 W/m^2 (79 Btu/(h ft^2)). ATES operates when temperatures fall between -8°C and 2°C (18°F and 35°F) and takes about 4 hours to start. The heated aircraft parking stands averaged from 275,000 USD to 375,000 USD to build, and the annual operation cost for each stand amounted to approximately 16,500 USD. OSL personnel consider the heated stands a necessity because of quicker aircraft turnaround times and safety of ground crews and passengers. OSL currently has 10 larger heated stands under construction, which would increase their heated pavement area to 36,836 m^2 (396,500 ft^2) [6 and 12]. Stockholm-Arlanda Airport (ARN), also uses ATES to heat 54 aircraft parking stands, which cover an area of over 92,900 m^2 [6 and 12].

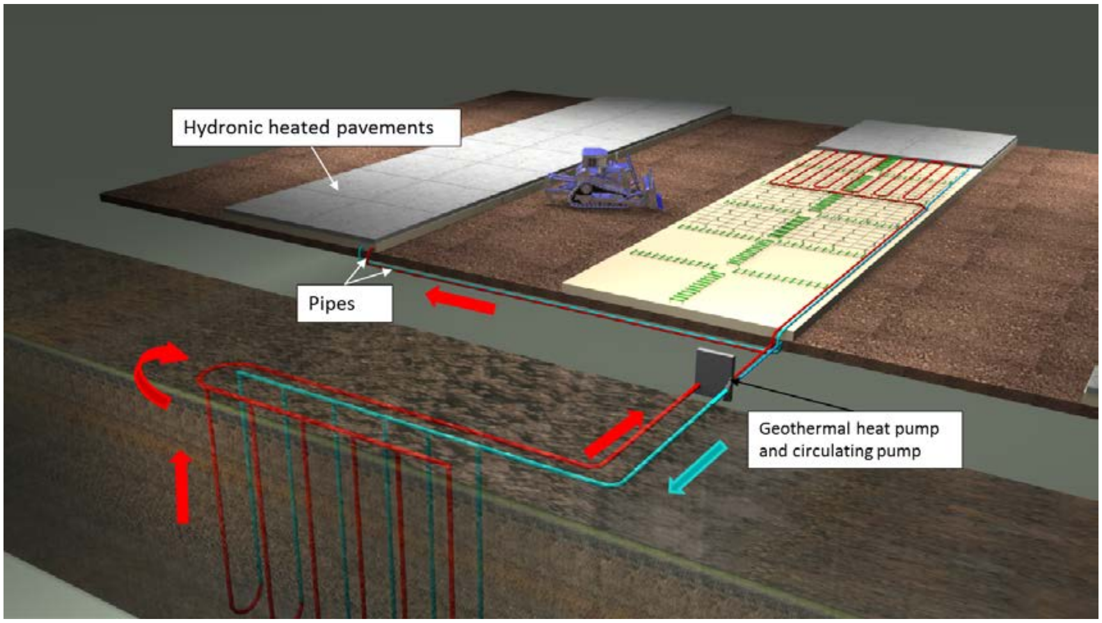

Figure 2. The ATES Heats the Airport Terminal and the Aircraft Parking Stands

2.2.2 The EHPS.

EHPS has been infrequently used in practice in comparison to HHPS. An electrically conductive asphalt pavement system (with the commercial name Snowfree®) was developed by Superior Graphite in 1995, which incorporates copper cables embedded in a conductive asphalt layer consisting of 25% synthetic graphite [13].

In collaboration with the FAA, a conductive asphalt concrete pavement system was installed on 697 m^2 (7,500 ft^2) of taxiway at Chicago O'Hare International Airport (ORD) [14]. Copper cables, alternating between live and ground were placed at intervals of 4.88 m (16 ft) and cast within a 5-cm (2-in.) layer of the graphite-infused asphalt concrete. The asphalt mix appropriately attained the FAA Advisory Circular (AC) 150/5370-10F P-401 standard [15] for airport surfaces. During the 3.5-year duration of the study, 200,000 aircraft traveled on the graphite infused asphalt concrete, and no significant cracking was observed. The system's performance was evaluated for 3.5 years from 1995 to 1999. Throughout the evaluation period, the conductive asphalt concrete system consistently produced a power density of 484 W/m^2 (153 Btu/(h·ft^2)) while in operation. The study reported that an estimated operating cost of 2,400 USD/h (value in 2003 USD) would run the conductive asphalt concrete system for a 10,000 foot-long runway. Although the Snowfree satisfactorily cleared snow and ice, its operating cost was high, and other airports have not used this technology to date [13]. The practical implementation of EHPS in concrete surfaced airfields is not reported by any study.

2.3 OVERVIEW OF FAA ADVISORY CIRCULAR—HPS.

The heat requirement for designing and sizing any kind of deicing systems and equipment depends mainly on atmospheric factors (such as humidity and air temperature), thermal conductivity of the pavement surface, and the classification of heat expectations [8]. Convection and radiation loss from the melted snow depends on the film coefficient and the difference in temperature between the surface and air. The film coefficient is a function of wind speed alone, and since the pavement temperature is fixed, convection and radiation losses vary with changes in air temperature and wind speed [11 and 16].

2.3.1 The HHPS.

HHPS are typically closed-loop systems, as shown in figure 3, where, after the fluid releases heat into the pavement, it returns to the heat source to be sent through the pipes again [11]. HHPS use metal or PEX pipes. The fluid can be heated by a variety of sources from burning fossil fuels to more environmentally friendly options such as natural gas, geothermal wells, and waste heat from local industries. Geothermally heated hydronic systems often incorporate heat pumps to obtain a higher range of heat, as in many places the ground temperatures are not high enough to melt the snow [17].

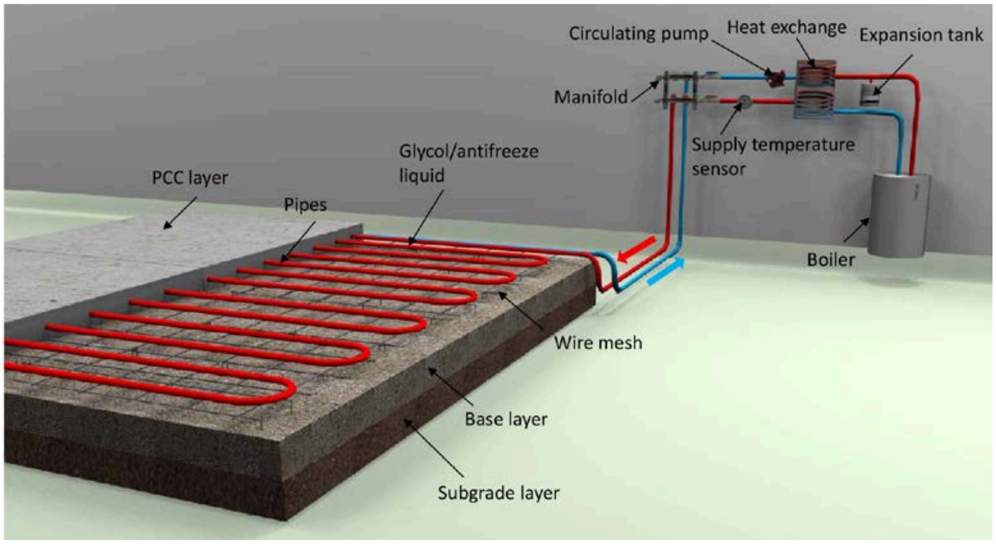

Figure 3. Detail of a Hydronic Heated Pavement System

The issue of surface runoffs from the heated pavement is a major design consideration. Commonly, the designers of drainage systems consider a maximum design storm depending on the geography and climate. The water drainage from melted snow can exceed the design capacity, which would affect traffic and cause damages to the facilities. Thus, measurements for proper water drainage or storage/removal should be also considered. Since HHPS is implemented previously in airports, this study only focused on financial viability of HHPS.

2.3.2 The EHPS.

When electrical current flows through a conductor, it encounters resistance, which converts electrical energy to heat energy. The heat produced is a function of the current that flows through the conductor and is also the composition of the conductor that offers resistance to the current flow. Two methods of electrical heating are used for in-pavement snow-melting applications [8]. One method involves embedding insulated conductors, such as heating cables or grid/mesh mats, in the pavement. The other method involves adding conductive materials to the pavement material mix and then applying electrical energy through uninsulated conductors, thereby having the pavement serve as the heat source. Since EHPS are not implemented in airports yet, in this study, this option is not considered.

2.3.3 Heat Requirements.

When calculating design heat requirements, it is important to take into account atmospheric factors including rate of snowfall, air temperature, relative humidity, and wind velocity. The detailed equations for each of these parameters are available in FAA AC 150/5370-17 [8]. Heat requirements for snow-melting installations are classified as Class I, II, or III. Class I systems have a snow-free area ratio of 0 and are designed to melt snow after it has stopped. Class II expectations are for areas that must be kept clear of accumulating snow, but the pavement may remain wet. Class II systems are designed for a snow-free area ratio of 0.5. Class III systems have a snow-free area ratio of 1 and are designed to melt snow and ice while it is falling and keep the surface dry. The required heat design load should be based on expected rate of snowfall, air temperature, humidity, wind speed, dimensions, and characteristics of the pavement. Class III systems have been selected for this study.

The Class III heating system [8] must be capable of

- maintaining a surface condition of "no worse than wet,"
- attaining surface temperature above the freezing point before the start of expected snow accumulation, and
- maintaining surface temperature above the freezing point until snow accumulation has ceased.

3. METHODOLOGY.

The methodology followed in the study is outlined in figure 4. The basic strategy started by selecting airports that had an annual snowfall of at least 35 inches and icy conditions prevailing for most of the winter. Next, data were collected from these airports through surveys and on-site visits. In addition to weather conditions, passenger and delay statistics were gathered using public available data [18]. Then, all costs and benefits related to the collected data were monetized and analyzed for a 20-year period. Finally, the costs and benefits of installing HHPS were compared with the conventionally used snow-removal methods to investigate their economic feasibility.

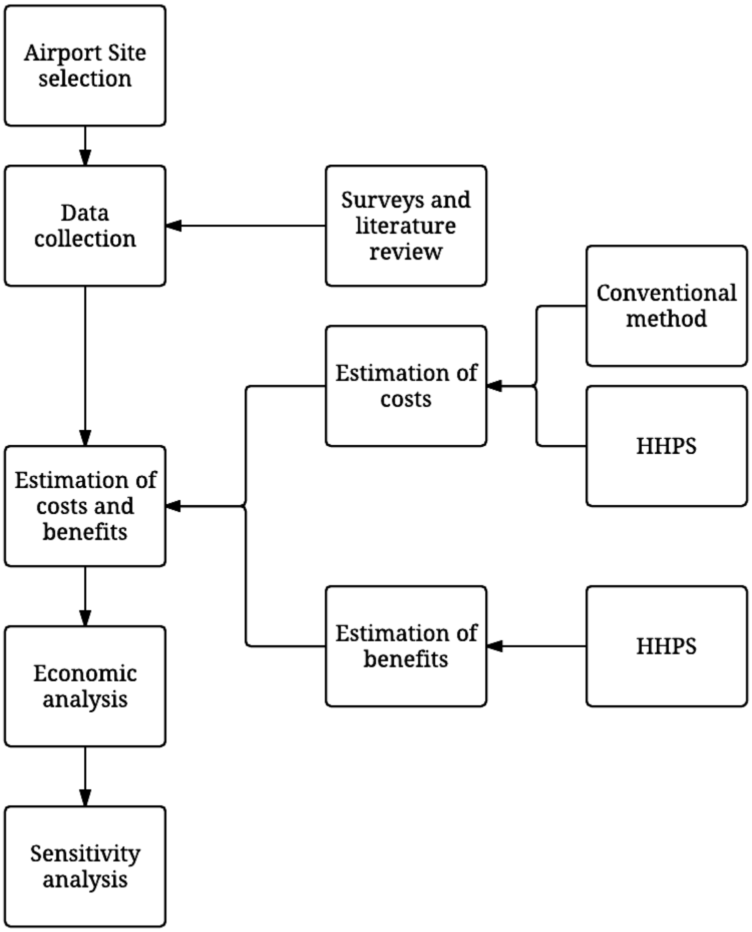

Figure 4. General Methodology Flow Chart

3.1 AIRPORT SITE SELECTION.

U.S. commercial and GA airports that would benefit from heated pavements during winter operations were identified.

According to the FAA, Commercial Service Airports are publicly owned airports that have at least 2500 passenger boardings each calendar year and receive scheduled passenger service [19]. Here, passenger boardings refer to all revenue passengers boarding on an aircraft in service in air commerce, whether or not in scheduled service. This also includes passengers who continue onto an international flight that stops at a U.S. airport for a nontraffic purpose, such as refueling or aircraft maintenance, which is not considered passenger activity.

GA airports are the largest single group of airports in the U.S. system. This category also includes privately owned, public airports that enplane 2500 or more passengers annually and receive scheduled airline service [19]. Figure 5 shows the various airports selected for the study.

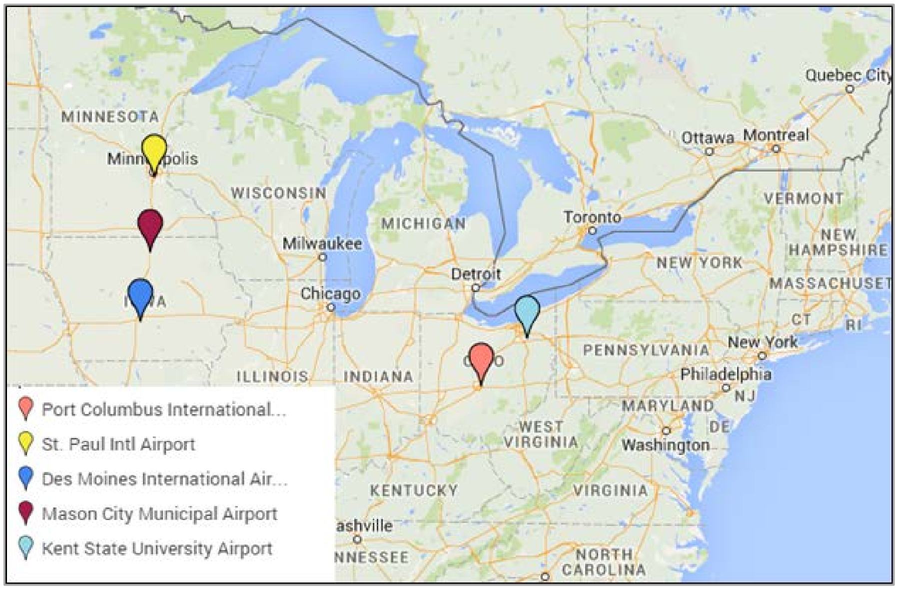

Figure 5. Map of Selected Airports for HHPS Study

The following criteria were used for airport selection:

- Airports with average annual snowfall greater than 35 inches per winter season.

- Snow- and ice-clearing operations that average at least 20 days per winter season.

- Airports with plans for installing new pavement due to airport expansion or rehabilitation within the next 10 years.

An extensive list of airports was made based on the aforementioned criteria. The snowfall history and number of enplanements for each airport was extracted and analyzed. The airport managers were contacted, and the most suitable airports for the study were finalized.

The three commercial airports selected for this study are:

- Minneapolis-St. Paul International Airport, Minneapolis, Minnesota (MSP)
- John Glen Columbus International Airport, Columbus, Ohio (CMH)
- Des Moines International Airport, Des Moines, Iowa (DSM)

The two GA airports selected for this study are:

- Kent State University Airport, Stow, Ohio (1G3)
- Mason City Municipal Airport, Mason City, Iowa (MCW)

3.2 DATA COLLECTION.

A detailed questionnaire (appendix A) was sent to all five commercial and GA airports in this study to gather information on various aspects such as operations and maintenance costs during snow removal, staffing levels, SRE purchasing costs, and the challenges faced during snow-removal operations. The summary of the responses can be found in appendix B. In July 2014, site visits were made to MSP and DSM to understand the operation of snow removal in depth, as shown in figure 6. There were some limitations in the data for CSRS operations because the operating costs and usage could not be separated to per-unit levels. Therefore, costs were assumed to be a function of the area considered. This assumption was further supported by discussions with the airport managers.

Figure 6. The MSP Site Visit

In this study, there were attempts to collect data directly from the airports on the number of delays and their root cause, but airports do not keep track of number and duration of delays. Therefore, such data are unavailable. Therefore, data collection for this study was a challenge, and most data were obtained from the Bureau of Transportation Statistics [20] or from interviews with the airport managers.

As shown in figure 7 [18], there can be many causes of scheduled air service delays, such as severe weather delays, air carrier delays, security delay, National Aviation System (NAS) delay, or the aircraft arriving late. Weather-related delays can be due to high winds, low visibility, and extreme snowfall. Figure 8 [21] depicts the on-time arrival performance and delay causes for all airports and all domestic carriers in U.S for 2015. A flight is considered to be delayed if it arrives 15 or more minutes later than its scheduled arrival time [18]. The focus of this study was delays due to snowfall.

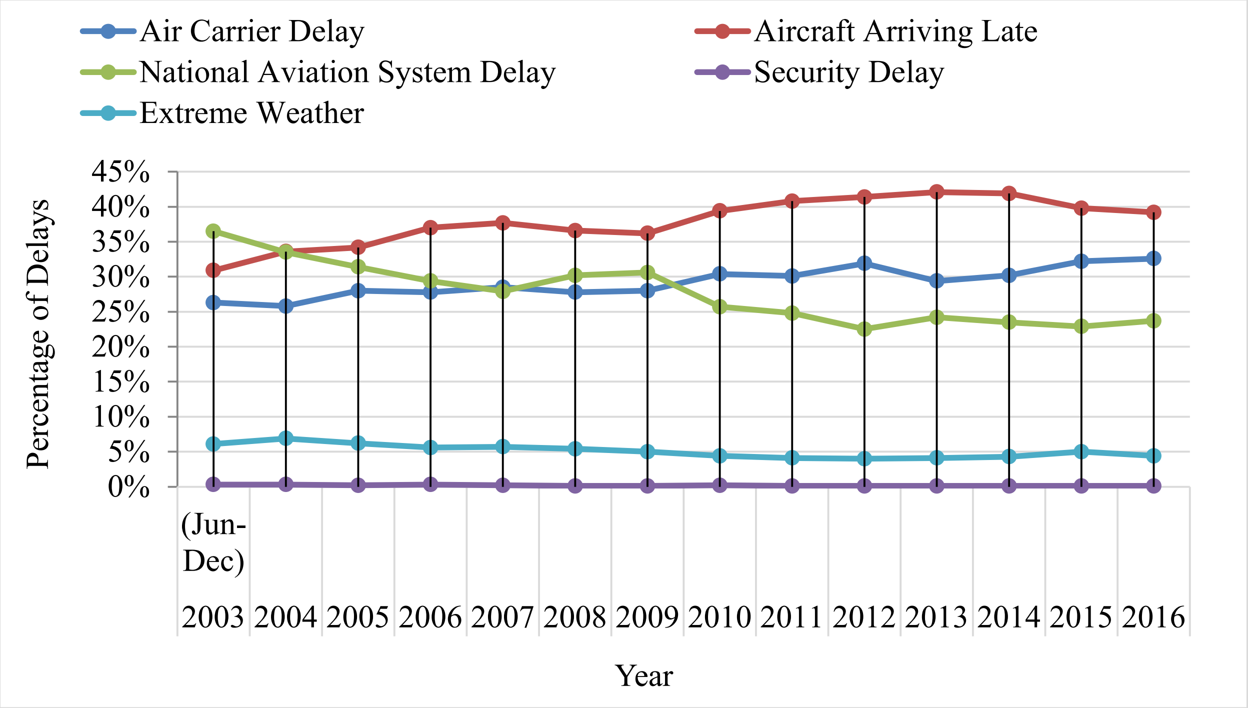

Figure 7. Factors Contributing to Aircraft Delays

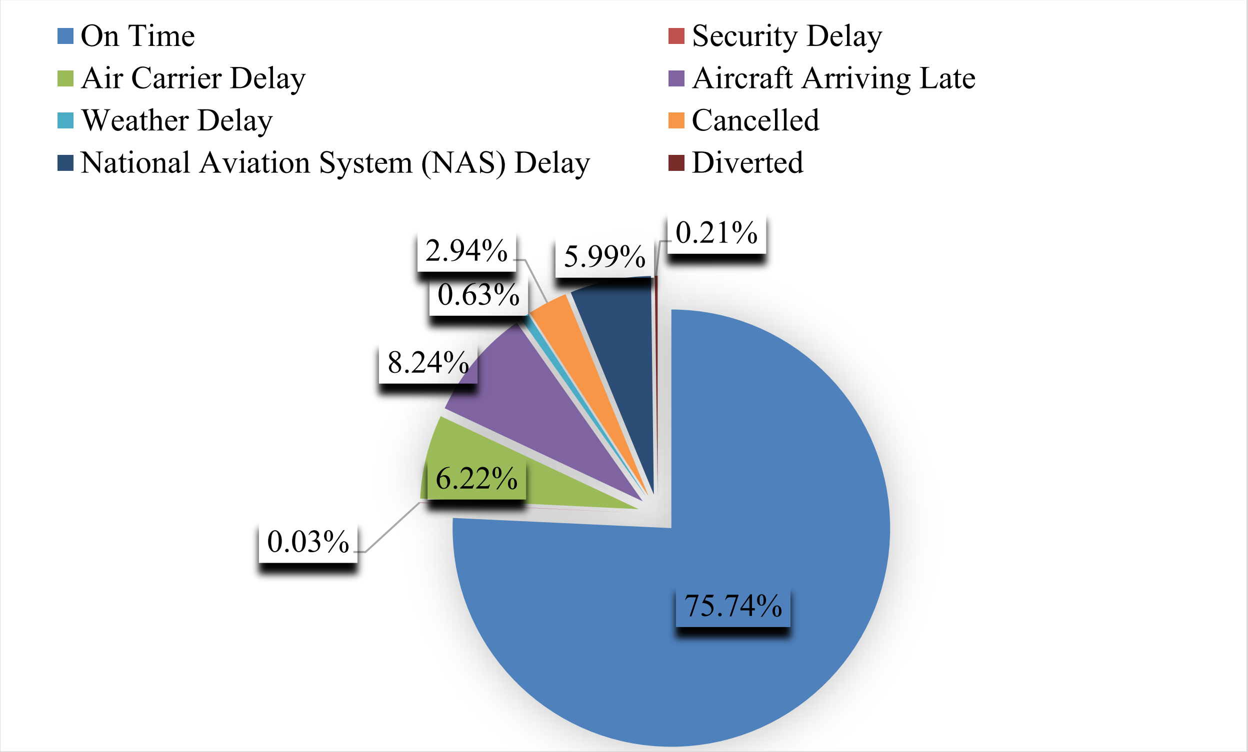

Figure 8. On-Time Arrival Performance and Delay Causes for All Airports and All Domestic Carriers in U.S. for 2015

Also, most of the delays during winter happen due to snow fall [22]. Weather-related delays were estimated to be approximately 3% of the total operations. Airports do not keep track of the number and causes of aircraft delays; also, the delay-related data reported from the airlines is not detailed. Since there are uncertainties attributed with this variable, sensitivity analysis was conducted.

3.3 ENERGY REQUIREMENTS FROM SELECTED AIRPORT SITES.

This step involved collecting data on energy and cost requirements for the identified airport sites. After selecting airports that could benefit from the installation of an HHPS, pavement areas to be considered for heating were identified. Using guidance provided by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) [16], the required amount of energy (W/ft^2) necessary to melt snow and leave a wet residue 90% of the time was calculated for the airport's geographic location.

3.3.1 General Equation to Calculate Heat Load.

According to Chapman [16 and 23], the general equation for the heat required to melting snow (q_o) in Btu/h ft^2 is:

$$q_o = q_s + q_m + A_r (q_e + q_h) \tag{1}$$

where:

q_s = sensible heat transferred to the snow (Btu/h·ft^2)
q_m = heat of fusion (Btu/h·ft^2)
A_r = snow-free area ratio must equal 1 for areas with aircraft operations
q_e = heat of evaporation (Btu/h·ft^2)
q_h = heat transfer by convection and radiation (Btu/h·ft^2)

The parameters in equation 1 take into account atmospheric factors including rate of snowfall, air temperature, relative humidity, and wind velocity. The detailed equations for each parameter are available in the FAA AC 150/5370-17 [8] and provided in appendix C. The ratio of the uncovered (or free) area A_f to the total area A_t is the free area ratio A_r. To maintain $A_r = 1$, the system must melt the snow so rapidly that accumulation is zero. This may not be practically possible in all situations. When determining the solution for general equation q_o, the snow-free area ratio A_r can be assumed as 1. This is a conservative measure used to get the maximum required heat load.

For hydronic heating systems, the fluid temperature can be calculated using equation 2 [16]:

$$t_m = 0.5q_o + t_f \tag{2}$$

where:

t_m = average fluid temperature (°F)
t_f = water film temperature (°F), accepted as 33°F

It is expected that the heated pavement will be operated from just before the winter season until after the last winter storm event. A series of precipitation-free days may mean that the system could be turned off, depending on how long it takes for the pavement to be reheated in advance of the next storm. Additionally, it is recommended to follow a fixed maintenance plan for the maximum life expectance, and to take measurements for efficient emergency repair.

3.3.2 Total Heat Output Requirement Estimations.

Depending on the energy source and equipment required to operate the system, an estimated cost for equipment maintenance was calculated. These values were based on the weather conditions of the airports under study. Average temperature, wind speed, and snowfall (in./h) at airports weather stations during winter seasons from 2009 to 2015 [24] were considered as the ambient temperature and wind speed in these calculations.

The energy source used was natural gas. Minneapolis receives on average 199 hours of snowfall per year [16]. Using this data, costs required to melt snow with natural gas were approximated. Total heat output requirement values for each snowfall case scenario were calculated using equation 1 (table 1). The recurring costs related to natural gas are summarized in the case study sections.

Table 1. Energy Requirement and Annual Snowfall Events in the Concerned Airports

Airport	No. of Annual Snowfall Events [16]	Energy Requirement (Btu/h/ft^2)
MSP	31.0	256
DSM	29.0	162
CMH	26.2	136
MCW	28.2	159
1G3	28.2	141

It is expected that the heated pavement will be operated for 24 hours for each snow event. Also, the average unit natural gas price in each state (where each airport is located) from 2011-2015 was considered as a unit natural gas price in this analysis [25]. Assumptions for energy analysis and estimated required energy for each case study were tabulated in table 2.

Table 2. Assumptions and Result of Energy Analysis

Category	MSP	DSM	CMH
No. of Annual Snowfall Events [16]	31	29	26.2
Ambient Temperature (°F) [23]	18	21.2	28
Wind Speed (mph)	10.45	15.8	7.4
Average Snowfall in One Hour (inch)	1.17	1.05	0.86
Gas Price (USD per Thousand Cubic Feet)	7.33	7.26	7.21
Energy Requirement (Btu/h/ft^2) [24]	157	133	104

3.4 DEVELOPMENT OF BCA FRAMEWORK.

To achieve the research objectives, it is necessary to develop a set of criteria to objectively evaluate HHPS benefits and costs. The goal is not necessarily to prove that heated pavements are cost effective, but rather to give a realistic assessment of the true cost and benefit that could be realized as well as the payback period. The basic BCA framework is outlined in figure 9.

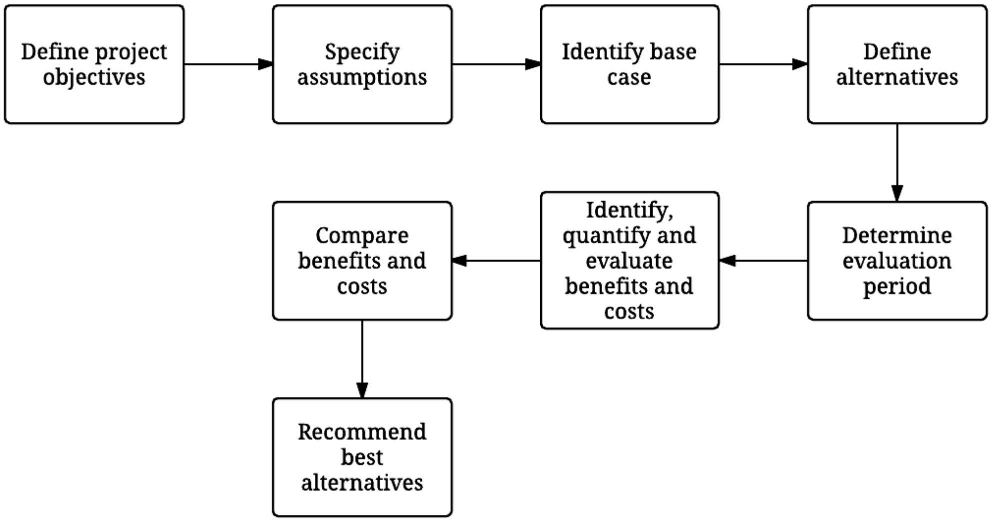

Figure 9. Basic BCA Framework

3.4.1 Define BCA Project Objectives.

The primary BCA project objective was to investigate the HHPS economic advantages, including factors such as operational savings by reducing staffing requirements to operate SRE and improved safety. The next objective was to appraise the initial installation costs of a heating system and ascertain how they may be absorbed over a period of time under operation. The last objective was to compare the potential net costs and benefits of installing an HHPS and examine differences in cost benefits between large, high-traffic airports and small, GA airports.

3.4.2 Identify BCA Base Case.

In general, the BCA base case is defined as the best course of action that would be pursued in the absence of a major alternative to obtain the specified objectives. The BCA base case represents the reference point against which the incremental benefits and costs of various possible investment alternatives are measured. In this study, the use of CSRS (i.e., SRE and deicing chemicals) is taken as the base case.

3.4.3 Identify BCA Alternatives.

This step involves identifying all reasonable alternatives to achieve the desired objective. The alternative in this study is use of hydronic heated pavements. The heating may be achieved by means of natural gas, electricity, or geothermal energy. In this study, natural gas has been taken as an example of the proposed methodology.

3.4.4 Determine Evaluation Period.

The analysis period for a BCA must be sufficiently long such that each alternative pavement strategy includes at least one future rehabilitation event. FAA pavement design practice requires the use of a 20-year design life period [7]. The year 2015 has been taken as year 0, and all monetary values correspond to the U.S. dollar (USD).

3.4.5 Identify, Quantify, and Evaluate Benefits and Costs.

A few relevant terms and concepts used to identify, quantify, and evaluate the benefits and costs involved are briefly outlined in sections 3.4.5.1 through 3.4.5.9.

3.4.5.1 Initial Costs.

A project's initial costs are those that are incurred during the design and construction process. Initial costs include: planning, preliminary engineering, project design, project-related staff training, final engineering, land acquisition, and construction (including improvements to existing facilities, equipment and vehicle purchases, equipment required for project operation, etc.). The initial costs considered here refer to the cost of installation of a HHPS and the purchasing cost of SRE.

3.4.5.2 Recurring Operations and Maintenance Costs.

Operations and Maintenance (O&M) costs are the recurring costs required to operate and maintain the proposed investment project. Expenses associated with O&M can occur annually or periodically. The recurring costs are annual costs that include maintenance, operation, and labor. Recurring O&M costs for CSRS include: fuel, labor, deicing agents, and SRE maintenance. However, HHPS incur no costs for labor or deicing chemicals. Recurring O&M costs associated with the HHPS include the natural gas required to heat pipes and system maintenance.

3.4.5.3 Discount Rate.

Discounting requires the division of an annual discount rate into future benefits and costs. The annual discount rate (also known as the marginal rate of return of capital) represents the prevailing level of capital productivity that can be achieved at any particular time by investing resources, i.e., the opportunity cost. The real discount rate relevant to all airport projects to be funded with Federal grant funds is 7% [7].

3.4.5.4 Opportunity Cost.

Opportunity cost is the value of the benefits foregone when resources are shifted from satisfying one objective to satisfying another. An all-inclusive measure, it represents what society as a whole—government and all private groups—must give up to obtain the desired objective. Theoretically, it is the correct measure of cost for use in economic analyses of projects funded with government funds. Opportunity costs in the event that HHPS are not installed were not considered as it would be complex to estimate the costs of competing projects for the same funding source. Also, opportunity costs could vary by airport.

3.4.5.5 Indirect Costs.

Indirect costs are costs that are not directly accountable to a cost object (such as a particular project, facility, function, or product). Indirect costs may be either fixed or variable. In this study, the indirect benefits of installing an HHPS are the enhanced safety of ground personnel, reduced passenger waiting times, and reduced fuel wastages. Other costs, such as the increased number of airport operations leading to higher revenues, are also indirect costs but have not been quantified in this study.

3.4.5.6 Incremental Cost.

A BCA refers to the differences between options (the base case and its alternatives). All cost elements that differ between these options are defined as incremental costs, which must be reflected in the comparison of options. Costs that are common to all options are not relevant to the investment decision and should be offset when calculating differences among options.

3.4.5.7 Sunk Cost.

Sunk costs are costs of resources that have already been consumed and cannot be recovered at the time the BCA is being conducted. As a consequence, they are not relevant for current decision making and should not be included in the BCA. Occasionally, projects can be implemented for very little additional or incremental cost because they make use of existing fixed assets. If these assets have no opportunity cost (i.e., no alternative uses), they are available without cost to the project under consideration.

3.4.5.8 Depreciation.

Frequently, large costs must be incurred in the beginning of a project in order to obtain benefits (or revenues) in later years. It is often useful to know by how much annual benefits (or revenues) exceed annual costs, or the net benefit (or income) of the project. For this value to be reasonable, it is necessary to allocate the large initial costs to later years when benefits occur.

3.4.5.9 Inflation.

All costs and benefits must be converted to USD in order to be compared. However, due to inflation, the amount of physical resources that may be purchased by a dollar will decrease over time. Consequently, it is necessary to cost all resources in the form of dollars of a given year, known as constant dollars, to facilitate year-to-year comparisons. For this study, the year 2015 was taken as the base year, and all monetary values are in terms of 2015 USD values.

3.5 ECONOMIC ANALYSIS TECHNIQUES.

Sections 3.5.1 and 3.5.2 present the methodology used in the economic analysis.

3.5.1 Net Present Value.

NPV is a method of calculating the return on investment (ROI) for a project. The sum of the PV of cash flows (both positive and negative) is calculated for each year associated with the investment. Then, that amount is discounted so it expresses value in terms of the base year's dollars. If NPV is greater or equal to zero, the project is acceptable [26]. Equation 3 can be used to calculate the NPV.

$$NPV = C_0 + \sum_{i=1}^{T} \frac{C_i}{(1+r)^i} \tag{3}$$

where:

C_0 = Initial investment
T = Time
C_i = cash flow
r = Discount rate

3.5.2 Benefit Cost Ratio.

Benefit cost ratio (BCR) is a widely used economic analysis technique for evaluating a project or investment. It is used to compare the benefits and costs, and to help policymakers identify the best option to pursue. Specifically, the BCR is a ratio of the net benefits to the net costs involved in a project. If the ratio of the sum of the PV of benefits of the project or policy to the costs exceeds one, there is a general economic argument supporting the action to make the investment or implement the policy in a project. The BCR formula is shown in equation 4.

$$BCR = \frac{Present\ value\ of\ benefits}{Present\ value\ of\ costs} \tag{4}$$

The methods used in BCR require an examination of all benefits resulting from the production and consumption of the output, regardless of who realizes the benefits [7]. The first step in estimating a BCR is to establish the base case conditions from which any proposed alternatives can be differentiated and analyzed. This is crucial, since BCR focuses on monetizing only those effects that differ significantly between the base case and alternative cases. In general, the base case represents the best course of action that would be pursued in the absence of a major alternative to obtain the specified objectives. As such, the base case represents the reference point against which the incremental benefits and costs of various possible investment alternatives will be measured. The base case should be modeled for the analysis period with as much information as possible about changing conditions that are expected to occur, regardless of the final decision regarding construction of an alternative system.

In this study, the use of CSRS (i.e., SRE and deicing chemicals) is taken as the base case.

To examine the net costs and benefits of HHPS and CSRS, incremental BCR was also calculated. Incremental BCR analysis is used to select the best alternative from a set of mutually exclusive alternatives. First, the differences in benefits and costs between an HHPS powered by natural gas (alternative) and CSRS (base case) are calculated. Then, the ratio of the equivalent worth of incremental benefits to that of incremental costs is calculated using equation 5 [26].

$$Incremental\ BCR = \frac{Present\ Value\ of\ benefits(Alternative\ 1 - Alternative\ 2\ or\ base\ case)}{Present\ value\ of\ costs\ (Alternative\ 1 - Alternative\ 2\ or\ base\ case)} \qquad (5)$$

3.6 ESTIMATION OF COSTS AND BENEFITS.

This section compares the relative costs and benefits related to the removal of snow and ice using CSRS and HHPS. Once the costs and benefits were identified, they were quantified in monetary terms. The effect of lost time and reduced efficiency in preparing an aircraft for arrival and departure during snowy conditions were studied and estimated in terms of monetary values. This preparation included passenger movement, aircraft refueling, luggage allocation, change of crew, cleaning the aircraft, navigating and hauling the aircraft, and most importantly clearing the areas of snow. The potential cost and benefits studied in the analysis are listed in table 3.

Table 3. Potential Costs and Benefits of CSRS and HHPS Strategies

Cost/Benefit Category	CSRS	HHPS
Initial Cost	SRE purchase	HHPS installation
Operation Cost	Labor, fuel, and deicing agents	Energy source (geo-thermal energy, fuel, natural gas, etc.)
Maintenance Cost	System maintenance	System maintenance
Benefit	-	Minimized aircraft and passenger delay costs Enhanced crew safety and better working conditions

3.6.1 Estimation of Costs for CSRS.

Machinery, deicing agents, and labor are the units required for deicing pavements. Airport apron areas were selected for this analysis, and the cost of equipment required to deice this area was estimated. After meeting with each airport's manager, the various types of SRE and the associated purchase costs were identified (see table 4). Purchase cost of snow-removal equipment would serve as the initial cost in 2015 (year 0) for the CSRS. A fraction of these costs corresponds to the apron areas. In this study, it is assumed that initial cost can be approximated by using a ratio between the apron areas and the total paved area. Figure 10 shows the various cost factors considered in the cost estimation of CSRS, which can be calculated using equations 6 and 7.

Table 4. Purchasing Cost of SRE Identified From Airport Site Visits and Questionnaire

Item	Unit Price 2015 values (USD)
Displacement Plows	485,000
Rotary Brooms	650,000
Blowers	875,000
Loaders	250,000
Sprayer Truck and Spreader	34,560
Deicer Truck	44,000
Multifunctional Vehicle	910,000

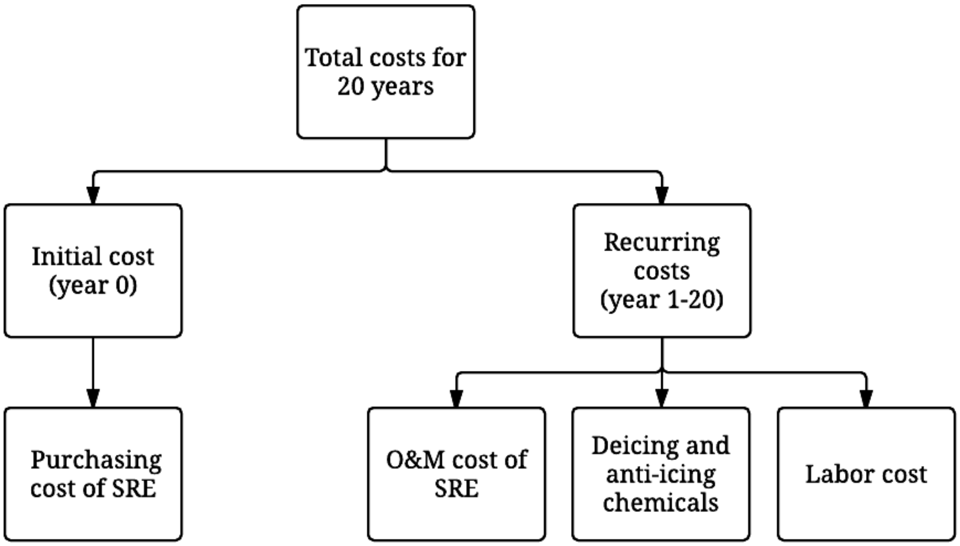

Figure 10. The CSRS Cost Factors

The initial capital cost can be estimated using equation 6:

$$\text{Capital cost} = \text{Purchasing cost of entire SRE fleet} \times (\text{Area of pavement under consideration}/\text{Total pavement area}) \qquad (6)$$

The recurring costs associated with snow removal using CSRS consist of the fuel, labor, deicing agents, and equipment maintenance. The type, amount, and costs of the deicing agents were obtained using surveys and questionnaire conducted at the airports under study. Follow-up discussions with the airport managers through site visits and questionnaire revealed that the use of deicing and anti-icing agents are limited whenever possible as they are expensive, and airport staff only rely on SRE to clear snow.

The labor costs involved in snow-removal operations at commercial airports may range from 65 USD/h to 80 USD/h. The higher values indicate work during late nights or overtime. For simplicity, a value of 75 USD/h per person was adopted for calculations. Values were provided by the airport managers through site visits, surveys, and questionnaires. The duties of the responsible personnel are limited to operating machines to clear snow and dumping it in designated areas. The number of personnel and the amount of deicing agents and fuel required for the operation of equipment increases as the storm intensity increases. Average annual values were taken for different snowfall intensities and calculated using equation 7. A fraction of these costs corresponds to the apron areas. In this study, it is assumed that recurring cost can be approximated by using a ratio between the apron areas and the total paved area.

$$\text{Annual recurring cost} = \text{Total cost of (labor + fuel + deicing agents + O\&M costs of SRE)} \times \text{(Area of pavement under consideration/Total pavement area)} \quad (7)$$

3.6.2 Estimation of Costs for Hydronic HHPS.

The total cost of HHPS can be divided into initial construction costs and O&M costs, as shown in figure 11. The initial cost of the HHPS consists of installing the hydronic pipes in or below the pavement along with the heating system facility including control systems. It is not advisable to use asphalt in HHPS, as the high temperature of asphalt during the laying process may damage the PEX pipes. As the installation costs of HHPS would play a crucial role in estimating their economic usefulness, it was decided to analyze various cost scenarios. These scenarios include the entire installation and startup costs.

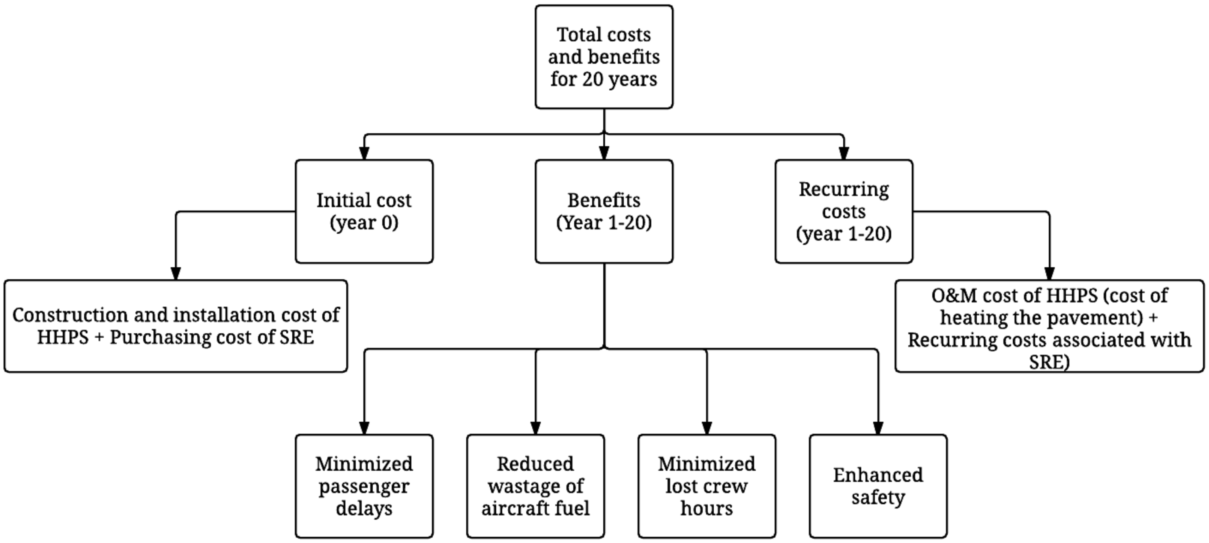

Figure 11. The HHPS Cost Factors

It was assumed that the HHPS would be operated by means of automated valves and switching equipment and hence, would not involve labor cost. It is expected that the HHPS will be sufficient to clear the snow, and thus assumed that deicing agents or SRE would not be required for the apron areas.

Operation costs consist of the cost of natural gas needed to heat antifreeze circulating in the pipes and electricity needed to power the control system. To quantify the amount of natural gas needed, the energy required to melt snow or the design heat load was first calculated. The HHPS design should be able to meet both design load requirements and heating needs of the system [8]. The required system performance includes maintaining a surface condition of not covered with ice or snow ("no worse than wet") by maintaining a surface temperature above freezing [8]. The required heat design load can be determined by considering the expected rate of snowfall, air temperature, humidity, wind speed, dimensions, and material characteristics of the pavement. These design requirements impact the cost of an HHPS.

3.6.3 Estimation of Benefits for Hydronic HHPS.

This analysis was conducted to compare the benefits of a HHPS to those of the base case scenario (CSRS). After the HHPS installation, the anticipated benefits are fewer passenger delays, minimized aircraft fuel wastage, loss of crew working hours, and enhanced safety.

3.6.3.1 Value of Lost Passenger Time.

When defining delays, the FAA Air Traffic Organization considers flights delayed 15 minutes or more as delays. The Bureau of Transportation Statistics (BTS) provides publically accessible data on several aviation operation components including delay and delay causes for each airport on a monthly basis. Another important factor is the value of time (VOT) of the passengers that suffer a delay. Specifically, passenger delay costs herein consist of the opportunity costs of time lost due to weather-related delays at airports. These represent indirect costs as, in general, aircraft operators do not offer any form of compensation, such as discounts on meals or hotels, due to weather-related delays [18].

Passenger costs associated with flight delays were based on air traffic demand. Specifically, the total aircraft seats available and an approximation of the load factor were used to estimate the demand. Load factor is a measure of the use of aircraft capacity that compares revenue passenger miles (RPMs) as a proportion of available seat miles (ASMs) [18]. The average total load factor for U.S. domestic flights for 2015 was 84.59 % [27]. In addition, the air traffic does not remain constant but is expected to increase approximately every year. Thus, the average traffic growth forecast of 2.8% for the next 20 years was considered based on the FAA recommendation [19].

The time that passengers spend waiting due to CSRS operations needs to be accounted for in monetary terms. The elimination or reduction of this cost will constitute a benefit for the HHPS. According to a report generated by the National Center of Excellence for Aviation Operations Research (NEXTOR), passenger travel is highly disrupted by weather delays; an annual cost of 16.7 billion USD (2010 value) was estimated to account for passenger delay out of a total cost of 31.2 billion USD to the U.S. economy [28].

To estimate this cost, passengers were grouped into two categories, those traveling for business and those for personal purpose or leisure [29]. Different values are available for passengers depending on trip purpose, as shown in table 5. Based on the load factor and type of aircraft considered, an average load of 74.5 passengers traveling for leisure and 50.5 passengers traveling for business was calculated [30]. Based on the data obtained from BTS weather-related delays during winter months were assumed to be 45 minutes, 39 minutes, 57 minutes for DSM, CMH, and MSP respectively [27]. Also, sensitivity analysis was conducted to reflect effect of delays duration on the BCR. Passenger delay costs can be calculated using equations 8 and 9.

Total delay hours in a season = No. of daily operations ×30 (days) × 4 (months) × 2% of snow-related delays × Passenger growth rate × Average duration of one delay (hours) (8)

Annual monetary value of lost passenger time = (Total no. of seats in an aircraft × Load factor × Total delay hours in a season) × [(Percentage of passengers traveling for leisure × VOT for leisure) + (Percentage of passengers traveling for business × VOT for business) (9)

Table 5. Opportunity Cost of Time for Passengers on a Delayed Flight [27]

VOT	Cost (USD/h, 2015)	Percentage Distribution (%) [28]	Number of Passengers in Flight
Personal	36.1	59.6	74.5
Business	63.2	40.4	50.5

3.6.3.2 Fuel and Crew Costs.

The number of delayed flights was calculated in the same way as for the lost passenger time. Aircrafts can incur delays in three possible ways: mid-air, gate, and ground delays. The mid-air delays will result in the most amount of fuel wastage, while the others will be related to only idling fuel wastages. According to the Airport Cooperative Research Program (ACRP) report 123 [29], mid-air delays are assigned a value of 4,960 USD/h, ground delays as 2,148 USD/h, and gate delays as 1,442 USD/h. Each category of delay would contribute in different percentages to the total delays and hence, incur different costs. Due to such information is not available; it was assumed that all the delays would occur in an equal proportion as seen in equation 10. This gave an average value of 2,850 USD/h suffered by airlines in weather delays. The annual (four concerned months) cost to airlines due to weather-related delays can then be computed by multiplying this value by the total number of operations in four months. This value comes out to be 8,208,576 USD for the year 2016. Annual growth rate of operations is also accounted for in this case for subsequent years.

Annual additional aircraft operating cost due to delays=
Total delay hours in a season × Operating cost of aircrafts (mid, ground, and gate delays) (10)

3.6.3.3 Enhanced Safety.

Aprons incur tremendous activity in the form of baggage handlers and oil refueling operations. Working conditions in the winter are dangerous, and there are possibilities that workers can slip and fall during loading and unloading operations. These workers are employed either by the airport or the airlines depending on airports or airlines policies. Potential accidents can cause additional monetary burdens to the airport or airlines. With the use of an HHPS, the working conditions may improve, and the risks of injury may reduce considerably.

The benefit of preventing a fatality is measured by the value of statistical life (VSL) and defined as the additional costs that the individuals are willing to bear for improvements in safety. According to the U.S. Department of Transportation (DOT), the VSL is set as 9.6 million USD (2015 value) [30]. Relative disutility factors by injury severity levels (AIS) are shown in table 6. BLS maintains a database of occupational incidence rates for workplace injuries, with rate involving ice, sleet, and/or snow of occupations related to support activities for air transportation reported as 3.8 injuries per 10,000 full-time employees [31]. The airport or the airlines that assumes financial responsible for any injuries may employ the ground staff. These costs can be calculated using equation 11.

Table 6. Relative Disutility Factors by AIS [30]

AIS Level	Severity	Fraction of VSL
AIS 1	Minor	0.003
AIS 2	Moderate	0.047
AIS 3	Serious	0.105
AIS 4	Severe	0.266
AIS 5	Critical	0.593
AIS 6	Unsurvivable	1.000

$$\textit{Annual cost due to injuries} = \textit{Percentage of a type of injury (minor, moderate, serious)} \times \textit{VSL} \times \textit{Fraction of VSL for injury type} \times \textit{Incidence rate} \times \textit{No. of full-time employees} \tag{11}$$

3.6.4 Sensitivity Analysis.

The outcome of a BCA depends on numerous estimates, forecasts, assumptions, and approximations. Each of these factors has the potential to introduce error into the results. The importance of such errors in affecting the outcome of the BCA must be known to the decision maker if informed decisions are to be made and confidence placed in such decisions. Moreover, the degree of uncertainty associated with each alternative is itself a factor to be considered when selecting between competing alternatives.

To eliminate such concerns, a sensitivity analysis was conducted. Specifically, the sensitivity analysis was used to determine how different values of certain variables impact the BCR under a given set of assumptions, which helps to predict the outcome of a decision under different scenarios. Sensitivity analysis can be a valuable tool for evaluating the impacts of uncertainty on proposed investment projects. The basic approach is to vary key assumptions, estimates, and forecasts systematically over appropriate ranges and observe the impact on the results. For certain items, the impact may be insignificant while for others it may be quite large. In some cases, the relative desirability of competing alternatives might be altered while in others might not [32].

Monte Carlo simulation (MCS) was employed and used in the sensitivity analysis to better understand and quantify the cost uncertainties within the theoretical estimate [32]. The MCS allows to quantify the range of possible BCR values and perform a sensitivity analysis to identify how each of the input variables affects the overall BCR model. Any input variables with enough including uncertainty and able to have significantly impacts on the BCR model were plugged in to sensitivity analysis model. BCR were considered treated as random variables within the MCR. Note that "In a stochastic model, a range of possible values for each variable is used and each value range has an associated probability density function." [32]

The results of this analysis can be used to identify components to which the BCR is sensitive. This can lead to additional effort on toward improving the reliability of the estimates for those components. In addition, in situations where reliability cannot be improved, it puts the decision maker on notice with regard to potential BCA weaknesses.

Sections 4 through 7 present case studies performed at the various commercial and GA airports to illustrate the methodology described in this section.

4. CASE STUDY OF COMMERCIAL AIRPORT—MSP.

4.1 DESCRIPTION OF MSP AIRPORT.

MSP is a commercial airport surrounded by Minneapolis, St. Paul, and several suburbs. MSP, which is a large hub (1% of total U.S. enplanements) [19], was selected as one of the case studies. With an annual snowfall of at least 35 inches and icy conditions prevailing for most of the winter, MSP is a good candidate for HHPS. MSP has one airfield with four runways and two terminal buildings (see figure 12(a)). There are 125 gates at the airport, and it was the 17th busiest airport in 2016 based on air traffic volume [33].

The average annual snowfall hours in MSP is 199 [16]. The gate areas are congested, and there is not enough space to maneuver large SRE or to pile snow as shown in figure 12(b). Most injuries (slip and fall) to ground handling staff occur in this area, and HHPS may offer a solution for this situation. Thus, the energy and economic analyses presented throughout the remainder of section 4 focus on apron areas totaling 5 million ft^2.

Source: Google Maps™, 2016

(a)

(b)

Figure 12. The MSP (a) Lindbergh Terminal and (b) Snow Plow and Broom Equipment

MSP has approximately 100 pieces of SRE and more than 110 snow-removal personnel including on-call workers. As MSP receives a large amount of snow every winter, there are designated accommodation for the workers because they are frequently required to stay at the airport. Some general facts about MSP operations gathered from the site visit, surveys, and questionnaire are summarized in table 7.

Table 7. General Facts About MSP

Item	Description	Value
Runways	Open during general operations	4
	Open during winter operations	2 or 3
Time Taken to Clear Snow	Primary taxiway and apron area	10-35 minutes
SRE and Personnel	Number of SRE	More than 100
	Annual maintenance cost of SRE	600,000 USD
	Personal required to aid in snow removal	110
	Labor rate	75 USD/h
	Average life of SRE	Approximately 20 years
Anti-Icing and Deicing	Types of anti-icer and deicers	Potassium acetate and sodium acetate
Average Pavement Heat Output to Melt Snow From Considered Area	5 million ft^2	1.7 billion Btu/h

4.2 BENEFIT AND COST CALCULATIONS—MSP.

The benefit and cost calculations for MSP as the representative of commercial airports are shown in appendix D. Similar calculation procedures can be applied to other commercial airports (i.e., CMH and DSM).

4.2.1 The CSRS—MSP.

Total costs are divided into two categories: initial and recurring. An initial cost is a one-time expense, which includes the cost for purchasing the entire fleet of SRE. The analysis period was 20 years, and it was assumed that the airport will not have any more SRE purchases during this timeframe. The number of SRE and their costs were obtained directly from the airport manager. The SRE costs were assumed to be a function of the pavement area. In MSP, the entire pavement area is 28 million ft^2, and the apron area is 5 million ft^2. The costs were taken only for the apron area. These costs were calculated by a ratio of the apron area to the total pavement area using equation 6. Recurring costs are annual costs, which include maintenance, operation, and labor and can be calculated using equation 7. The recurring costs were obtained from the airport managers and were also a function of the area. The NPV of the costs involved in the CSRS was calculated to be 23,221,754 USD.

4.2.2 The HHPS Capital Cost Calculations—MSP.

The installation cost of HHPS is a critical factor in this assessment, yet there is not a suggested value available as these systems have not been widely installed to date. As such, it was decided to assume 35 USD/ft^2 (2015 value) as the base value [17] and analyze various cost scenarios ranging from 25 USD/ft^2 to 65 USD/ft^2. Note that this average value refers to the entire installation and startup costs. Because of the uncertainty involved in installation cost and to capture the variations of installation cost due to different concrete thickness and heating system, this item is considered as one of the input variables for sensitivity analysis.

4.2.3 The HHPS Annual Cost Calculations—MSP.

Annual or recurring costs are comprised of the O&M costs to run the HHPS. Operation costs consist of the cost of natural gas needed to heat antifreeze circulating in the pipes and electricity needed to power the control system. The amount of natural gas required was calculated based on the annual heat energy required to melt snow or the design heat load of the system. The heat load was calculated using equation 1. The cost for natural gas was calculated to be 5,302,329 USD for a winter season. Maintenance cost was taken as 1% of the capital cost based on surveys and questionnaires from contractors, and the total O&M costs in 2015 were calculated to be approximately 7.05 million USD. The use of HHPS can increase the pavement durability because freezing-induced damage and cracks caused by deicing chemicals will be eliminated. On the other hand, the maintenance cost of the HHPS can be costly. Therefore, different scenarios were developed in this study to estimate the cost of maintenance. The scenarios were developed for the situations in which the cost of maintenance was 0.5% (lower than 1%) and 1.5% (higher than 1%). Additionally, this item is considered as one of the input variables for sensitivity analysis.

4.2.4 The HHPS Annual Benefit Calculations—MSP.

As discussed in section 3.6.3, the potential benefits of installing the considered HHPS are: reduced lost passenger time, airline staff time cost savings, reduced fuel wastage, and ground staff safety. In this analysis, benefits related to reduce cargo delays were also considered. In MSP, UPS® and FedEx® are the two major cargo airlines, which operate a total of 16 aircrafts every night. The cargo planes fly to MSP three times a week, and pilots adjust their operations according to the expected snowfall forecast and patterns. Cargo airlines operate under much worse weather conditions than commercial airlines. Discussions with airport managers and available data [33] revealed that the effect of snowstorms on cargo operations is not as significant as on passenger operations. Therefore, cargo operations may not involve loss of revenue and resources as their operations are usually adjusted according to the weather forecast. Thus, cargo-related benefits have been ignored in this analysis.

4.2.4.1 Value of Lost Passenger Time—MSP.

The reduced lost passenger time is calculated by first determining the seasonal percentage of delays. As discussed in section 3, a value of 3% of total number of operations is adopted as the percentage of weather-related delays. The costs can be estimated using equations 8 and 9. Four months (November-February) are considered peak winter months, and delays were calculated for this time period. Monthly operations were calculated by multiplying the daily number of operations by 30. Then, this value was multiplied by 4 to get the number of operations in 4 months. For example, in 2016, the total operations over the 4 months considered were 144,000. Two percent of this (i.e., 2,880) were assumed to be the number of delays caused by snow during the 4 winter months for the year 2015. Each of these delay events were assumed to last 57 minutes.

As per table 5, the values assigned to business passengers are 63.2 USD/h and leisure passengers are 36.1 USD/h. It was assumed that 40.40% of the total passengers fly for business purposes, and 59.60% are leisure travelers. The total number of seats in a mid-sized aircraft is about 150. The average overall load factor for U.S. domestic flights in 2016 was 84.59%. This translates to 84.59% of 150 seats being occupied, which gives a value of 125.07 seats. The value of lost time can be calculated by multiplying the total number of passengers (each case) by the VOT and the number of delays in 4 months. The combined value of lost time for the two categories of travelers was found to be approximately 25.78 million USD for 2016. As the number of passengers is expected to grow every year, a value of 2.8% annual passenger growth rate [7] is considered in the VOT calculation for subsequent years; and thus, the total value of lost passenger time increases over time.

4.2.4.2 Value of Airline Crew Time and Airplane Fuel Consumption—MSP.

The number of delayed flights is calculated the same way as lost passenger time. Aircrafts can incur delays in three possible ways: mid-air, gate, and ground. Mid-air delays will result in the highest amount of fuel wastage, and gate and ground delays will be related to only idling fuel wastages. According to the ACRP report 123 [29], mid-air delays are assigned a value of 4456 USD/h, ground delays as 2148 USD/h and gate delays as 1442 USD/h. It is undeniable that each delay category would contribute in different percentages to the total delays and hence, incur different costs. However, for ease in computations, it was assumed that all delays would occur in an equal proportion, as shown in equation 11. This gave an average value of 2850 USD/h suffered by airlines in weather delays. The annual (four concerned months) cost to airlines due to weather-related delays can be computed by multiplying this value by the total number of operations in 4 months. This value is 11,599,200 USD for the year 2015. Annual growth rate of operations is also accounted for in this case for subsequent years.

4.2.4.3 Enhanced Safety of Ground Staff—MSP.

It was established in section 1 that the apron has tremendous human and mechanical activity. It is imperative to ensure safety of the ground staff in harsh winter conditions as there are chances of slip-and-fall injuries due to icy pavement conditions. Data for categorizing injuries for this level of detail is not available at the BLS. The available data as per the BLS report [30] on occupational injuries were analyzed, and certain assumptions were established to quantify cost due to injuries. The ground staff may be employed by the airport or the airlines, which will be financially responsible for any injuries. The categories of injuries and their ratio to VSL are shown in table 6.

As per discussions with airport managers, it was assumed that slips and falls do not result in critical and fatal injuries. Consequently, in this analysis only three classes of injuries were considered: minor, moderate, and serious. Bruises and strains were classified as minor, fractures as moderate, and multiple traumatic injuries as serious. Minor injuries occurring most frequently were assumed to constitute 60% of total injuries. Moderate were assumed as 25% and serious as 15%. Also this item is considered as one of the input variables for sensitivity analysis.

Incident rates are an indication measure that captures the number and severity of injuries. The information for incident rates was not accessible by the airport authority as such information is generally confidential. The BLS maintains occupational incident rates for workplace injuries. Incident rates are an indication measure that captures how many incidents of injuries have occurred, and how severe they were. The information for incidence rates was not accessible by the airport authority as such information is generally confidential. The BLS maintains occupational incidence rates for workplace injuries. The incident rate reported for snow removal for air transportation is 3.8 per 10,000 full-time employees in year 2015 [31]. In MSP, there are approximately 19,206 full-time workers [33]. Thus, the estimated number of incidents was 9,603 per year. Based on the above data, the injury cost was calculated by multiplying the percentage of each injury by its contributing fraction of the VSL, as shown in equation 12. The summed value of all injury cases for MSP for the concerned four months was calculated as 2,052,860 USD per year.

4.2.5 Benefit and Cost Comparison—MSP.

4.2.5.1 The NPV—MSP.

NPV is the sum of the PVs of incoming and outgoing cash flows over a period of time. All costs (cash outflow) and benefits (cash inflow) as calculated in section 3.5.1are discounted 7% over a 20-year analysis period and then summed to get the NPV of the cost, as shown in table 8.

Table 8. The NPV of Cost and Benefits for HHPS Over a 20-Year Analysis Period and Discounted at 7% at MSP

Cost Category	Annual Value (USD)	PV of HHPS Costs (USD)
Capital Cost	175,000,000	249,712,480
Annual Recurring Cost	7,052,330	
Benefit Category	**Annual Value (USD) in Year 1 (2016)**	**PV of HHPS Benefits (USD)**
Value of Lost Passenger Time	25,789,261	512,303,874
Airline Crew Time and Fuel Wastage	11,599,200	
Safety of Ground Staff	2,052,860	

The PV of benefits is 512,303,874 USD (cash inflow is positive) and of cost is 249,712,480 USD (cash outflow is negative). The NPV is the sum of the cash inflow and outflow; thus, the NPV is calculated as 262,591,754 USD (positive). A positive NPV value indicates that the project is economically feasible.

Figure 13 represents the cash flow of the likely benefits and costs related to the HHPS. The benefits are due to reduction in lost passenger time, lost crew hours, and aviation fuel wastage. The costs include the installation and O&M. The benefits of the HHPS far exceed their cost of installation and O&M. The difference minimizes as the years progress as a result of discounting. Figure 13 shows a distinction between the cost of CSRS and the net cost/benefits of HHPS. The results indicate that the cost of clearing snow using CSRS is consistently and significantly higher than HHPS. This may be an argument against the installation of such pavements. However, the use of CSRS does not entail significant benefits, and without the HHPS, the snow will continue to disrupt smooth airline operations.

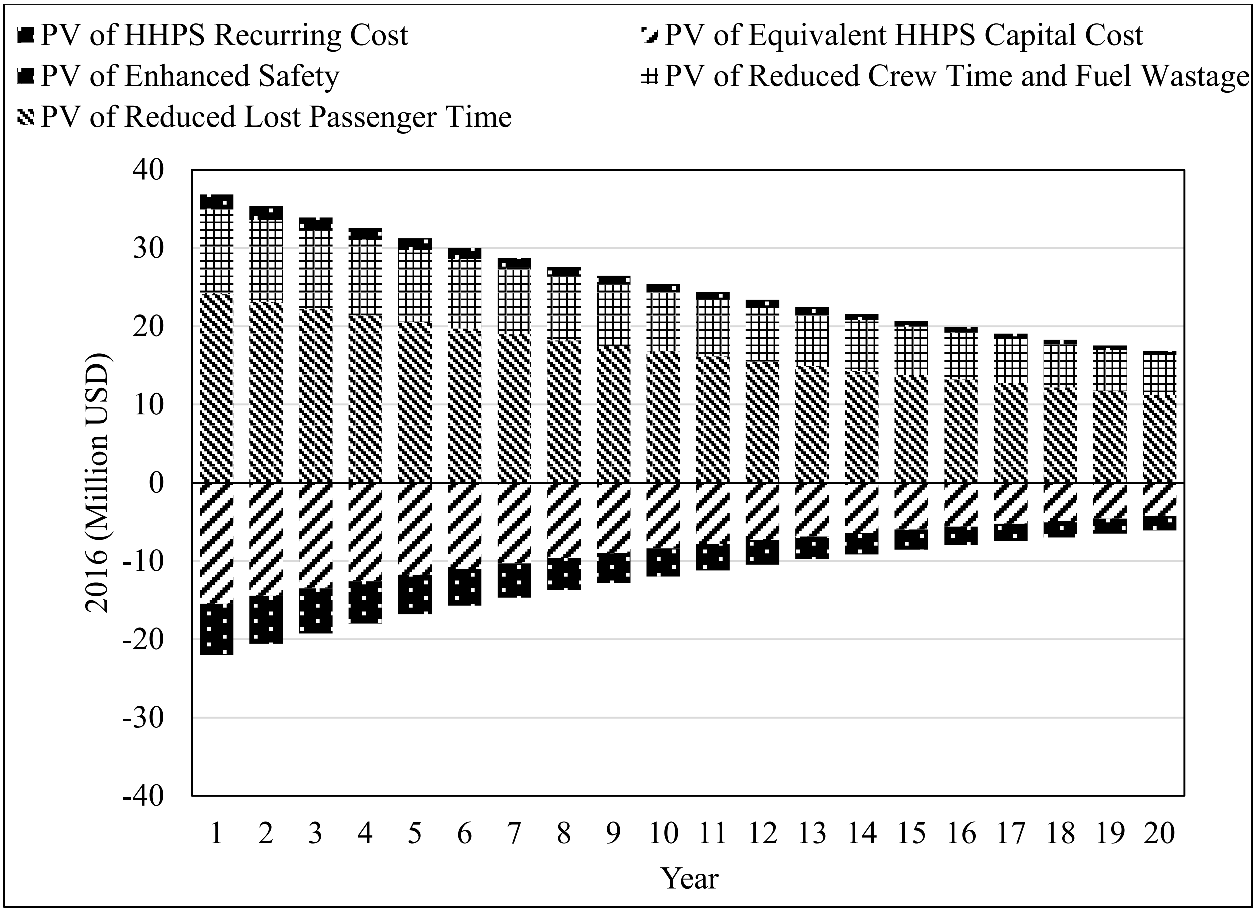

Figure 13. Cash Flow for HHPS Showing the Distributions of Costs and Benefits at MSP

<u>4.2.5.2 The BCR—MSP</u>.

After the NPV is calculated, the BCR is calculated by dividing the net benefits by cost for 20 years. The BCR was found to be 2.05. Section 3.6.4 describes a sensitivity analysis that presents changes in the BCR based on a set of different conditions.

4.2.5.3 Sensitivity Analysis—MSP.

MCS was employed in the sensitivity analysis described in section 3.6.4 to better understand and quantify the cost uncertainties within the theoretical estimate. The variables and each variable range used in MCS on sensitivity analysis of MSP case are shown in table 9.

Table 9. Variables and Each Variable Range Used in MCS for MSP

Input Variable	Range
Hydronic Heated Pavement Construction Cost (USD/ft^2)	(25-65)*
Percentage of Weather-Related Delays (%)	(2.5-3.5)
Portion of Initial Construction Cost Dedicated to Maintenance (%)	(0.5-1.5)
Cost Due to Injuries	{minor, moderate, serious}** possibility of the occurrence respectively {60%,25%, and 15%}
Duration of Each Delay (Minutes)	MSP
	(47-67)
Ambient Temperature (°F)	(17-19)
Snowfall in One Hour (in.)	(1.14-1.20)

*() represents uniform distribution
**{} represents discreet distribution

The initial construction cost is a key factor in influencing the BCRs. It is anticipated that the BCR would be expected to decrease as the initial cost of construction increases. Delays are naturally unpredictable because they depend on various other factors such as weather, preparedness of airports, and airline procedures. Delays may change drastically every year, and hence, a sensitivity analysis is warranted to determine their influence on the BCR.

Some input variables were common in all three cases studies (i.e., MSP, CMH, and DSM). However, some factors (such as duration of each delay, ambient temperature, and amount of snowfall in one hour) are different in each case. Therefore, for the mentioned items, such situations different values were used to run the MCS. Also, since historical records were obtained for these variables, standard deviations were calculated to measure the amount of variation in the data set.

To determine the impacts of the input variables to the BCR, sensitivity analysis was performed on all the random variables to understand determine how the uncertain behavior of each variable would affect the total BCR. Figure 14 illustrates the results of the sensitivity analysis for MSP. The sensitivity analysis results illustrate that, among all the random variables, the installation cost has the greatest potential impact on the overall BCR among the random variables.

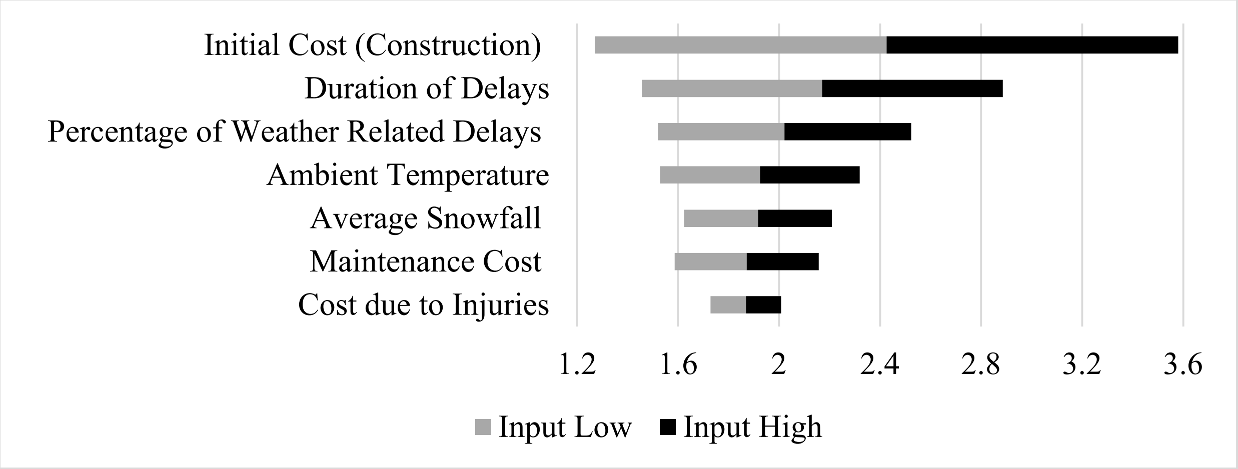

Figure 14. Sensitivity Analysis Results for MSP

Another objective of running sensitivity analysis is to provide a basis of decision making about choice of solutions and actions. To reach this objective, BCR is estimated at different reliability levels under MCS. Table 10 shows the BCR for MSP with different reliability percentages. The estimate range with a two-tailed 90% confidence interval is 1.16 to 2.43 with a median value of 1.61 and a standard deviation value of 0.40. Note that "The median is a good measure because, irrespective of the shape of the distribution, half the population is below the median and half is above the median." [32]

Table 10. The BCR With Different Reliability Percentages for MSP

Reliability Percentage	95%	85%	75%	65%	55%	Median	45%	35%	25%	15%	5%
MSP	1.16	1.22	1.35	1.45	1.54	1.61	1.67	1.80	1.96	2.15	2.43

4.2.5.4 Overall Cost of Snow Removal for MSP.

This section explores the overall costs and benefits of snow-removal operations in an airport, as incurred by installing an HHPS in the aprons, in order to put the effects of such an investment into perspective. It is assumed that an HHPS is used at aprons and CSRS are used at the remaining areas to clear snow. The total costs for this method of clearing snow is the sum of the following: HHPS installation, O&M of HHPS, purchase of SRE, O&M of SRE, labor, and deicing agents. Detailed cost calculation procedures for apron only for MSP case study is provided in appendix D.

Strategic placement of HHPS will reduce the installation costs but will not sacrifice on the benefits. The apron area at MSP is 5 million ft^2, and it is possible that only a part of it requires heating. The results of the comparisons between different cases of apron areas with HHPS are presented in figure 15.

Specifically, figure 15 shows the net benefits and costs over a 20-year period for clearing snow from an airport that has HHPS at aprons. Although aprons are a significantly small area of the airport, the total cost over the 20-year period of study of clearing snow from them that involves the installation and operation of an HHPS is higher than clearing snow from the remaining areas using CSRS. However, HHPS have several benefits that offset these high costs. Figure 15 illustrates that even when the entire apron is heated, the overall BCR is above 1. When the area to be heated is only 1 million ft^2, the BCR is slightly above 2, depicting a strong investment and a more realistic scenario. According to these results, HHPS are a financially viable option to heat aprons when used with CSRS to reduce winter weather-related delays.

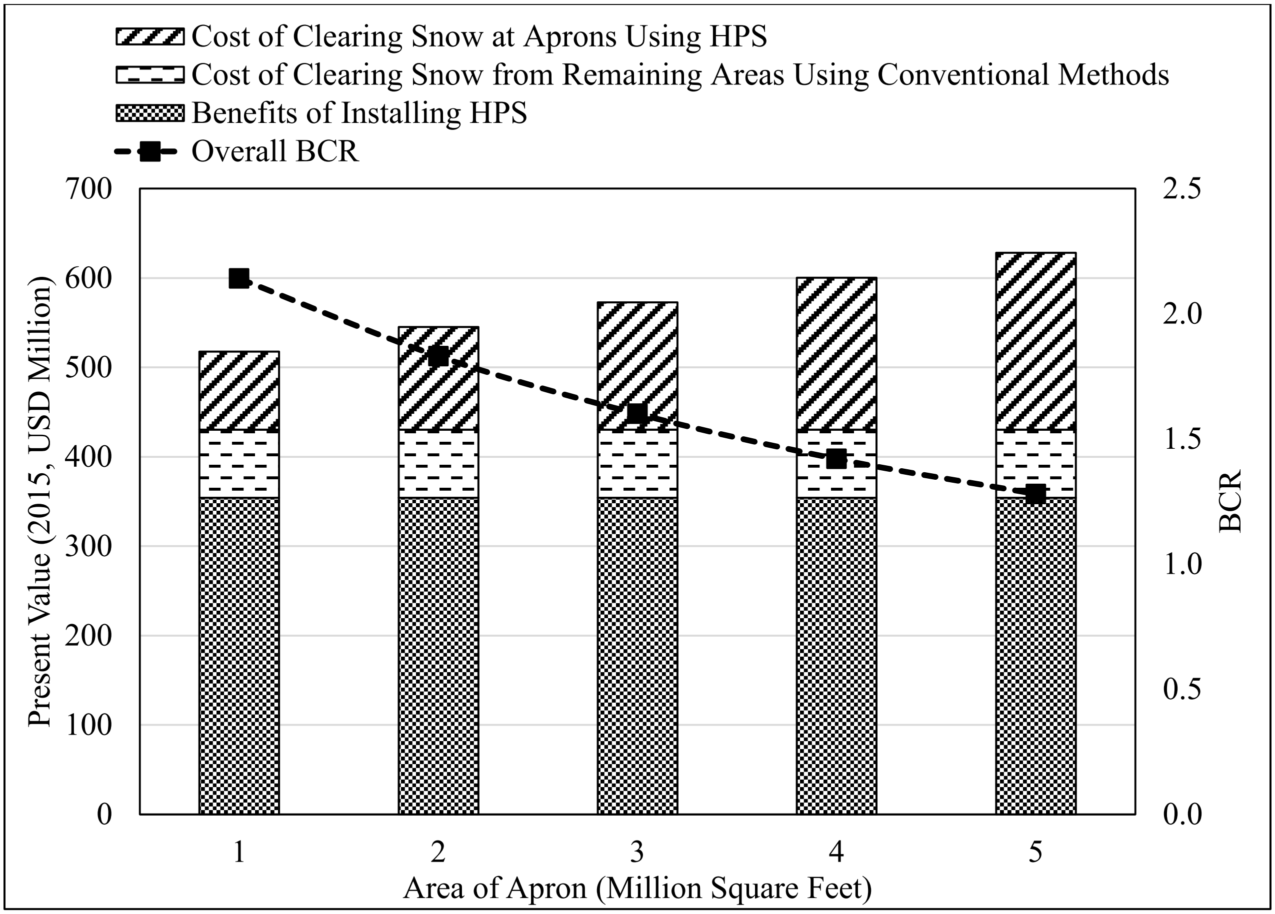

Figure 15. Costs, Benefits, and BCR of Using HHPS at Aprons and CSRS at the Remaining Areas at MSP

5. CASE STUDY OF COMMERCIAL AIRPORT—CMH.

5.1 DESCRIPTION OF CMH AIRPORT.

CMH is a commercial service international airport located in Columbus, Ohio. The area receives approximately 27 inches of snow annually. Based on the questionnaire presented in appendix A, information pertaining to the current snow-removal methods was collected and used for the economic analysis. CMH handled more than 3 million enplanements in 2013. It has two parallel runways and both are operational during winter storms. The apron area is approximately 2.2 million ft^2. CMH has 17 pieces of SRE, 20 snow-removal personnel, 3 airport concourses, and about 40 gates. An aerial view of CMH is shown in figure 16.

The CMH airport manager explained that the high cost of chemicals, aging equipment, insufficient labor, and large apron clearance times during high snowfalls contribute greatly to delays.

According to the data provided by CMH managers, the labor cost ranges between 65 USD/h to 80 USD/h depending on the time and day of the snowstorm. Snow removal crews usually employ a liquid deicer (potassium acetate) for runways and a solid deicer (sodium formate) for taxiways, taxi lanes, and aprons.

Source: Google Maps™, 2016

Figure 16. Aerial View of CMH

5.2 BENEFIT AND COST CALCULATIONS—CMH.

5.2.1 The CSRS—CMH.

The number of SRE and their costs were obtained directly from the airport managers. The SRE costs were assumed a function of the pavement area. The costs, which were assessed only for the apron area, were calculated using equation 6. The recurring costs were obtained from the airport managers and were calculated using equation 7.

5.2.2 The HHPS Capital Cost Calculations—CMH.

The capital cost consists of HHPS installation. The costs per unit feet are multiplied by the total area to be heated to get the capital cost. Based on the literature [17] and consultation with companies dealing with HHPS, a base value of 35 USD/ft^2 was adopted. To make the analysis more complete, a sensitivity analysis was conducted for different unit cost values such as 15 USD/ft^2 to 65 USD/ft^2.

5.2.3 The HHPS Annual Cost Calculations—CMH.

The amount of natural gas required was calculated based on the annual heat energy required to melt snow or the design heat load of the system. The heat load was calculated using equation 1. The average annual cost of commercial natural gas in the state of Illinois was 8.15 USD per 1000 cubic feet per average year [25]. The cost for natural gas was calculated to be 1,150,789 USD for a season. Maintenance cost was taken as 1% of the capital cost based on surveys and questionnaires from contractors, and the total O&M costs were calculated to be approximately 1.92 million USD.

In addition, because conductive concrete is a conceptual system and has not been implemented yet in a large scale, there is no historical data regarding the cost of the maintenance. The use of hydronic heated pavement can increase the durability of the pavement because freezing-induced damage and cracks caused by deicing chemicals will be eliminated. In the other hand, the maintenance cost of the heating system can be costly. Therefore, different scenarios were developed in this study to estimate the cost of maintenance. The scenarios were developed for the situations in which the cost of maintenance was 0.5% (lower than 1%) and 1.5% (higher than 1%). Also this item is considered as one of the input variables for sensitivity analysis.

5.2.4 The HHPS Annual Benefit Calculations—CMH.

As discussed in section 3.6.1, the potential quantified benefits of installing HHPS will be reduced lost passenger time, airline staff time cost savings, reduced fuel wastage, and safety of ground staff.

5.2.4.1 Value of Lost Passenger Time—CMH.

As per table 5, the values assigned to business passengers is 63.2 USD/h and 36.1 USD/h for leisure passengers; 40.40% of the total passengers fly for business purposes and 59.60% are leisure travelers. The combined value of lost time for the two categories of travelers was approximately 7.73 million USD for 2016 using equations 8 and 9. As with MSP, the annual growth rate of operations is considered; and thus, the total value of lost passenger time increases over time.

5.2.4.2 Value of Airline Crew Time and Airplane Fuel Consumption—CMH.

Equation 11 was used to calculate the number of delayed flights, which totals approximately 2.08 million USD for 2016. The annual growth rate of operations is also accounted for in this case for subsequent years.

5.2.4.3 Enhanced Safety of Ground Staff—CMH.

In CMH, the ground staff includes about 2,500 full-time workers, and the numbers of cases were determined using this data. An incident rate of 3.8 injuries per 10,000 full-time employees was used in this analysis [31]. Based on the above data, the injury cost was calculated by multiplying the percentage of each injury by its contributing fraction of the VSL. The summed value of all injury cases for CMH for the concerned 4 months was calculated using equation 12 as 250,950 USD annually.

5.2.5 Benefit and Cost Comparison—CMH.

5.2.5.1 The NPV—CMH.

All the costs (cash outflow) and benefits (cash inflow) calculated in this section are discounted at 7% over a 20-year analysis period and then summed to get the NPV of the cost, as shown in table 11.

Table 11. The NPV of Costs and Benefits for HHPS Over a 20-Year Analysis Period and Discounted at 7% at CMH

Cost Category	Annual Value (USD)	PV of HHPS Costs (USD)
Capital Cost	77,000,000	97,348,867
Annual Recurring Cost	1,920,789	
Benefit Category	Annual Value (USD) in Year 1 (2016)	PV of HHPS Benefits (USD)
Value of Lost Passenger Time	7,736,778	131,735,147
Airline Crew Time and Fuel Wastage	2,087,856	
Safety of Ground Staff	267,216	

As shown in table 11, the PV of benefits is 131,735,147 USD and the PV of cost is 97,348,867 USD. The NPV is calculated as a positive 34,386,279 USD and a positive NPV indicates that the project is economically feasible.

Figure 17 represents the cash flow of the likely benefits and costs related to the HHPS. The benefits are due to reduction in lost passenger time, lost crew hours, and aviation fuel wastage. The costs include the HHPS installation and O&M. The benefits of HHPS far exceed their cost of installation and O&M. The difference minimizes as the years progress as a result of discounting.

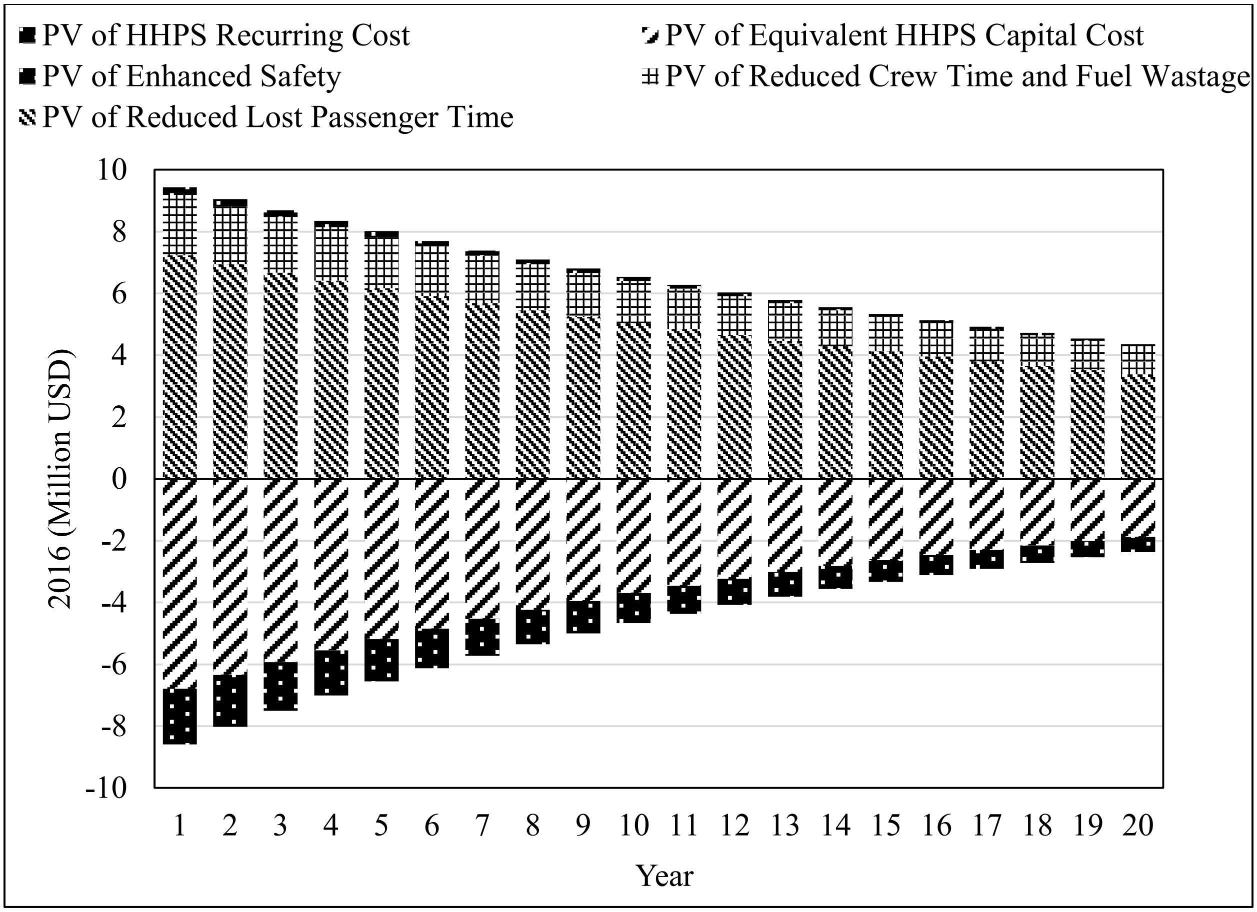

Figure 17. Cash Flow for HHPS at CMH

5.2.5.2 The BCR—CMH.

After the NPV was calculated, the BCR was calculated by dividing the net benefits by cost for 20 years. Then, the BCR was calculated as 1.35 for the base case values. In comparison, in MSP the BCR was higher (2.05).

5.2.5.3 Sensitivity Analysis—CMH.

The initial construction cost is a key factor in influencing the BCRs. It is anticipated that the BCR should be expected to decrease as the initial cost of construction increases. Delays are very unpredictable in nature because they depend on various other factors such as weather, preparedness of airports, and airline procedures. Delays may change drastically every year, and hence, a sensitivity analysis is warranted to determine their the influence on the BCR.

Similar to the sensitivity analysis conducted for MSP, MCS (described in section 3.6.4) was employed in the sensitivity analysis for CMH to better understand and quantify cost uncertainties within the theoretical estimate. The variables and each variable range are shown in table 12.

Table 12. Variables and Each Variable Range Used in MCS for CMH

Input Variable	Range
Hydronic Heated Pavement Construction Cost (USD/ft^2)	(25-65)*
Percentage of Weather-Related Delays (%)	(2.5-3.5)
Portion of Initial Construction Cost Dedicated to Maintenance (%)	(0.5-1.5)
Cost Due to Injuries	{minor, moderate, serious}** possibility of the occurrence respectively {60%,25%, and 15%}
Duration of Each Delay (Minutes)	(33-45)
Ambient Temperature, (°F)	(26-30)
Ambient Temperature (°F)	(0.83-0.89)

*() represents uniform distribution
**{} represents discreet distribution

To determine the impacts of the input variables to the BCR, a sensitivity analysis was performed on all the random variables to determine how the uncertain behavior of each variable would affect the total BCR. Figure 18 shows the results of the sensitivity analysis for CMH.

The sensitivity analysis results illustrate that, among all the random variables, the installation cost has the greatest potential impact on the overall BCR among the random variables.

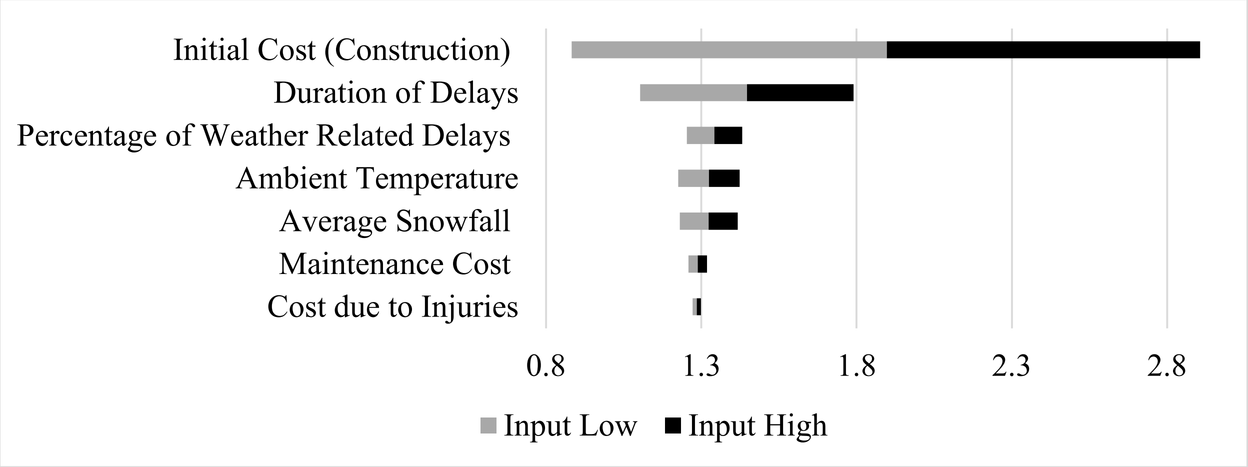

Figure 18. Sensitivity Analysis Results for CMH

BCR is estimated at different reliability levels under MCS. Table 13 shows the BCR for CMH with different reliability percentages. The estimate range with a two-tailed 90% confidence interval, is 0.82 to 1.92 with a median value of 1.20 and a standard deviation value of 0.30.

Table 13. The BCR With Different Reliability Percentages for CMH

Reliability Percentage	95%	85%	75%	65%	55%	Median	45%	35%	25%	15%	5%
CMH	0.82	0.93	1.01	1.08	1.16	1.20	1.25	1.36	1.50	1.68	1.92

6. CASE STUDY OF COMMERCIAL AIRPORT—DSM.

6.1 DESCRIPTION OF DSM AIRPORT.

DSM is a commercial service airport located in the capital city of Des Moines, Iowa. Based on the questionnaire (appendix A), information pertaining to the current snow-removal methods was collected and used for the economic analysis. DSM handled more than 3 million enplanements in the year 2013. It has daily operations of approximately 220 aircrafts and can handle about 140 million pounds of cargo annually. DSM receives an average of 35 inches of snow annually, owns 22 pieces of SRE, and employs 28 snow-removal personnel. The airport has two operational runways and both are operational during winter storms. The apron area is approximately 1.5 million ft^2.

DSM uses the FAA-specified deicing and anti-icing agents that do not cause any known environmental harm. The contaminated snow is drained into storm water drains and then travels to the city waste water treatment plant. There are separate tanks to collect water with high concentrations of aircraft deicing fluid.

6.2 BENEFIT AND COST CALCULATIONS—DSM.

6.2.1 The CSRS—DSM.

The number of SRE and their costs were obtained directly from the airport managers. The SRE costs were assumed to be a function of the pavement area. The costs, which were assessed only for the apron area, were calculated using equation 6. The recurring costs were obtained from the airport managers and were calculated using equation 7.

6.2.2 The HHPS Capital Cost Calculations—DSM.

The capital cost consists of the HHPS installation. The costs per unit feet are multiplied by the total area to be heated to get the capital cost. Based on the literature [17] and consultation with companies dealing with heated pavements, a base value of 35 USD/ft^2 was adopted. To make the analysis more complete, a sensitivity analysis was conducted for different unit cost values, such as 25 USD/ft^2 to 65 USD/ft^2.

6.2.3 The HHPS Annual Cost Calculations—DSM.

The heat load was calculated using equation 1. The average annual cost of commercial natural gas in the state of Iowa was 7.46 USD per 1000 cubic feet per average year [25]. The cost for natural gas was calculated to be 1.6 million USD for a season. Maintenance cost was taken as 1% of the capital cost based on the questionnaire (appendix A), and the total O&M costs were calculated to be approximately 1.21 million USD. As mentioned in section 4.2.2, different possible scenarios were developed in this study to estimate the cost of maintenance. The scenarios were developed for the situations in which the cost of maintenance was 0.5% (lower than 1%) and 1.5% (higher than 1%). Also, this item is considered as one of the input variables for sensitivity analysis.

6.2.4 The HHPS Annual Benefit Calculations—DSM.

As discussed in section 3.6.1 the potential quantified benefits of installing an HHPS will be reduced lost passenger time, airline crew time cost savings, reduced fuel wastage, and safety of ground staff.

6.2.4.1 Value of Lost Passenger Time—DSM.

As per table 5, the values assigned to business passengers was 63.2 USD/h and leisure passengers is 36.1 USD/h; 40.40% of the total passengers fly for business purposes and 59.60% are leisure travelers. Using equations 8 and 9, the combined value of lost time for the two categories of travelers was found to be approximately 4.72 million USD in 2016. As in the previous cases, the annual growth rate of operations is considered; and thus, the total value of lost passenger time increases over time.

6.2.4.2 Value of Airline Crew Time and Airplane Fuel Consumption—DSM.

Using equation 11, the value of loss due to extra airline crew time and fuel wastage was approximately 1.59 million USD for 2016. Annual growth rate of operations was also accounted for subsequent years in this case.

6.2.4.3 Enhanced Safety of Ground Staff—DSM.

In DSM, the ground staff includes about 2,000 full-time workers, and the number of cases were determined using this data. The number of cases for an incidence rate of 5 were 9.603. Based on the above data, the injury cost was calculated by using equation 12. The summed value of all the injury cases for DSM for the concerned 4 months was calculated as 213,772 USD.

6.2.5 Benefit and Cost Comparison—DSM.

6.2.5.1 The NPV—DSM.

NPV is the sum of the PVs of incoming and outgoing cash flows over a period of time. All the costs (cash outflow) and benefits (cash inflow) as calculated in this section were discounted at

7% discount rate over a 20-year analysis period and then summed to get the NPV of the cost, as shown in table 14.

Table 14. The NPV of Costs and Benefits for HHPS Over a 20-Year Analysis Period and Discounted at 7% at DSM

Cost Category	Annual Value (USD)	PV of HHPS Costs (USD)
Capital Cost	52,500,000	70,925,414
Annual Recurring Cost	1,739,229	
Benefit Category	Annual Value (USD) in Year 1 (2016)	PV of HHPS Benefits (USD)
Value of Lost Passenger Time	4,728,031	85,224,691
Airline Crew Time and Fuel Wastage	1,594,890	
Safety of Ground Staff	213,772	

As shown in table 14, the PV of benefits is 85,244,691 USD (cash inflow is positive), and the PV of cost is 70,925,414 USD (cash outflow is negative). The NPV is the sum of the cash inflow and outflow, and is calculated here as positive 14,229,277 USD. A positive NPV indicates that the project is feasible.

Figure 19 represents the cash flow of the likely benefits and costs related to the HHPS. The benefits are due to reduction in lost passenger time, lost crew hours, and aviation fuel wastage. The costs include the HHPS installation and O&M. The benefits of HHPS far exceed their cost of installation and O&M. The difference minimizes as the years progress as a result of discounting.

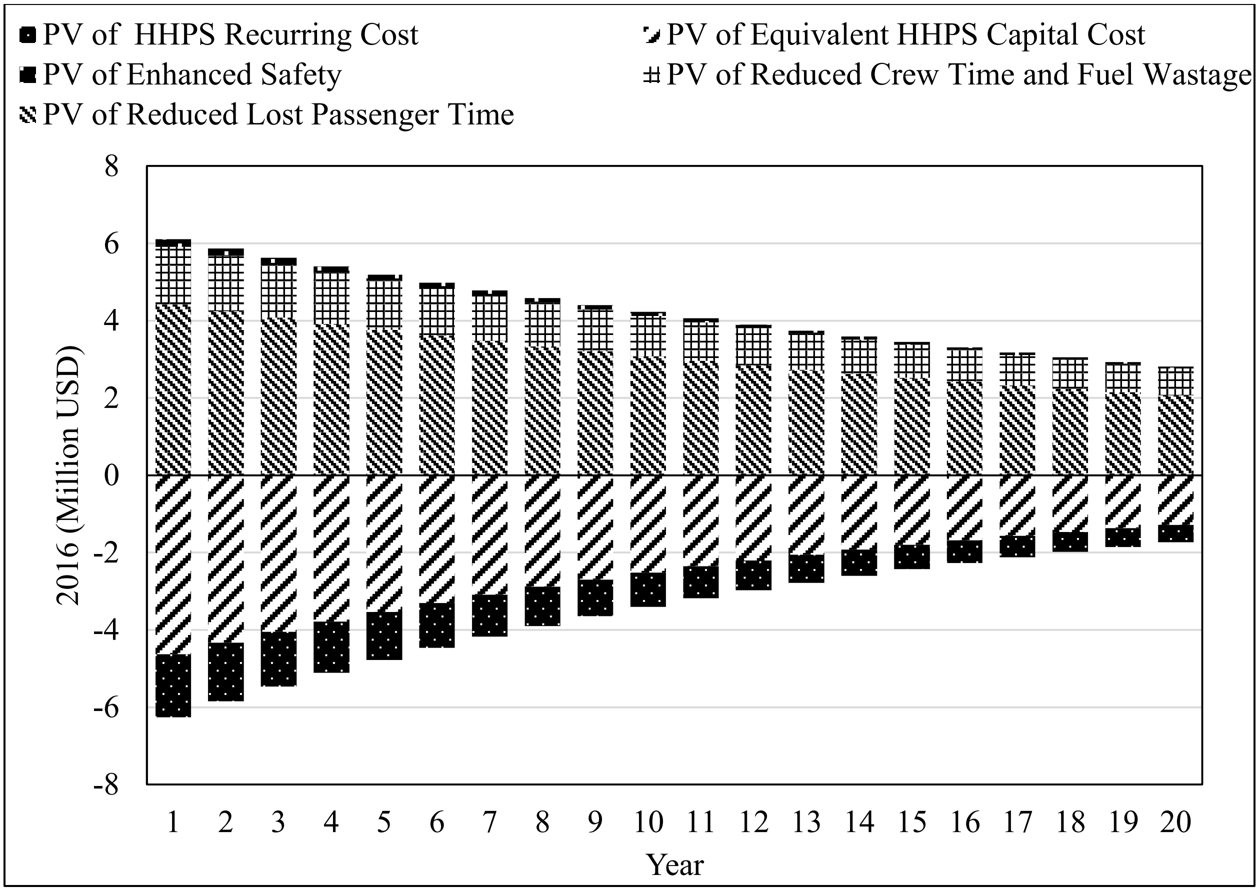

Figure 19. Cash Flow for HHPS at DSM

6.2.5.2 The BCR—DSM.

Only the apron area, not the entire airport, was considered for all comparisons. All costs corresponding to base case in use of CSRS was taken as a ratio of the apron area to the total area of the airports. Total cost for base case in use of CSRS is a fraction of the entire SRE and O&M cost. Total costs for alternative case in use of HHPS at aprons are the installation and O&M costs of HHPS. After the NPV was calculated, the BCR was calculated by dividing the net benefits by cost for 20 years. Then, the BCR was calculated as 1.20, much lower than MSP and CMH.

6.2.5.3 Sensitivity Analysis—DSM.

Similar to the sensitivity analysis conducted for MSP, MCS (described in section 3.6.4) was employed in the sensitivity analysis for CMH to better understand and quantify cost uncertainties within the theoretical estimate. The variables and each variable range are shown in table 15.

Table 15. Variables and Each Variable Range Used in MCS for DSM

Input Variable	Range
Hydronic Heated Pavement Construction Cost (USD/Ft^2)	(25-65)[*]
Percentage of Weather-Related Delays (%)	(2.5-3.5)
Portion of Initial Construction Cost Dedicated to Maintenance (%)	(0.5-1.5)
Cost Due to Injuries	{minor, moderate, serious}[**] possibility of the occurrence respectively {60%,25%, and 15%}
Duration of Each Delay (Minutes)	(33-57)
Ambient Temperature, (°F)	(20-22.4)
Ambient Temperature (°F)	(1.01-1.09)

*() represents uniform distribution
**{} represents discreet distribution

Figure 20 shows the results of the sensitivity analysis for DSM. The sensitivity analysis results show that, among all the random variables, installation cost has the greatest potential impact on the overall BCR.

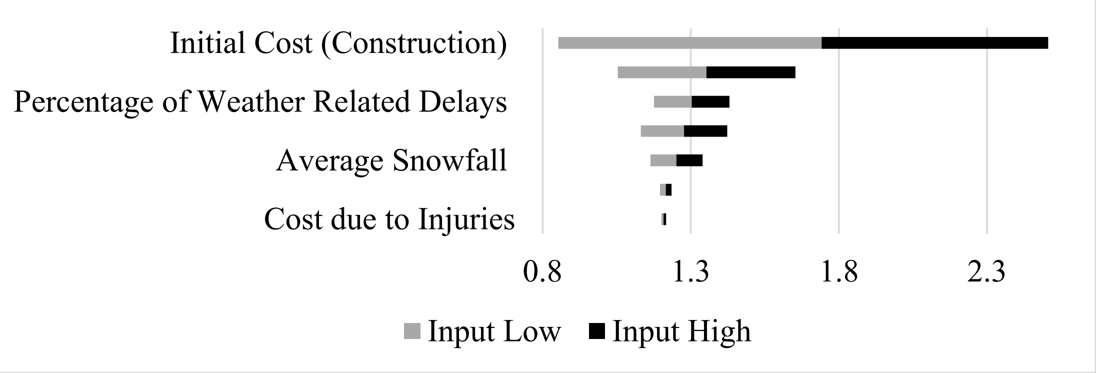

Figure 20. Sensitivity Analysis Results for DSM

BCR is estimated at different reliability levels under MCS. Table 16 shows the BCR for DSM with different reliability percentages. The estimate range with a two-tailed 90% confidence interval is 0.80 to 1.80 with a median value of 1.14 and a standard deviation value of 0.27.

Table 16. The BCR With Different Reliability Percentage for DSM

Reliability Percentage	95%	85%	75%	65%	55%	Median	45%	35%	25%	15%	5%
DSM	0.80	0.89	0.96	1.03	1.10	1.14	1.19	1.29	1.41	1.56	1.79

7. CASE STUDIES OF GA AIRPORTS.

GA airports mainly focus on more specialized services that scheduled airlines cannot provide, such as:

- Emergency medical services
- Aerial firefighting, law enforcement
- Border control, agricultural functions
- Flight training
- Time-sensitive air cargo services
- Business travel, and scheduled services

Some GA airports provide all of these aeronautical functions, and others provide only a few. Some GA airports are large and have multiple runways and extensive facilities, and others are relatively small and may need only a short, single runway, helipad, or sea lane to serve a critical function.

According to the FAA, GA airports are divided in to four categories [19]:

- National*:* Serve the national and state systems by providing communities with access to national and international markets throughout the United States. They have approximately 200 based aircrafts and 30 jets.

- Regional*:* Support regional economies by connecting communities to statewide and interstate markets. They have approximately 90 based aircrafts and 3 jets.

- Local*:* Serve the local or regional markets with 33 based propeller-driven aircraft and no jets.

- Basic*:* Have low levels of activity with about 10 propeller-driven aircrafts and no jets.

There are 2,952 GA airports in the U.S. and about half of these are local GA airports. Usually, smaller GA airports charge very low or zero landing fees; however, a fixed-base operator (FBO) can charge for additional services such as apron usage. An FBO is a commercial business granted the right to operate on the airport and provide aeronautical services such as fueling, tie down, parking, aircraft rental, aircraft maintenance, flight instruction, etc. Owning an aircraft does incur regular parking space and utility charges, but such costs are not related to the rate of snow removal and hence, not considered [34].

In GA airports, the airport owner, FBO, or other contractors hired by the owner may be responsible for snow removal and maintenance. Charters and private plane owners will usually give their flying schedule to the airport staff beforehand, and they may prepare the pavements accordingly. For GA airports, as the pavements are not as large as the commercial airports, they may use the same SRE for the aprons and runways. Data were collected via email for two GA airports, Mason City Municipal Airport and Kent State University Airport. Data collection was particularly challenging for GA airports as the responses were missing or incomplete.

The benefits are very case specific and calculating their frequency requires more in-depth studies. In this report, only the benefits due to delays in scheduled airplane service were estimated. The results may be not in favor of installing airports with HHPS, but a tradeoff occurs between high cost and maintaining the airports in winter to respond to any emergency situation.

7.1 CASE STUDY OF GA AIRPORT—MCW.

MCW is a city-owned, public-use, regional airport located in Mason City, Iowa. The aerial view of the airport is shown in figure 21. Since MCW handles a low volume of traffic, airport managers coordinate snow-removal operations around them. MCW does not handle any cargo, and the airport has two operational runways.

Source: Google Maps™, 2014

Figure 21. Aerial View of MCW

Site visits, surveys, and questionnaires reveal that Delta Connection (operated by Great Lakes Airlines) previously provided service from MCW to MSP. In January 2014, the airline ended all commercial service. In November 2014, Air Choice One started service from MCW to Chicago O'Hare International Airport and early this year to St. Louis Lambert International Airport. In addition, Air Choice One offers charter services and flight training. The exact numbers of these operations were not available even after the questionnaire was completed. The benefit and cost calculations for MCW as the representative of GA airports are shown in Appendix D. Similar calculation procedures can be applied to another GA airport (i.e., 1G3).

7.1.1 The HHPS Capital Cost Calculations—MCW.

The MCW capital costs, which include HHPS installation, were calculated in a similar manner as the commercial airports. To estimate the capital cost, the costs per unit feet were multiplied by the total area to be heated. Based on the literature [17] and consulting with companies dealing with HHPS, a base value of 35 USD/ft^2 was adopted. To make the analysis more complete, a sensitivity analysis was conducted for different unit cost values such as 15 USD/ft^2 to 45 USD/ft^2. The total area of MCW pavements is approximately 3 million ft^2, and aprons comprise of about 600,000 ft^2.

7.1.2 The HHPS Annual Cost Calculations—MCW.

Annual or recurring costs comprise of the operational and maintenance costs to run the HHPS. Operation costs consist of the cost of natural gas needed to heat antifreeze circulating in the pipes and electricity needed to power the control system. The amount of natural gas required was calculated based on the annual heat energy required to melt snow or the design heat load of the system. The heat load was calculated using equation 1. The average annual cost of commercial natural gas in the state of Iowa was 7.46 USD per 1000 cubic feet per average year [25]. The cost for natural gas was calculated to be 485,691 USD for a season. Maintenance cost was taken as 1% of the capital cost based on questionnaires from contractors (appendix A), and the total O&M costs were calculated to be approximately 635,691 USD for 2015.

7.1.3 The HHPS Annual Benefit Calculations—MCW.

7.1.3.1 Value of Lost Passenger Time—MCW.

As per table 5, the values assigned to business passengers is 63.2 USD/h and leisure passengers is 36.1 USD/h; 40.40% of the total passengers fly for business purposes and 59.60% are leisure travelers. The combined value of lost time for the two categories of travelers was found to be approximately 4,585 USD annually using equations 8 and 9.

7.1.3.2 Value of Airline Crew Time and Airplane Fuel Consumption—MCW.

Since MCW is a GA airport, there are only four flight operations in a day, and the airplane seats eight passengers. This value is calculated to be 38,626 USD for the year 2015 using equation 11. The annual growth rate of operations for subsequent years is also accounted for in this case.

7.1.3.3 Enhanced Safety of Ground Staff—MCW.

There are 200 full-time workers at MCW, and the injury cost is estimated at 21,377 USD annually using equation 12.

Table 17 shows the NPV of cost and benefits for HHPS for MCW. As is evident from the table, the NPV is a negative value indicating that the use of HHPS at MCW is not feasible under the current assumptions. GA airports are not as frequently used as commercial airports, and so they do not have indirect or soft benefits that commensurate the high cost of HHPS installation. HHPS may be feasible in GA airports with higher numbers of aircraft operations. GA airports are used only in times of emergency or crisis, and interpreting the use of airports in these situations in monetary terms may be very case specific and challenging.

Table 17. The NPV of Cost and Benefits for HHPS Over a 20-Year Analysis Period and Discounted at 7% for MCW

PV of Cost or Benefit	Values (USD)
PV of HHPS Costs	(28,370,165)
PV of HHPS Benefits	793,413
NPV of HHPS	(27,576,752)
PV of Cost of CSRS	(3,326,165)

7.2 CASE STUDY OF GA AIRPORT—1G3.

Shown in figure 22, 1G3 is a public airport owned by Kent State University in Stow, Ohio. The airport is located along State Route 59 (Kent Road) approximately 3 miles west of the central business district of Kent.

Figure 22. Ground View of 1G3

The airport is used by the College of Applied Engineering, Sustainability and Technology for its in-house aeronautics program, which provides students with flight training and other professional aeronautical training, including air traffic control and airport management studies. The airport also operates a flight clinic for the general public who are interested in attaining private pilot instruction.

The airport does not handle any cargo, and it has one operational runway. The Kent State University Aeronautics program has a 30-aircraft fleet that cycles every 90 minutes. Five snow-removal personnel use five SRE and take about 90 minutes to clear the surface of snow, and the labor rate is approximately 75 USD/h.

7.2.1 The HHPS Capital Cost Calculations—1G3.

The 1G3 capital costs, which consist of HHPS installation, were calculated in a similar manner as the commercial airports. The costs per unit feet were multiplied by the total area to be heated to get the capital cost. Based on the literature [17] and consulting with companies dealing with HHPS, a base value of 35 USD/ft^2 was adopted. To make the analysis more complete, a sensitivity analysis was conducted for different unit cost values such as 15 USD/ft^2 to 45 USD/ft^2.

7.2.2 The HHPS Annual Cost Calculations—1G3.

Annual or recurring cost comprises of the O&M costs to run the HHPS. Operation costs consist of the cost of natural gas needed to heat antifreeze circulating in the pipes and electricity needed to power the control system. The amount of natural gas required was calculated based upon the annual heat energy required to melt snow or the design heat load of the system. The heat load was calculated using equation 1. The average annual cost of commercial natural gas in the state of Iowa was 7.46 USD per 1000 cubic feet per average year [25]. The cost for natural gas was calculated to be 121,422 USD for a season. Maintenance cost was taken as 1% of the capital cost based on questionnaires (appendices A and B) from contractors, and for 2015, the total O&M costs were calculated to be approximately 158,923 USD.

7.2.3 The HHPS Annual Benefit Calculations—1G3.

As 1G3 is used only as a flight-training airport, there are no costs to passengers or airplane carriers. Winter weather may disrupt the normal schedule of flight training, but that was not included as a part of the analysis.

7.2.3.1 Enhanced Safety of Ground Staff.

In 1G3, there are about 50 full-time workers, and the number of cases was determined using this data. An incident rate of 3.8 injuries per 10,000 full-time employees was used in this analysis [31]. Based on the above data, the injury cost was calculated by multiplying the percentage of each injury by its contributing fraction of the VSL. Using equation 12, the summed value of all the injury cases for 1G3 for the concerned 4 months was calculated as 5,121 USD.

Table 18 shows the NPV of cost and benefits for HHPS for 1G3. As is evident from the table, the NPV is a negative value, indicating that the use of HHPS at 1G3 is not feasible under the current assumptions. GA airports are not as frequently used as commercial airports, and so they do not have indirect or soft benefits that commensurate the high cost of HHPS installation. HHPS may be feasible in a GA airport with higher number of aircraft operations. GA airports are used only in times of emergency or crisis, and interpreting the use of airports in these situations in monetary terms may be very case specific and challenging.

Table 18. The NPV of Cost and Benefits for HHPS Over a 20-Year Analysis Period and Discounted at 7% for 1G3

PV of Cost or Benefit	Values (USD)
PV of HHPS Costs	(5,433,631)
PV of HHPS Benefits	392,453
NPV of HHPS	(5,534,631)
PV of Cost of CSRS	(944,780)

Maintaining operational status of GA airports during snow may have many benefits such as emergency medical services, aerial firefighting, law enforcement, border control, agricultural functions, and time-sensitive air cargo services. During emergency situations, there may not be enough time to look for labor and get the airport ready for an incoming aircraft. HHPS could be a good solution in this case, as labor requirements would not be required and the airport would be ready for aircraft arrival.

8. POTENTIAL HHPS BENEFITS.

HPSs offer a number of potential benefits over CSRS. The various categories of potential benefits that can be attributed to HPS are summarized in sections 8.1 through 8.5.

8.1 OVERALL BENEFITS.

Potential overall benefits of HPS include:

- Facilitates expedited and efficient snow- and ice-removal operations that can reduce traffic delays, especially at large airports.
- Reduces the risk of airplanes skidding off runways, high-speed taxiways, etc., thus possibly reducing accidents, injuries, and fatalities.
- Reduces the downtime required to clear ice and snow.
- Improves safety for ground crews servicing the aircraft at the gate areas.
- Improves safety of passengers embarking /disembarking the aircraft.
- Improves air travel capacity during winter operations. Utilization of an HPS assists airports to remain open and accessible during winter operations, enabling safe travels for the passengers.
- Reduces the time required to clear snow and/or ice in priority areas.
- Provides a platform for the development of innovative anti-icing systems, such as nanostructured superhydrophobic coatings and systems, conductive paving materials, etc.

- Provides an efficient operation time window, i.e., the HPS deicing operation can be automated to start and end exactly for the duration of ice and snow formation. (The heating process can be initiated ahead of an ice/snow storm and can be automated by using sensor systems.)

- Reduces the amount of labor and equipment costs associated with using and applying deicing methods.

Provides a viable option from an energy or financial perspective for achieving pavement surfaces free of ice/snow without using mechanical or chemical snow and ice removal methods.

8.2 ENVIRONMENTAL AND SUSTAINABILITY BENEFITS.

Potential environmental and sustainability benefits of HPS are listed below.

- Eliminates environmental concerns, such as the contamination of nearby bodies of water and foreign object debris/damage to aircraft engines. Both these concerns can be the result of using deicing and anti-icing chemicals.

- Saves airports significant money by eliminating the need to treat and clean the contaminated snow and storm water associated with the use of deicing chemical agents on airfield pavements.

- Curbs and prevents the corrosion and deterioration of airfield lighting fixtures by eliminating (or reducing) the use of deicing chemicals. This may provide significant cost savings, especially considering that some airports have between 20,000 and 50,000 airfield lighting fixtures installed in airfield pavements.

- Mitigates pavement durability failures that potentially result from using deicing chemicals. Also, extends the life of airfield pavement systems, thus leading to significant savings in maintenance and repair costs.

- Improves efficiency and sustainability of surface drainage systems.

- Facilitates of the application of clean energies, e.g., use of geothermal energy.

- Reduces GHG emissions and overall energy consumption compared to CSRS.

8.3 SAFETY BENEFITS.

Potential safety benefits of HPS include:

- Improved safety for ground crews servicing the aircraft at the gate areas by providing ice and snow free airfield pavements.

- Decreased risk of collision between aircraft and SRE.

- Zero-to-minimal noise pollution compared to that resulting from the use of SRE.

9. SUMMARY.

9.1 FINDINGS.

The potential benefits of HPS are numerous. The installation of such systems can potentially reduce the dependency on SRE and deicing chemicals. In addition, HPS have the capability to provide enhanced safety for ground staff and vehicles, reduce the labor of snow and slush removal, and create better working conditions at the airport. However, a major challenge involved with the installation of HPS is the high initial costs. In view of this, the objective of this study was to conduct a BCA on a set of case scenarios implementing HHPS as representing HPS in current practices.

The basic strategy started with selecting airports that had an annual snowfall of at least 35 inches. Then, data were collected from these airports through surveys and questionnaires and on-site visits. Next, the various costs and benefits of installing HHPS were identified and monetized. Finally, economic analysis techniques, such as NPV and BCR, were used to analyze the viability of installing HHPS over an analysis period of 20 years.

HHPS are expected to have maximum benefits in the aprons, where clearing and hauling snow is more time consuming and cumbersome than other airport areas, mainly due to skewed geometric designs and considerable human and machine activity. Correspondingly, this analysis focuses on an assessment of the installation of HHPS in apron areas.

The results of this analysis suggest that, among stakeholders, delays affect passengers the most. Specifically, it is anticipated that passengers' lost time would decrease with the installation of HHPS. In addition, the results of the sensitivity analyses show that the BCR is very sensitive to any changes in the duration and time period of delays, and a slight increase can cause the BCR to increase considerably. Furthermore, the findings suggest that strategic placement of HHPS after critical field investigations is the most desirable option with maximum benefits and least costs.

A Microsoft Excel® spreadsheet-based toolbox for evaluating the energy and economic viability of HPS and a user manual have been developed for use by airport managers. The user manual is available in appendix E.

9.1.1 Comparison of Financial Feasibility of HHPS in Commercial Airports.

The case studies suggest that HHPS may be feasible in all types of commercial airports under a given set of assumptions and conditions. It is interesting to compare how the BCR changes for each type of airport. The case study on MSP, representing a large primary hub in the analysis, indicates strongly that HHPS are economically feasible under the given set of assumptions. The findings of the case studies suggest that the larger the airport in terms of both the area of pavements and the number of operations, the more feasible the installation of HHPS. As shown in table 19, the BCR decreases as the size of the airport (number of operations and area) decreases. There is a 25% decrease in the BCR between a large-hub (MSP) and a medium-hub (CMH) airport and approximately 40% decrease between a large-hub and a small-hub (DSM) airport.

Table 19. The BCRs for the Airports in This Analysis

Airport	BCR	Median BCR (Based on Risk Analysis)
MSP	2.05	1.61
CMH	1.35	1.20
DSM	1.20	1.14

Nevertheless, HHPS are still a financially viable snow-melting option among small-hub airports (0.05% to 0.25% of total U.S. passenger enplanements) such as DSM.

Table 20 summarizes the BCR results presented in the MSP, CMH, and DSM case studies. The results of the study indicate that the high installation costs may be offset by the large amount of benefits over a 20-year analysis period. In addition, the costs of HHPS are area dependent. Thus, strategic placement of HHPS could reduce the capital costs without compromising the benefits. Reducing pavement areas with HHPS could reduce the capital costs, making them comparable to the cost of the current snow-removal methods. If site investigations can prove that heating only about 20% of the total apron area (instead of the entire apron) can help reduce delays, HHPS may prove to be very cost beneficial.

Table 20. Variation of BCR and Incremental BCR With the Change in the Percentage of Area Under HHPS for Airports

Area of Apron to be Heated (%)	BCR for MSP	Incremental BCR for MSP	BCR for CMH	Incremental BCR for CMH	BCR for DSM	Incremental BCR for DSM
20	3.78	4.56	2.75	3.51	2.25	2.78
40	3.14	3.66	2.19	2.64	1.85	2.18
60	2.69	3.06	1.82	2.12	1.56	1.79
80	2.34	2.63	1.77	1.55	1.36	1.52
100	2.05	2.30	1.35	1.51	1.20	1.33

The results can be transferred to other airports with similar operations and weather conditions. A few large-hub airports that would benefit from the study are Denver International Airport, Chicago O'Hare International Airport, Newark Liberty International Airport, John F. Kennedy International Airport, and LaGuardia Airport because they have similar snowfall characteristics, area, and number of operations.

9.1.2 Key Findings.

The key findings of all case studies in this study are summarized below.

- The results of this study indicate that HPS including both HHPS and EHPS could be expected to have maximum benefits in the aprons where clearing and hauling snow is more time consuming and cumbersome due to different geometric designs and ground crew activities.

- GA airports do not have as many indirect benefits and soft costs as commercial airports. GA airports would benefit from HPS in emergency situations when it becomes imperative to keep the airport functional.

- HPS application is a viable option from an energy or financial perspective for achieving pavement surfaces free of ice and snow without using mechanical or chemical methods. HPS may be exclusively beneficial at aprons that have a small area relative to the total paved surfaces of the airport but have the potential to cause winter weather-related delays. Airport managers explained that snow accumulation in aprons causes most of the airline delays, so it becomes crucial to keep these areas clear of snow.

- As the initial installation costs are very high, HHPS may be feasible only in commercial airports where the costs may be offset through airport usage and improvement charges or taxes. It may not be financially viable to install HPS for the entire area of airport paved surfaces.
- Strategic placement of HPS can reduce the initial construction costs significantly making a strong argument in favor of installing HPS. The BCA results of the BCA are dependent on the size of the airport examined both in terms of operations and of area.

- HPS have the potential to reduce the dependency on deicing salts, minimize the use of SRE, and reduce labor requirements.

- Passengers are greatly affected by weather-related delays. It is anticipated that if HPS were installed, the passengers' lost time would decrease.

9.2 LIMITATIONS AND FUTURE RESEARCH.

The limitations of using HPS as well as suggestions for future research are presented in sections 9.2.1 and 9.2.2, respectively.

9.2.1 Limitations.

The current study focused on the effect of delays due to winter storms. Instead of studying the annual effects of winter storms and averaging them for the entire analysis period, it may be more insightful to study each storm independently and categorize the effects based on the intensity or number of days it lasted. In view of the scope of this study, it is challenging to estimate the costs for one winter storm due to unavailability of data as it is case specific. However, airport managers may be able to collect this information and use the spreadsheet to examine the economic effects for different frequencies of a winter storm and not only the average seasonal effects.

In addition, the cost estimates for CSRS in this study was largely dictated by the area considered. It is challenging to break down the specific amount of SRE, labor, and deicing salts for specific areas. Nonetheless, airport managers may have this information or they may observe it during snow-clearing operations. This information can then be used in the spreadsheet to discern the exact economic impacts. Also, the number of weather-related delays was extracted from the BTS website [18]. Such statistics may be more accurate if they are maintained by the airport managers.

In addition, due to limited availability of data, the potential rise in the number of operations after installing HPS (i.e., induced demand) have not been considered in the analysis. These costs may further magnify the expected benefits. Nevertheless, it is believed that HPS will be able to reduce delays and improve the efficiency of daily aircraft operations, thereby having a direct effect on the revenue.

Furthermore, as discussed in the section 4.2.3, this report did not consider costs due to cargo delays, because they were not found to be significant factors in the airports studied. Nevertheless, each airport has different policies dealing with cargo, and the frequency of cargo movement varies with each airport. It is arduous to collect information on cargo delays. Airports usually do not have such information; it can only be obtained by the cargo carriers. Another factor to consider is belly cargo, which is the cargo transported in the passenger flights. Although the amount of belly cargo is significantly less than the normal cargo, it may be considered. Smaller airports with no dedicated cargo carriers may rely on passenger flights to transfer cargo. This data could be collected by contacting the concerned air carriers, but they may be apprehensive to publish such data. Usually, larger airports handle more cargo, which is either transferred to other states and countries or routed to smaller airports in the states. On a case-by-case situation, and upon discussion with the cargo carriers, it would be beneficial to consider the cost of cargo delays, especially for larger airports like MSP, to show the feasibility of installing HPS.

Finally, the justification for the use of HPS in aprons has been established in this report. Nevertheless, some airports may benefit from heating portions of the airports apart from the aprons. Thus, it is crucial to examine the relative benefits and costs of heating other pavement areas such as runways and taxiways. In any case, it is recommended that the installation of HPS in other such areas would be in addition to the aprons. The methodology described in section 3 can be adapted to explore the financial viability of installing HPS in the total paved area of an airport.

9.2.2 Future Research.

This study aims to serve as a guide for airport managers to use to investigate the feasibility of installing HPS. The spreadsheet accompanying this report can be used to examine any airport by changing the input values. This study focuses on the use of HPS at aprons because that is where they would have the maximum benefits. However, with the advancement in technology, HPS may be used cost effectively at other locations as well. MSP was used as an example to illustrate the methodology and economic outcomes that can be used to assess the viability of heating other areas of an airport as well.

Along the same line, this report only estimated the economic impact of installing HPS for domestic flights, as certain airports in the study do not cater to international flights. International delays are complicated to estimate due to their routing and knowledge of the delay. Such delays may be considered in future studies.

Advancements in HPS technology and construction practices may have the potential to significantly reduce the construction costs. This may make the cost of HPS comparable to CSRS. Use of innovative substances, such as phase change materials (PCM) or conductive concrete, alongside HPS may increase the efficiency of HPS and reduce the operational costs.

9.3 RECOMMENDATIONS.

There has been an attempt to study the energy and economic effects of using an alternative snow-removal system for airports. HPS have the capability to provide enhanced safety for ground staff, chemicals, and vehicles; reduce the labor of snow and slush removal; and create better working conditions at the airport. However, a major challenge involved with HPS is to reduce the high installation costs. Realistic assumptions have been made to estimate these costs due to the absence of full-scale HPS in the U.S. In view of this, the following recommendations have been proposed:

- This study, which quantified soft costs and hard costs of installing HPS, provides airport authorities with a more informed choice in selecting a snow-removal system for their airports.

- Advancements in HPS technology and construction practices are expected to reduce the installation cost, making them comparable to cost of CSRS.

- Disruption in the proper functioning of HPS may occur due to problems in the heat generation or distribution system. Therefore, airports may have to substitute snow removal by SRE. Costs related to this may be researched in future studies.

- Operation costs can be reduced by judicious use of HPS and appropriate weather monitoring, giving the slab enough time to heat just before the onset of a snow event.

- As all aprons are not used simultaneously, the capacity of the boiler system may be reduced, which would lower the initial costs.

- During medical emergencies or natural calamities at odd hours, keeping the GA airports accessible would be indispensable, emphasizing the provision of HPS at GA airports.

- Indirect costs, such as increase in the number of daily aircraft operations, may also be considered as a benefit in the commercial airports. The actual number of injuries that occur at aprons collected by airports during snow-removal operations could provide a more accurate estimate of the indirect benefits of installing HPS.

- Future analysis may include opportunity cost of installing HHPS to reflect other avenues of airport improvement.

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APPENDIX A—AIRPORT QUESTIONNAIRE

General Operations

1. What is the number of enplanements in a year?

2. Could you give the number of enplanements for different airlines using your airport? Do any of these airlines avoid using your airport in the winter months?

3. What is the annual cargo handling capacity?

4. How many operational runways does the airport have?

5. How many runways are open during snow storms? How does this effect on-time performance & schedules?

6. In case a flight is delayed or cancelled due to weather related events, would the airport cover any (or all) of the airline (aircraft) expenses related to the delay (such as cost of fuel, cost of crew, compensation to passengers If yes, how much and in what form?

7. Do you have any plans to extend, repair or renovate the existing runways in the next few years?

Pavement Deicing

1. What is the time taken to clear a primary taxiway and apron area?

2. What is the extent of damage on the pavements caused by snow or snow removal operations? How much do you spend on pavement maintenance annually?

3. What types of pavement deicers do you use?

Pavement Area

1. What is the area of the primary taxiway and apron?

2. What is the total area of the paved surfaces at the airport?

3. What is the total area of the paved surfaces typically deiced during winter operations?

Equipment Required for Clearing Snow

1. What is the current state of snow and ice removal practice?

2. What are the issues encountered in the current state of practice?

3. Typically, what is the number of equipment required to clear a primary taxiway, apron area and the entire paved surface, respectively, when an average snow fall of 10 inches per day occurs? Could you also please name them?

Initial Costs

1. What was the construction cost of the primary taxiway and apron and in what was the construction year?

2. What was the initial cost incurred on the purchase of the snow-removal equipment (and the purchase year)? Could you please specify the cost of each equipment separately?

3. Generally, what is the time period after which you replace the equipment with new ones?

Recurring Costs

1. What is the annual maintenance cost of the snow-removal equipment? Could you please specify it as a percentage relative to the initial cost of equipment?

2. How much is the fuel cost spent on running the snow-removal equipment to clear a primary taxiway and ramp area and in total for the entire airport?

3. How many personnel are required to aid in clearing a primary taxiway and apron area and in total for the entire airport?

4. What is the labor rate (per hour per person) to run this equipment that aid in snow-removal operations?

5. What is the application rate of the deicers you use?

6. What is the quantity of deicing agents required to clear the primary taxiway, apron and the entire paved surface? How much do you spend on these approximately?

Delays

1. What is the average number of delays faced at the airport per year?

2. What percentage of outbound flights out of the total operations are delayed and cancelled during the winter months?

3. Could you categorize and provide an approximate percentage of the number of outbound flights being delayed due to each of the causes like runway closure, heavy winds, low visibility or any other cause?

4. Could you give an approximate value as to how much these delays (closing of runways due to extreme snow) would cost you per annum?

5. How does severe weather affect cargo operations at your airport? Could you give an approximate value as to how much cargo delays (due to extreme snow) would cost you per annum?

Safety Issues

1. Any accidents or fatalities caused to the personnel aiding in snow removal and cargo handling by exposure to winter weather conditions and snow-removal operations?

2. Are there any known costs related to work related accidents? Who is responsible for it? What is the airport policy to deal with such accidents?

3. Any aircraft accidents reported in the last 20 years due to icy pavements?

4. If yes, how severe was the accident? How much was the cost of repair or compensation and who was responsible for paying for it?

Heating Facility

1. Is the airport currently using a geothermal or hydronic heating system to heat pavements, terminal building or parking area to clear ice/snow (could also you provide the name of the construction contractor)?

2. If yes, what are the installation and operation costs?

3. What is the capacity of the system?

4. What is the energy demand per hour?

APPENDIX B—AIRPORT QUESTIONNAIRE SUMMARY

Table B-1 is a compilation of questionnaire responses for the following airports: Minneapolis-St. Paul International Airport (MSP), John Glen Columbus International Airport (CMH), Des Moines International Airport (DSM), Mason City Municipal Airport (MCW), and Kent State University Airport (1G3).

Table B-1. Questionnaire Responses

Category	MSP	CMH	DSM	MCW	1G3
General Operations	360 aircraft daily operation	360 aircraft daily operation	220 aircraft daily operation	4 aircraft daily operation	Used only for flight training
Pavement Deicing	225,000 gallons of potassium and sodium acetate used annually	75,000 gallons of potassium and sodium acetate used annually	67,000 gallons of potassium and sodium acetate used annually	No information	No information
Pavement Area	Apron- 5 million ft^2; entire airport 28 million ft^2	Apron- 2.2 million ft^2; entire airport 9.4 million ft^2	Apron- 1.5 million ft^2	Apron- 600,000 ft^2; entire airport 3 million ft^2	Apron- 150,000 ft^2; entire airport 641,680 ft^2
Snow-Removal Equipment (SRE) and Personnel	Overall annual value provided only; more than 100 pieces of SRE with cost information; 110 laborers	More than 22 pieces of SRE; 28 workers	About 17 pieces of SRE; 16-22 workers	About 5 pieces of SRE; 7 laborers	About 5 pieces of SRE
Recurring Costs	SRE maintenance is 600,000 USD; hourly labor rate is 75 USD	SRE maintenance is 320,000 USD hourly labor rate is 55-80 USD	SRE fuel 180,000 USD; annual repair and maintenance (R&M) cost 230,000 USD; annual labor rate is 55-80 USD	Hourly labor rate is 75 USD	Annual R&M cost 10,000 USD; hourly labor rate is 75 USD
Injury Incidents of Ground Staff	Mentioned there are cases of injuries	No information	Mentioned there are cases of injuries	No information	No information
Delays	Usually airports do not track delays	Usually airports do not track delays	Usually airports do not track delays	Usually airports do not track delays	Usually airports do not track delays

APPENDIX C—ENERGY REQUIREMENTS FOR HYDRONIC HEATED PAVEMENT SYSTEMS

The sensible heat (q_s) to bring the snow to 32°F is:
$q_s = s\ c_{p\ snow}\ D\ (32 - t_a)\ /\ c_1$

where:
s = rate of snowfall (inches of water equivalent per hour)
$c_{p\ snow}$ = specific heat of snow (0.5 Btu/lb/°F)
D = density of water equivalent of snow (62.4 lb/ft^3)
t_a = air temperature (°F)
c_1 = conversion factor (12 in./ft)

The heat of fusion (q_m) to melt the snow is:
$q_m = s\ h_f\ D\ /\ c_1$

where:
h_f = heat of fusion for water (143.5 Btu/lb)

The heat of evaporation q_e is:
$q_e = P_{dry\_air}\ h_m(W_{f} \text{-} W_a)h_{fg}$

where:
P_{dry_air} = density of dry air (lb/ft^3)
h_m = mass transfer coefficient, concrete slab (ft/h)
W_f = humidity ratio of saturated air at film surface temperature @ 33°F
W_a = humidity ratio of ambient air @ 20°F
h_{fg} = heat of evaporation at the film temperature @ 33°F (Btu/lb)

The heat transfer q_h:
$q_h = h_c(t_{-}t_a) + \sigma\varepsilon_s(T^4{}_f - T^4{}_{MR})$

where:
h_c = convection heat transfer coefficient for turbulent flow (Btu/h·ft^2·°F)
t_f = liquid film temperature, (°F) usually accepted as 33
t_a = ambient air temperature coincident with snowfall (°F)
σ = Stephan-Boltzmann constant (Btu/h·ft^2·°F4)
ε_s = emittance of wet slab
T_{MRTf} = liquid film temperature (°F)
T_{MRT} = mean radiant temperature of surroundings (°F)

APPENDIX D—COST AND BENEFIT CALCULATIONS FOR APRON ONLY

D.1 COST CALCULATIONS FOR THE APRON AT MINNEAPOLIS-ST. PAUL INTERNATIONAL AIRPORT.

Section D.1 provides cost and benefit calculations for the apron at Minneapolis-St. Paul International Airport (MSP) as the representative of commercial airports.

CSRS: Initial Cost Calculations

- Cost of snow-removal equipment (SRE) is a function of the area
- Area of the total apron and gate = 5 million ft^2
- Area of the total paved surface = 28 million ft^2
- Ratio of the areas = 5 ÷28 = 0.179
- Fraction of cost for apron and gate = 45,569,920 × 0.179 = 8,137,800 USD

CSRS: Recurring Cost Calculations

- Deicing agents
  - Cost of potassium acetate = 933,750 USD
  - Cost of sodium acetate = 675,000 USD
- Labor cost
  - No. of personnel = 110
  - Cost of labor per person per hour = 25.6 USD
  - Labor hours = 600
  - Total labor cost =110 × 75 × 600 = 4,950,000 USD
- Fuel cost for SRE = 814,800 USD
- Maintenance cost for SRE = 600,000 USD
- Total annual recurring cost for entire paved surfaces = 933,750 + 675,000 +4,950,000+ 814,800 + 600,000 = 8,375,577 USD
- Total annual recurring cost for considered area = 8,375,577 USD × 0.179 = 1,423,848 USD

Hydronic Heated Pavement Systems (HHPS) Cost Calculations: Initial Cost

- Cost of installation of (HHPS) = 35 USD/ft^2 [D-1 and D-2]
- Area = 5 million ft^2
- Total installation cost = 35 × 5,000,000 = 175,000,000 USD

HHPS Cost Calculations: Recurring Cost

- No. of operations in 1 day = 1,200
- No. of operations in 4 months = 144,000
- 2% of flights are delayed in MSP due to winter weather [D-3]
- One winter season (year) is assumed to be approximately 4 months
- Delays in 4 months = 2,880 (2% × 144,000)
- Assuming each delay is 57 minutes (approximately one hour)
- Benefit from prevent delay costs (fuel and crew costs)
- The average total direct operating costs for the applicable aircraft type can be used to quantify the runway closure delay costs to airlines, aircraft owners, and the passengers
- Variable aircraft direct operating costs: [D-4]
  - Midair = 4,960 USD/h
  - Ground = 2,148 USD/h
  - Gate = 1,443 USD/h
  - Assuming equal no. of all 3 delays; combined value = 2,850 USD/h
  - Delays in 4 months = 2,850 × 2,880 = 8,208,000 USD/yr
- Benefit from prevent delay costs (passenger costs)
  - No. of passengers traveling for leisure = 72 (80.6% × 150 × 59.6%)
  - No. of passengers traveling for business = 49 (80.6% × 150 × 59.6%)
  - Value of lost time for leisure travelers = 72 × 35 × 2,880/yr = 7,257,600 USD/yr
  - Value of lost time for business travelers = 49 × 63 × 2,880/yr = 8,890,560 USD/yr

D.2 COST AND BENEFIT CALCULATIONS FOR THE APRON AT MASON CITY AIRPORT (MCW).

Section D.2 provides cost and benefit calculations for the apron at Mason City Airport (MCW) as the representative of GA airports.

CSRS: Initial Cost Calculations

- Cost of SRE is a function of the area
- Area of the total apron and gate = 600,000 ft^2

- Area of the total paved surface = 3 million ft^2
- Ratio of the areas = 0.6 ÷ 3 = 0.2
- Fraction of cost for apron and gate = 2,425,000 USD × 0.2 = 485,000 USD

CSRS: Recurring Cost Calculations

- Labor cost
  - No. of personnel = 7
  - Cost of labor per person per hour = 75 USD
  - Labor hours = 600
  - Total labor cost =7 × 75 × 600 = 315,000 USD

- Fuel cost for SRE = 42,000 USD

- Maintenance cost for SRE = 40,000 USD

- Total annual recurring cost for entire paved surfaces = 315,000 +42,000 + 40,000= 397,000 USD

- Total annual recurring cost for considered area = 397,000 USD × 0.2 = 79,400 USD

Hydronic Heated Pavement Systems (HHPS) Cost Calculations: Initial Cost

- Cost of installation of (HHPS) = 35 USD/ft^2 [D-1 and D-2]
- Area = 600,000 million ft^2
- Total installation cost = 35 × 600,000 = 21,000,000 USD

HHPS Benefit Calculations:

- No. of operations in 1 day = 4

- No. of operations in 4 months = 480

- 3% of flights are delayed in MSP due to winter weather [D-3]

- One winter season (year) is assumed to be approximately 4 months.

- Delays in 4 months = 14 (3% × 480)

- Each delay is assumed to be approximately one hour.

- The average total direct operating costs for the applicable aircraft type can be used to quantify the runway closure delay costs to airlines, aircraft owners, and the passengers.

- Benefit from prevent delay costs (fuel and crew costs) : [D-4]

  - Midair = 4,456 USD/h
  - Ground = 2,148 USD/h
  - Gate = 1,443 USD/h
  - Assuming equal no. of all 3 delays; combined value = 2,682 USD/h
  - Value of lost fuel and crew = 2,682 × 14 = 38,626 USD/yr

- Benefit from prevent delay costs (passenger costs)
  - No. of passengers traveling for leisure = 4.03 (84.59% × 8 × 59.6%)
  - No. of passengers traveling for business = 2.73 (84.59% × 8 × 40.4%)
  - Value of lost time for leisure travelers = 4.03 × 36.1 × 14/yr = 2,096 USD/yr
  - Value of lost time for business travelers = 2.73 × 65 × 14/yr = 2,488 USD/yr

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APPENDIX E—USER MANUAL FOR THE ECONOMIC ANALYSIS SPREADSHEET

E.1 INTRODUCTION.

Spraying large quantities of anti-ice chemicals on the ground and deploying a great number of snow plowing vehicles are common practices for removing ice and snow from transportation infrastructure surfaces. However, these methods are labor intensive and have environmental impacts for highway and airport pavements, as well as possible contamination of nearby bodies of water. Heated pavement systems (HPS), including both hydronic heated pavement systems (HHPS) and electrically heated pavement systems (EHPS), are practical and economically sensible alternatives to current ice and snow-removal practices for airport pavements frequently impacted by winter weather.

Alternate snow-removal strategies, such as HPS, may have the potential to keep airports operational during severe cold weather. The estimation of potential costs and benefits related to this alternative snow-removal method are discussed in this report. The description and documentation of an economic analysis tool developed specifically to serve as a guide to airport managers is the focus of this research. Ideally, the airports can use this tool for examining the feasibility of HPS for application on any airport paved area, (not only in the aprons). This spreadsheet can be tailored by using airport-specific data from commercial and general aviation (GA) airports.

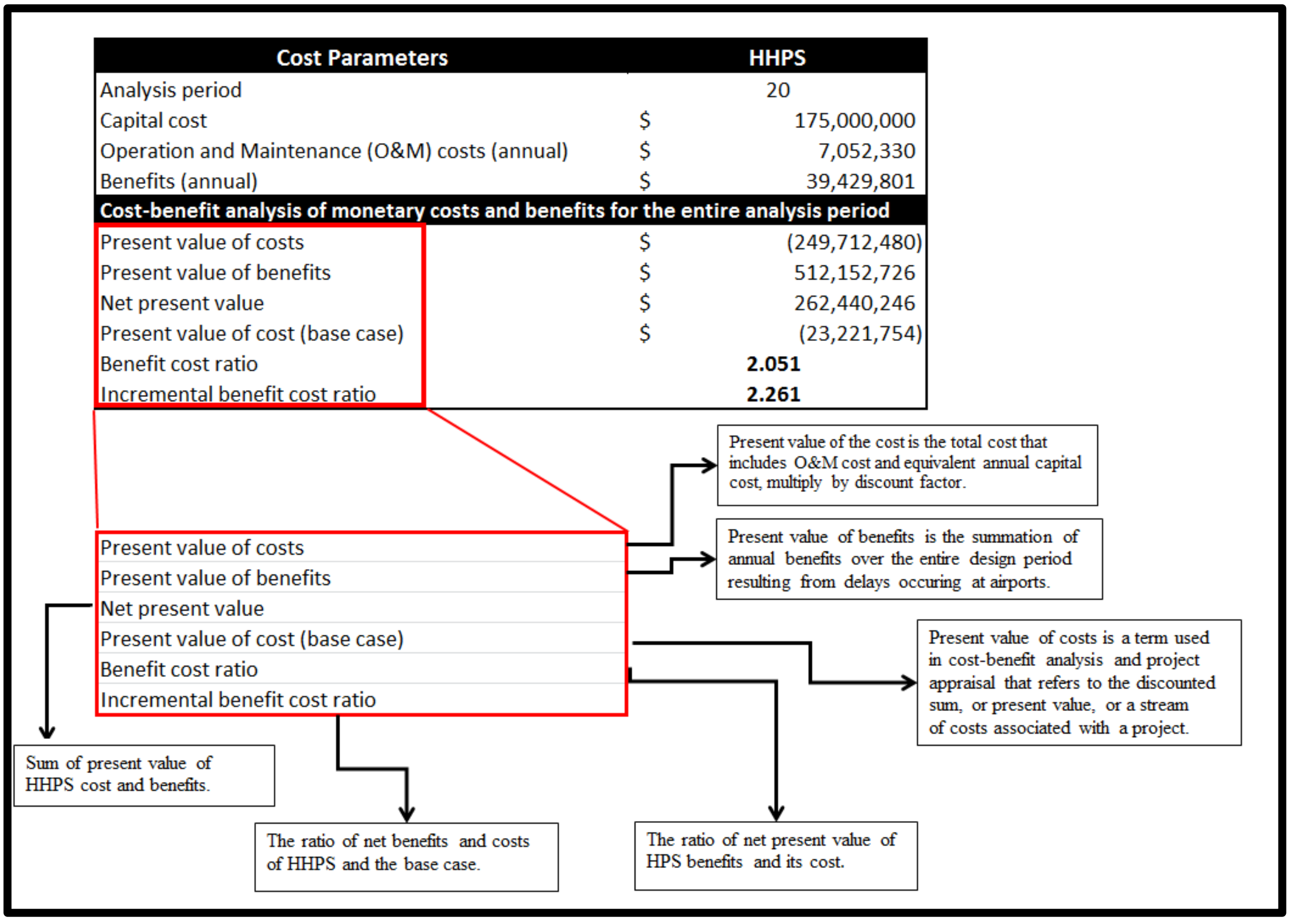
Airport managers can use this spreadsheet to calculate their benefit cost ratio (BCR) based on the HPS they want to deploy. The tool also allows the airport managers to predict the future cost associated with the implementation of such strategies by varying factors that could cause uncertainties. For example, values for Minneapolis-St. Paul International Airport (MSP) were used for HHPS implementations in figures E-1 through E-11. Data can be easily modified depending on the airport's HPS requirements.

E.2 SPREADSHEET 1—SUMMARY.

The summary is the first page of the spreadsheet, and it consists of two main tables, shown in figures E-1 and E-2, respectively.

The condensed analysis results, shown in figure E-1, presents the capital cost required to install HHPS for a given area and the summed value of annual costs and benefits incurred with the use of the HHPS selected. It then compares the net benefit and cost for a period of 20 years to show the BCR. A comparison is also drawn between HHPS and CSRS by means of an incremental BCR. The definitions and equations to calculate BCRs can be found in the report (section 3.5.2).

If any input value changes in figure E-2, the new results are reflected in figure E-1. Generally used for a public project, the purpose of benefit cost analysis (BCA) is to compare the benefits and costs associated with a policy or investment. If the ratio of the sum of the net benefits of a project or policy and the costs exceed 1, then the project is deemed feasible. The analysis period value for reviewing HHPS benefits can be changed. In this chart, the analysis period is 20 years. The discount factor is also listed, and 7% is used as a base value to analyze the net present value (NPV).



Cost Parameters		HHPS
Analysis period		20
Capital cost	$	175,000,000
Operation and Maintenance (O&M) costs (annual)	$	7,052,330
Benefits (annual)	$	39,429,801
Cost-benefit analysis of monetary costs and benefits for the entire analysis period		
Present value of costs	$	(249,712,480)
Present value of benefits	$	512,152,726
Net present value	$	262,440,246
Present value of cost (base case)	$	(23,221,754)
Benefit cost ratio		**2.051**
Incremental benefit cost ratio		**2.261**

Present value of the cost is the total cost that includes O&M cost and equivalent annual capital cost, multiply by discount factor.

Present value of benefits is the summation of annual benefits over the entire design period resulting from delays occuring at airports.

Present value of costs is a term used in cost-benefit analysis and project appraisal that refers to the discounted sum, or present value, or a stream of costs associated with a project.

Sum of present value of HHPS cost and benefits.

The ratio of net benefits and costs of HHPS and the base case.

The ratio of net present value of HPS benefits and its cost.

O&M = Operation and maintenance

Figure E-1. Summary Table From Sheet 1 “Summary” of the Economic Analysis Tool

E.2.1 Basic Input Parameters.

The red numbers in figure E-2 are the values that may be changed specific to each airport. The feasibility results shown in figure E-1 will be updated automatically once any changes are made. However, the black numbers are suggested values that act as a reference that may be changed depending upon the airport. The purple numbers are fixed values that cannot be changed. Lastly, the blue numbers depict the calculation after the red input values are entered.

E.2.1.1 Common Input Values.

The common input values include the basic values that are used to conduct the economic analysis such as analysis period, discount factor, and area of HHPS installation.

E.2.1.2 Cost of CSRS.

CSRS consist of both mechanical and chemical methods. The CSRS costs consist of snow-removal equipment (SRE), deicing agents, labor cost per hour, and SRE fuel cost.

Equipment costs cannot be changed through figure E-2, but may be altered using sheet 5 – "CSRS Cost." This was created to facilitate ease of use of the spreadsheet as the purchasing cost of equipment will not vary much between different airports.

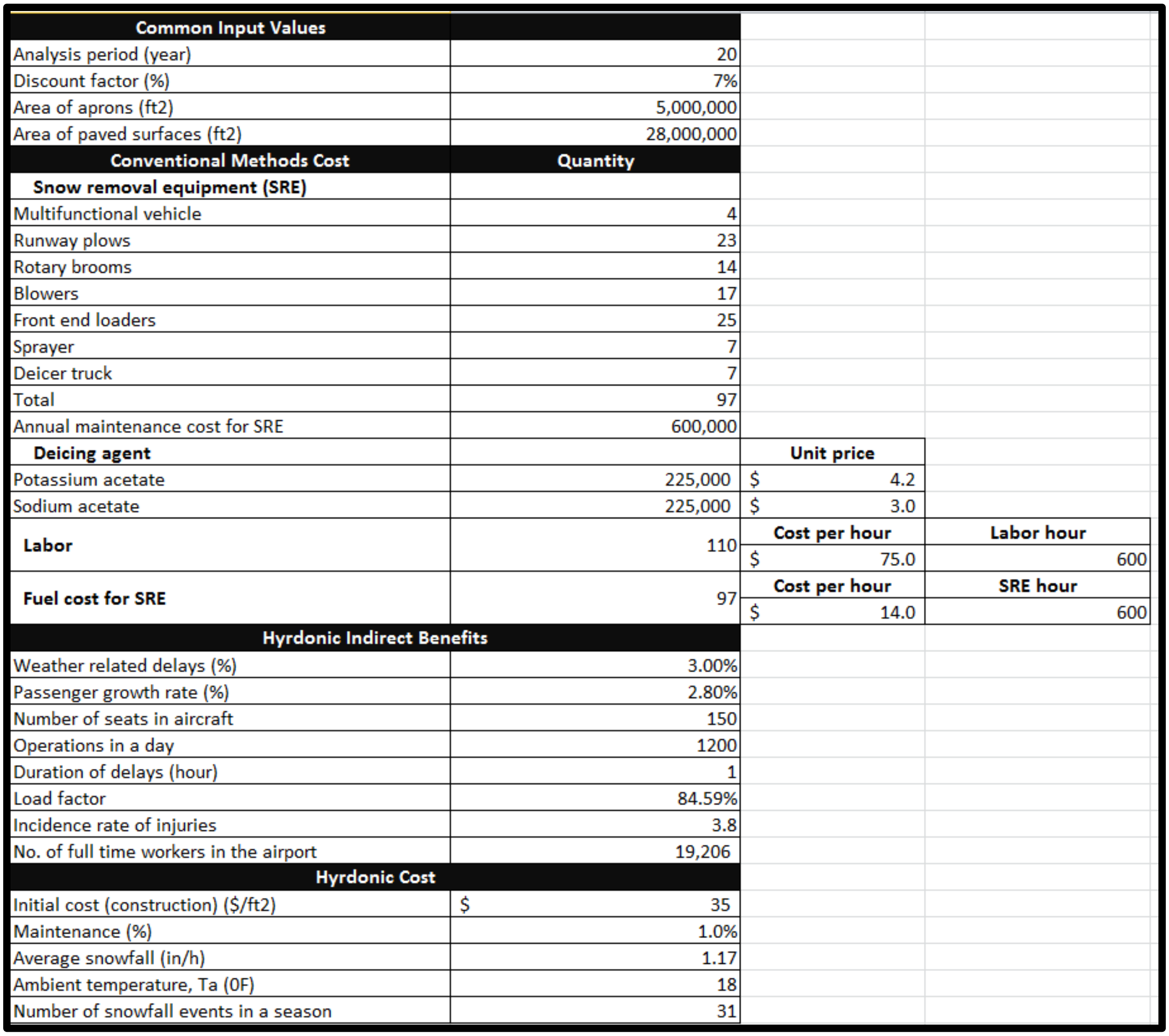
E.2.1.3 Indirect Benefits of HHPS.

Indirect benefits for HHPS are the costs that are not directly accountable to a cost object and can be either fixed or variable. The inputs are:

- duration of delayed flights,
- number of seats in the aircraft,
- number of operations per day,
- load factor, and
- injury data.

E.2.1.4 Cost of HHPS.

The HHPS costs include the initial construction cost and the operation and maintenance (O&M) costs.



Common Input Values			
Analysis period (year)	20		
Discount factor (%)	7%		
Area of aprons (ft2)	5,000,000		
Area of paved surfaces (ft2)	28,000,000		
Conventional Methods Cost	**Quantity**		
Snow removal equipment (SRE)			
Multifunctional vehicle	4		
Runway plows	23		
Rotary brooms	14		
Blowers	17		
Front end loaders	25		
Sprayer	7		
Deicer truck	7		
Total	97		
Annual maintenance cost for SRE	600,000		
Deicing agent		**Unit price**	
Potassium acetate	225,000	$ 4.2	
Sodium acetate	225,000	$ 3.0	
Labor	110	**Cost per hour**	**Labor hour**
		$ 75.0	600
Fuel cost for SRE	97	**Cost per hour**	**SRE hour**
		$ 14.0	600
Hyrdonic Indirect Benefits			
Weather related delays (%)	3.00%		
Passenger growth rate (%)	2.80%		
Number of seats in aircraft	150		
Operations in a day	1200		
Duration of delays (hour)	1		
Load factor	84.59%		
Incidence rate of injuries	3.8		
No. of full time workers in the airport	19,206		
Hyrdonic Cost			
Initial cost (construction) ($/ft2)	$ 35		
Maintenance (%)	1.0%		
Average snowfall (in/h)	1.17		
Ambient temperature, Ta (0F)	18		
Number of snowfall events in a season	31		

Figure E-2. Basic Input Parameters From Sheet 1 "Summary" of the Economic Analysis Tool

E.2.2 SPREADSHEET 2—HHPS INDIRECT BENEFITS.

This section details the estimation of benefits related to the installation of HHPS. The benefits are due to passenger time savings, reduced fuel wastage and loss of crew time, and enhanced safety of ground staff.

E.2.2.1 Value of Lost Passenger Time.

The following are the requirements to calculate the value of lost passenger time:

- Determine the seasonal percentage of delays.

- The percentage of weather-related delays is assumed to be 2% of total number of operations.

- Four months (November-February) in a year are considered.

- By knowing the daily number of operations, operations for four months was calculated.

- The value of time (VOT) is 63.2 USD/h for business passengers and 36.1 USD/h for leisure passengers.

- Total number of passengers that fly for business purposes is 40.40% and 59.60% are leisure travelers.

- Total number of seats in a mid-sized aircraft is about 150, and the average overall load factor for domestic flights was 83.38%.

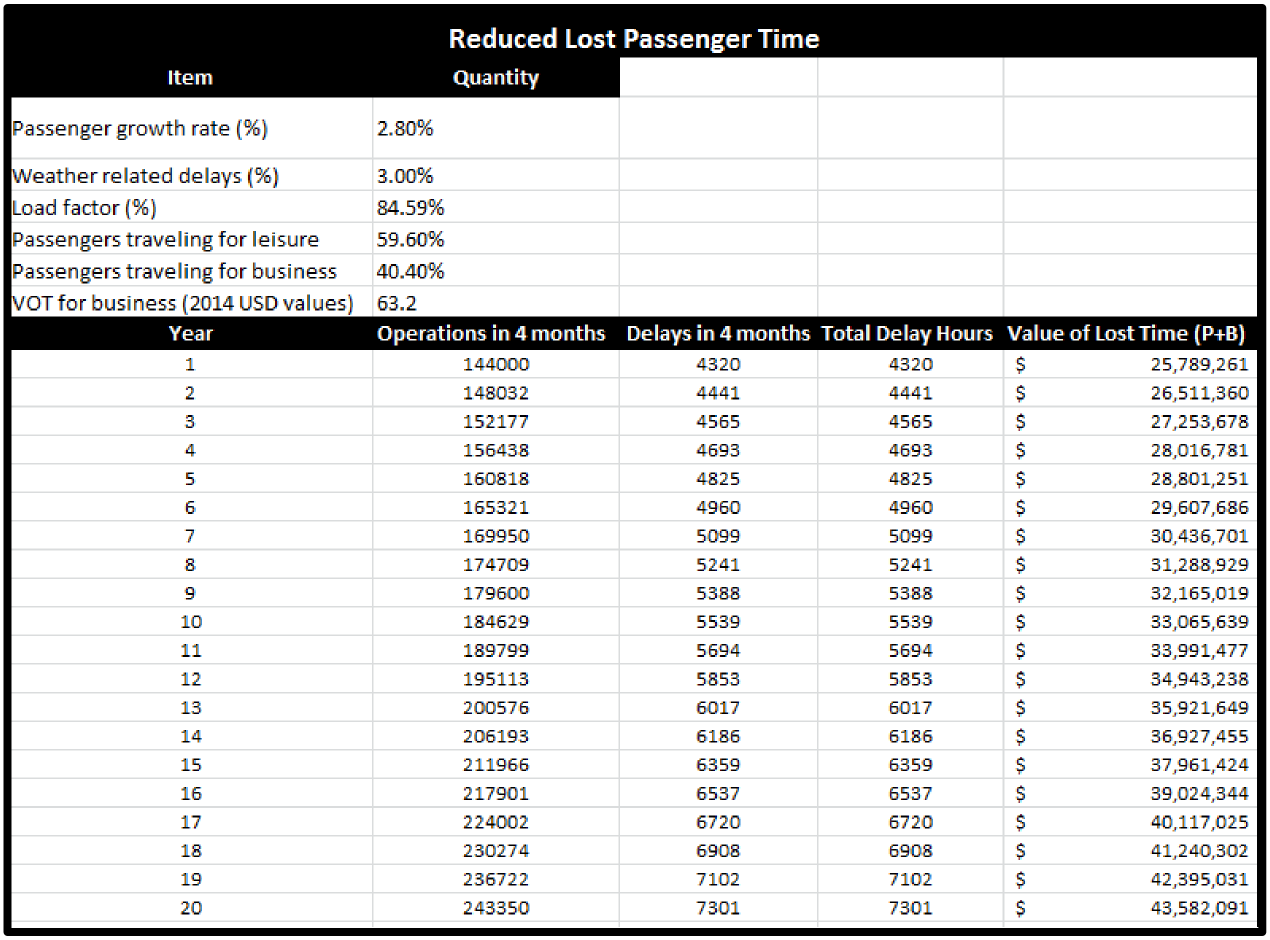
- The number of occupied seats was determined by multiplying the number of seats in aircraft with the average load factor.

- The value of lost time was calculated by multiplying the total number of passengers (each case) by the VOT and the number of delays in four months.

The above steps are summarized by means of equations 1 and 2, and are shown in figure E-3.

Total delay hours in a season = No. of daily operations ×30 (days) × 4 (months) × 2% of snow-related delays × Passenger growth rate × Average duration of one delay (hours) (1)

Annual monetary value of lost passenger time = (Total no. of seats in an aircraft × Load factor × Total delay hours in a season) × [(Percentage of passengers traveling for leisure × VOT for leisure) + (Percentage of passengers traveling for business × VOT for business)] (2)



Reduced Lost Passenger Time

Item	Quantity			
Passenger growth rate (%)	2.80%			
Weather related delays (%)	3.00%			
Load factor (%)	84.59%			
Passengers traveling for leisure	59.60%			
Passengers traveling for business	40.40%			
VOT for business (2014 USD values)	63.2			
Year	**Operations in 4 months**	**Delays in 4 months**	**Total Delay Hours**	**Value of Lost Time (P+B)**
1	144000	4320	4320	$ 25,789,261
2	148032	4441	4441	$ 26,511,360
3	152177	4565	4565	$ 27,253,678
4	156438	4693	4693	$ 28,016,781
5	160818	4825	4825	$ 28,801,251
6	165321	4960	4960	$ 29,607,686
7	169950	5099	5099	$ 30,436,701
8	174709	5241	5241	$ 31,288,929
9	179600	5388	5388	$ 32,165,019
10	184629	5539	5539	$ 33,065,639
11	189799	5694	5694	$ 33,991,477
12	195113	5853	5853	$ 34,943,238
13	200576	6017	6017	$ 35,921,649
14	206193	6186	6186	$ 36,927,455
15	211966	6359	6359	$ 37,961,424
16	217901	6537	6537	$ 39,024,344
17	224002	6720	6720	$ 40,117,025
18	230274	6908	6908	$ 41,240,302
19	236722	7102	7102	$ 42,395,031
20	243350	7301	7301	$ 43,582,091

Figure E-3. Calculating Value of Lost Passenger Time From Sheet 2 "HPS Indirect Benefits" of the Economic Analysis Tool

E.2.2.2 Fuel and Crew Costs.

The cost of annual additional aircraft operating cost can be calculated using equation 3 and is shown in figure E-4.

Annual additional aircraft operating cost due to delays = *Total delay hours in a season* × *Operating cost of aircrafts (mid, ground, and gate delays)* (3)

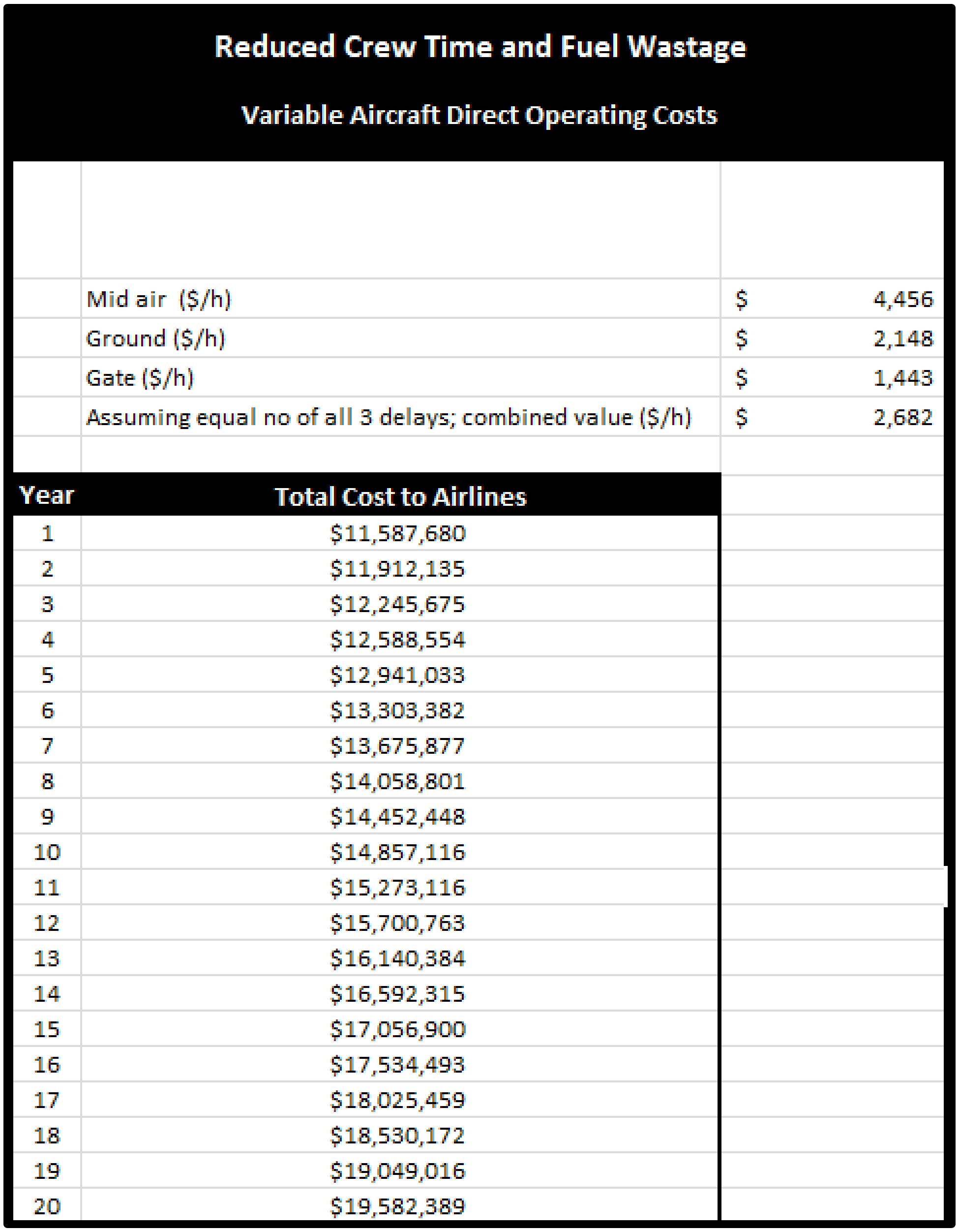
Equation 3 is based on the following.

- Aircraft can have delays in three possible ways: mid-air, gate, and ground delays.

- The mid-air delays will have the most amount of fuel wastage while the others will draw only idling fuel wastages.

- Mid-air delays are assigned a value of 4960 USD/h, ground delays as 2148 USD/h, and gate delays as 1442 USD/h according to the Airport Cooperative Research Program (ACRP) Report 123 “A Guidebook for Airport Winter Operations.” [E-1]

- If all the delays were in equal proportion, this gave an average value of 2850 USD/h suffered by airlines in weather delays. Annual (four months) cost to airlines due to weather-related delays can be computed by multiplying 2850 USD/h by the total number of operations.



Reduced Crew Time and Fuel Wastage

Variable Aircraft Direct Operating Costs

Mid air ($/h)	$	4,456
Ground ($/h)	$	2,148
Gate ($/h)	$	1,443
Assuming equal no of all 3 delays; combined value ($/h)	$	2,682

Year	Total Cost to Airlines
1	$11,587,680
2	$11,912,135
3	$12,245,675
4	$12,588,554
5	$12,941,033
6	$13,303,382
7	$13,675,877
8	$14,058,801
9	$14,452,448
10	$14,857,116
11	$15,273,116
12	$15,700,763
13	$16,140,384
14	$16,592,315
15	$17,056,900
16	$17,534,493
17	$18,025,459
18	$18,530,172
19	$19,049,016
20	$19,582,389

Figure E-4. Calculating Fuel and Crew Costs From Sheet 2 “HPS Indirect Benefits” of the Economic Analysis Tool

E.2.2.3 Enhanced Safety.

Enhanced safety benefits are calculated based on the following.

- Data for categorizing injuries for this level of detail is not available at the United States (U.S.) Bureau of Labor Statistics (BLS). The available data, as per the BLS report on occupational injuries [E-2], is used and certain assumptions are established to quantify cost due to injuries.

- The ground staff may be employed by the airport or the airlines, and they will be financially responsible for any injuries. It is assumed that slipping and falling will not result in critical and fatal injuries, and hence, are not taken into consideration.

- Only three classes of injuries were assumed: minor, moderate, and serious.

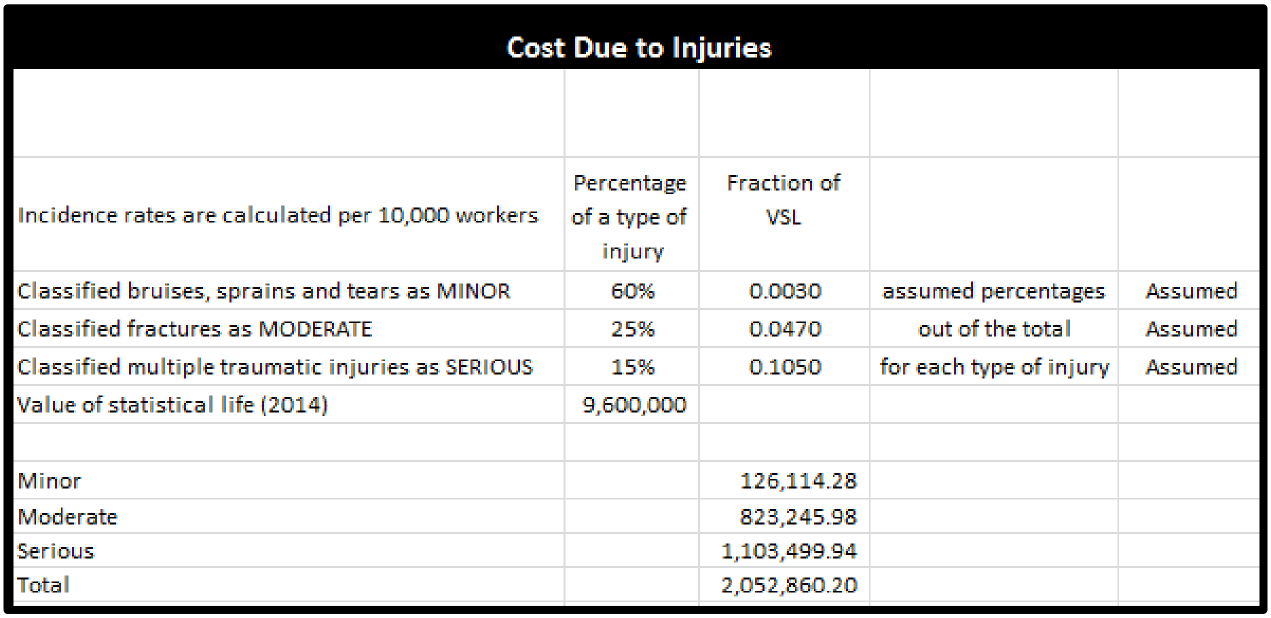
- Bruises and strains were classified as minor, fractures as moderate, and multiple traumatic injuries as serious.

- Minor injuries were assumed to have maximum cases and were assumed as 60% of total injuries. Moderate injuries were assumed as 25% and Serious as 15%.

- Based on the above data, the injury costs were calculated by multiplying the percentage of each injury by its contributing fraction of the value of statistical life (VSL). The VSL is set as 9.6 million USD (2015 USD) [E-3]. Guidance on treatment of the economic VSL in U.S. Department of Transportation analyses. The summed value of all the injury cases for MSP for the concerned four months was calculated.

This can be better explained by equation 4 and figure E-5.

Annual cost due to injuries = Percentage of a type of injury (minor, moderate, serious)
× VSL × Fraction of VSL for injury type × Incidence rate × No. of full time employees (4)



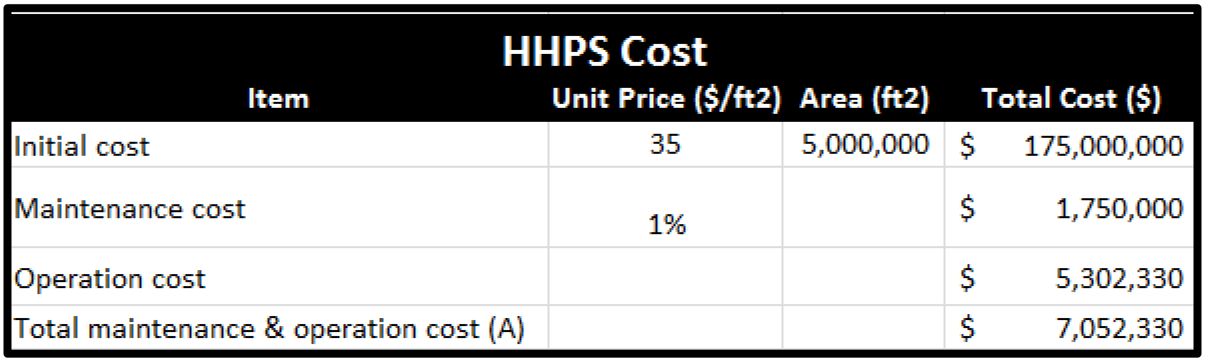
Cost Due to Injuries

Incidence rates are calculated per 10,000 workers	Percentage of a type of injury	Fraction of VSL		
Classified bruises, sprains and tears as MINOR	60%	0.0030	assumed percentages	Assumed
Classified fractures as MODERATE	25%	0.0470	out of the total	Assumed
Classified multiple traumatic injuries as SERIOUS	15%	0.1050	for each type of injury	Assumed
Value of statistical life (2014)	9,600,000			
Minor		126,114.28		
Moderate		823,245.98		
Serious		1,103,499.94		
Total		2,052,860.20		

Figure E-5. Calculating Cost Due to Injuries From Sheet 2 “HPS Indirect Benefits” of the Economic Analysis Tool

E.3 SPREADSHEET 3—HHPS COST.

The initial cost of the HHPS consists of installing the hydronic pipes in or below the pavement along with the heating system facility including control systems. As the installation costs of HHPS would play a crucial role in estimating their economic usefulness, various cost scenarios ranging from 15 USD/ft^2 to 45 USD/ft^2 taking 35 USD/ft^2 as the base value were analyzed. Operation costs consist of the cost of natural gas needed to heat anti-freeze circulating in the pipes and electricity needed to power the control system, as shown in figure E-6.



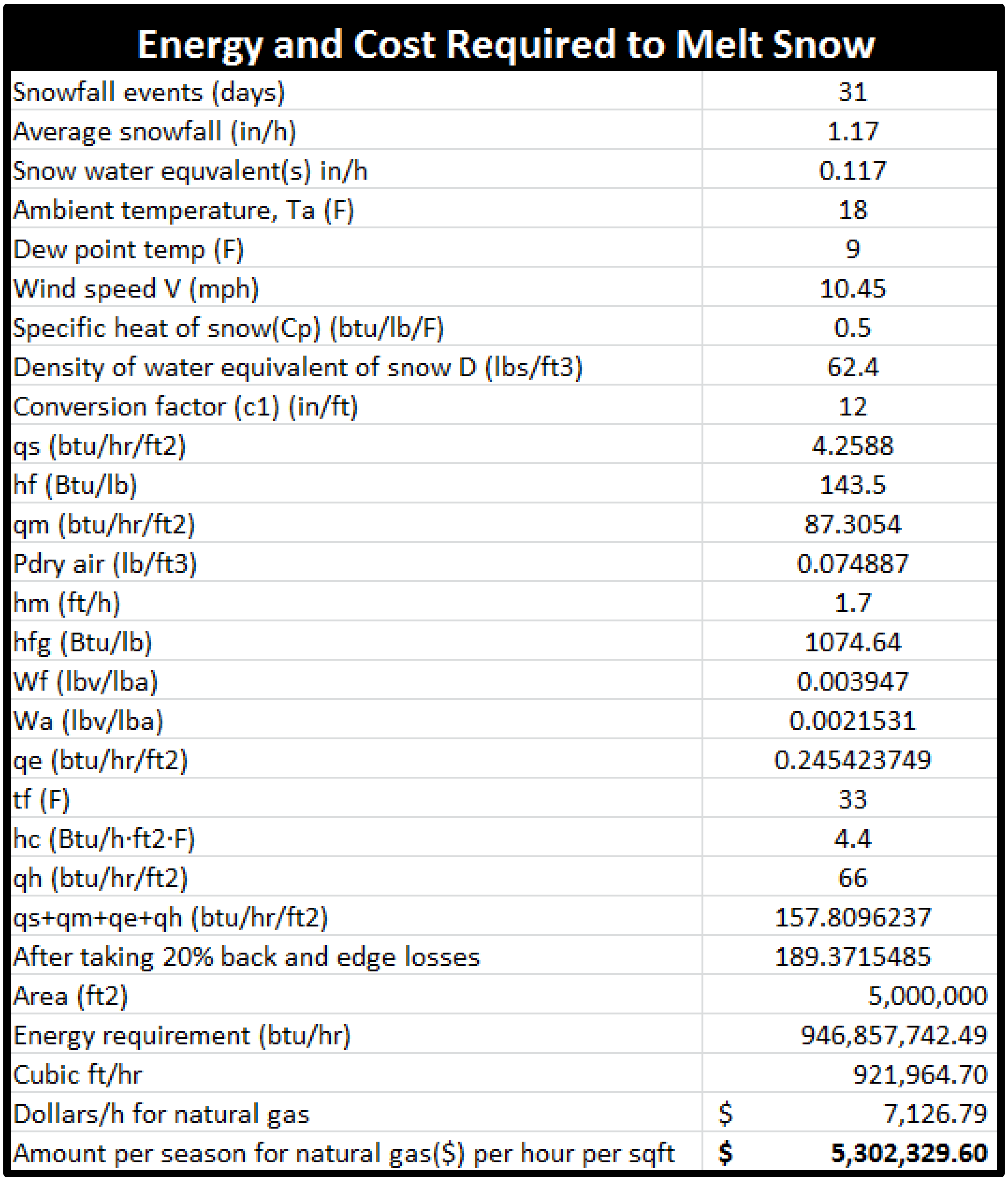
HHPS Cost

Item	Unit Price ($/ft2)	Area (ft2)	Total Cost ($)
Initial cost	35	5,000,000	$ 175,000,000
Maintenance cost	1%		$ 1,750,000
Operation cost			$ 5,302,330
Total maintenance & operation cost (A)			$ 7,052,330

Figure E-6. Calculating Cost of HHPS From Sheet 3 "HHPS Cost" of the Economic Analysis Tool

E.4 SPREADSHEET 4—SNOW MELT CALCULATIONS.

Using the equations provided in the Federal Aviation Administration Advisory Circular (AC) 150/5370-17 [E-1] and the American Society of Heating, Refrigeration and Air-Conditioning Engineers (ASHRAE) Handbook 2003 [E-4], energy to melt snow was calculated. After the energy was calculated for the area under consideration, the cost was calculated by price and amount of natural gas, as shown in figure E-7. To quantify the amount of natural gas needed, the energy required to melt snow or the design heat load was first calculated.



Energy and Cost Required to Melt Snow	
Snowfall events (days)	31
Average snowfall (in/h)	1.17
Snow water equvalent(s) in/h	0.117
Ambient temperature, Ta (F)	18
Dew point temp (F)	9
Wind speed V (mph)	10.45
Specific heat of snow(Cp) (btu/lb/F)	0.5
Density of water equivalent of snow D (lbs/ft3)	62.4
Conversion factor (c1) (in/ft)	12
qs (btu/hr/ft2)	4.2588
hf (Btu/lb)	143.5
qm (btu/hr/ft2)	87.3054
Pdry air (lb/ft3)	0.074887
hm (ft/h)	1.7
hfg (Btu/lb)	1074.64
Wf (lbv/lba)	0.003947
Wa (lbv/lba)	0.0021531
qe (btu/hr/ft2)	0.245423749
tf (F)	33
hc (Btu/h·ft2·F)	4.4
qh (btu/hr/ft2)	66
qs+qm+qe+qh (btu/hr/ft2)	157.8096237
After taking 20% back and edge losses	189.3715485
Area (ft2)	5,000,000
Energy requirement (btu/hr)	946,857,742.49
Cubic ft/hr	921,964.70
Dollars/h for natural gas	$ 7,126.79
Amount per season for natural gas($) per hour per sqft	**$ 5,302,329.60**

Figure E-7. Calculating the Energy and Cost Required to Melt Snow From Sheet 4 "Snow Melt Calculations" of the Economic Analysis Tool

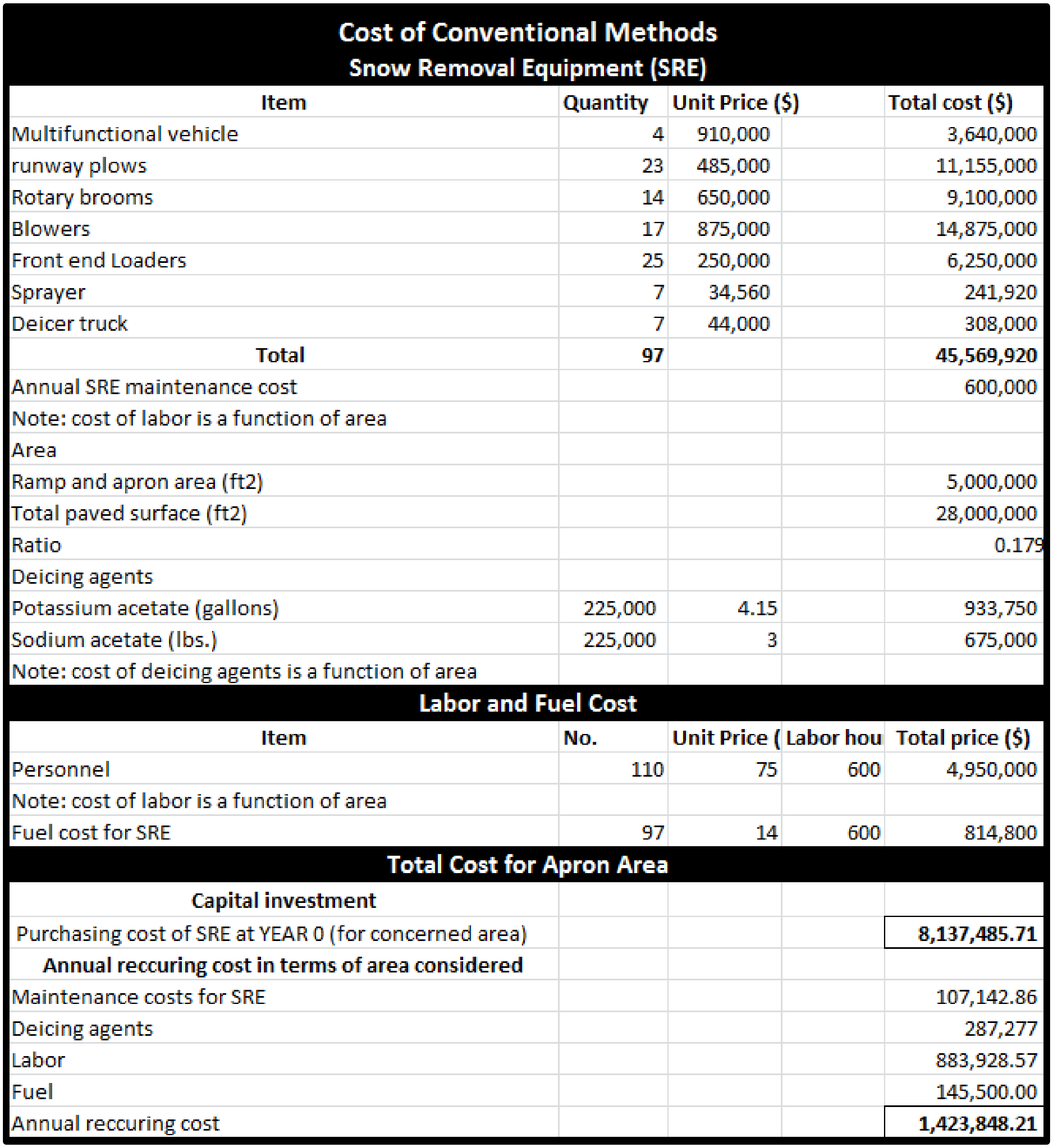
E.5 SPREADSHEET 5—CSRS COST.

The cost of CSRS may be calculated using equations 5 and 6, and the spreadsheet is shown in figure E-8.

Capital cost = Purchasing cost of entire SRE fleet × (Area of pavement under consideration/Total pavement area) (5)

The recurring costs associated with snow removal using CSRS consist of the fuel consumed by the equipment, labor, deicing agents, and equipment maintenance, which can be calculated using equation 2. The labor costs involved in snow-removal operations at commercial airports may range from 14 USD/h to 50 USD/h. The higher values indicate work during late nights, early mornings, and overtime. For simplicity, a value of 27 USD/h per person was used for calculations (values were provided by the MSP airport managers through airport site visits and questionnaires). Equation 6 and figure E-7 are used to calculate the costs.

Annual recurring cost = Total cost of (labor + fuel + deicing agents + O&M costs of SRE) × *(Area of pavement under consideration/Total pavement area)* (6)

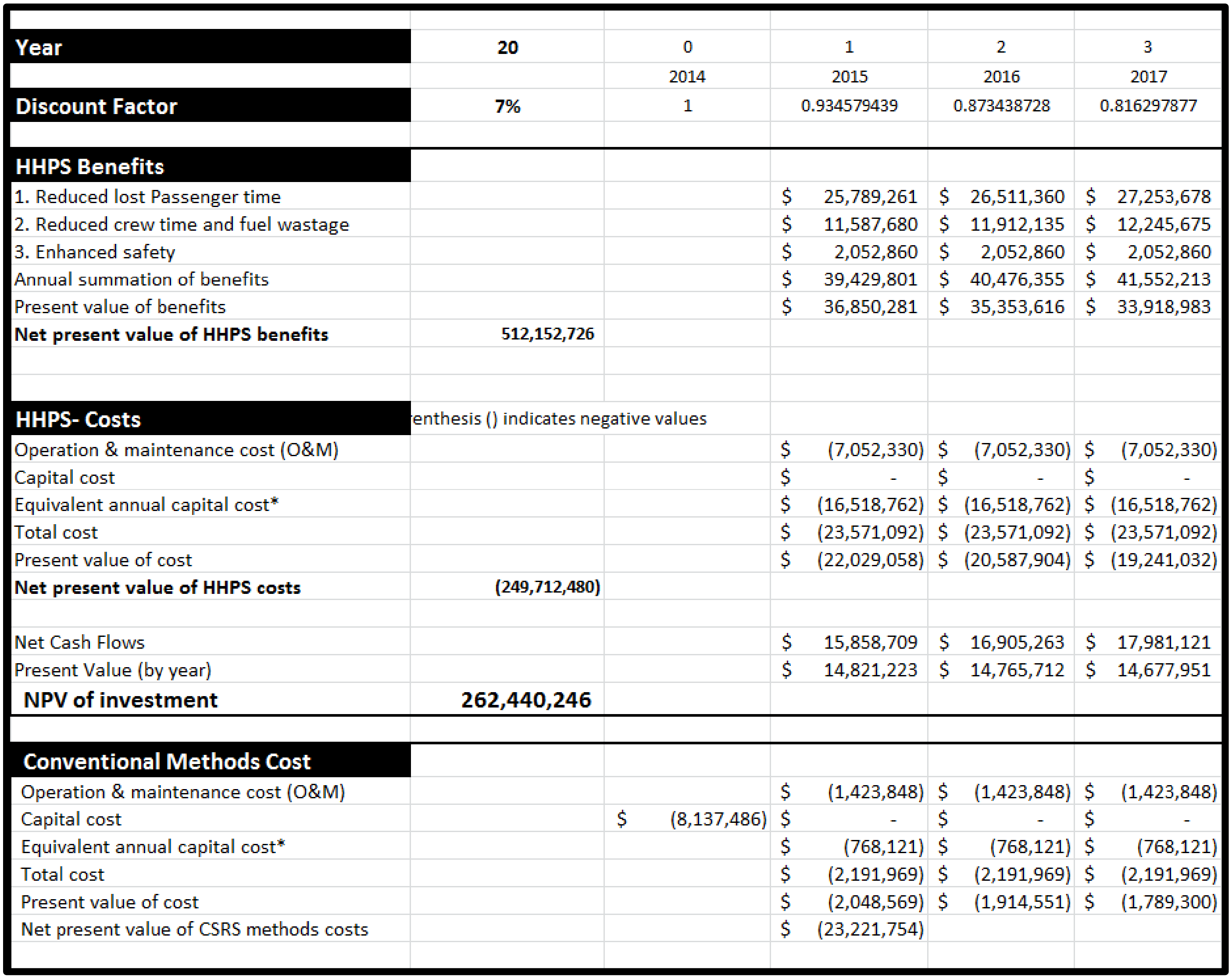


Cost of Conventional Methods Snow Removal Equipment (SRE)				
Item	**Quantity**	**Unit Price ($)**		**Total cost ($)**
Multifunctional vehicle	4	910,000		3,640,000
runway plows	23	485,000		11,155,000
Rotary brooms	14	650,000		9,100,000
Blowers	17	875,000		14,875,000
Front end Loaders	25	250,000		6,250,000
Sprayer	7	34,560		241,920
Deicer truck	7	44,000		308,000
Total	**97**			**45,569,920**
Annual SRE maintenance cost				600,000
Note: cost of labor is a function of area				
Area				
Ramp and apron area (ft2)				5,000,000
Total paved surface (ft2)				28,000,000
Ratio				0.179
Deicing agents				
Potassium acetate (gallons)	225,000	4.15		933,750
Sodium acetate (lbs.)	225,000	3		675,000
Note: cost of deicing agents is a function of area				
Labor and Fuel Cost				
Item	**No.**	**Unit Price (**	**Labor hou**	**Total price ($)**
Personnel	110	75	600	4,950,000
Note: cost of labor is a function of area				
Fuel cost for SRE	97	14	600	814,800
Total Cost for Apron Area				
Capital investment				
Purchasing cost of SRE at YEAR 0 (for concerned area)				**8,137,485.71**
Annual reccuring cost in terms of area considered				
Maintenance costs for SRE				107,142.86
Deicing agents				287,277
Labor				883,928.57
Fuel				145,500.00
Annual reccuring cost				**1,423,848.21**

Figure E-8. Calculating Cost of Using CSRS to Remove Snow From Sheet 5 "CSRS Cost" of the Economic Analysis Tool

E.6 SPREADSHEET 6—ECONOMIC ANALYSIS.

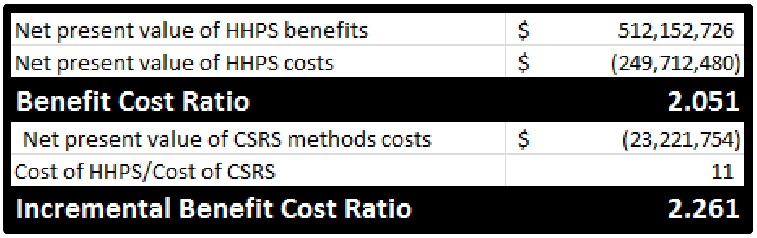
As shown in figure E-9, the value of analysis period (20 years) and discount factor (7%) can be changed from sheet 1 "Summary." The various costs and benefits are calculated from sheets 2 through 5.



Year	**20**	0	1	2	3
		2014	2015	2016	2017
Discount Factor	**7%**	1	0.934579439	0.873438728	0.816297877
HHPS Benefits					
1. Reduced lost Passenger time			$ 25,789,261	$ 26,511,360	$ 27,253,678
2. Reduced crew time and fuel wastage			$ 11,587,680	$ 11,912,135	$ 12,245,675
3. Enhanced safety			$ 2,052,860	$ 2,052,860	$ 2,052,860
Annual summation of benefits			$ 39,429,801	$ 40,476,355	$ 41,552,213
Present value of benefits			$ 36,850,281	$ 35,353,616	$ 33,918,983
Net present value of HHPS benefits	**512,152,726**				
HHPS- Costs	enthesis () indicates negative values				
Operation & maintenance cost (O&M)			$ (7,052,330)	$ (7,052,330)	$ (7,052,330)
Capital cost			$ -	$ -	$ -
Equivalent annual capital cost*			$ (16,518,762)	$ (16,518,762)	$ (16,518,762)
Total cost			$ (23,571,092)	$ (23,571,092)	$ (23,571,092)
Present value of cost			$ (22,029,058)	$ (20,587,904)	$ (19,241,032)
Net present value of HHPS costs	**(249,712,480)**				
Net Cash Flows			$ 15,858,709	$ 16,905,263	$ 17,981,121
Present Value (by year)			$ 14,821,223	$ 14,765,712	$ 14,677,951
NPV of investment	**262,440,246**				
Conventional Methods Cost					
Operation & maintenance cost (O&M)			$ (1,423,848)	$ (1,423,848)	$ (1,423,848)
Capital cost		$ (8,137,486)	$ -	$ -	$ -
Equivalent annual capital cost*			$ (768,121)	$ (768,121)	$ (768,121)
Total cost			$ (2,191,969)	$ (2,191,969)	$ (2,191,969)
Present value of cost			$ (2,048,569)	$ (1,914,551)	$ (1,789,300)
Net present value of CSRS methods costs			$ (23,221,754)		

Figure E-9. Presenting the Calculations of Present Values of Costs and Benefits From Sheet 6 "Economic Analysis" of the Economic Analysis Tool

After the present values (PV) of cost and benefits of HHPS are calculated, the BCR and incremental BCR are calculated in figure E-10, which are also presented in the "Summary" sheet shown in figure E-1.



Net present value of HHPS benefits	$	512,152,726
Net present value of HHPS costs	$	(249,712,480)
Benefit Cost Ratio		**2.051**
Net present value of CSRS methods costs	$	(23,221,754)
Cost of HHPS/Cost of CSRS		11
Incremental Benefit Cost Ratio		**2.261**

Figure E-10. The BCRs From Sheet 6

Figure E-11 data is presented on the “Cash flow” chart in the spreadsheet. It represents cash flow for 20 years and the distribution of the cost and benefits related with the installation of HHPS. In this example, it is evident that the delays affect passengers the most, but may vary among different airports. The benefits are due to reduction in lost passenger time, lost crew hours, and aviation fuel wastage. The costs include the installation, operation, and maintenance costs. The benefits of HHPS exceed the cost of installation, operation, and maintenance.

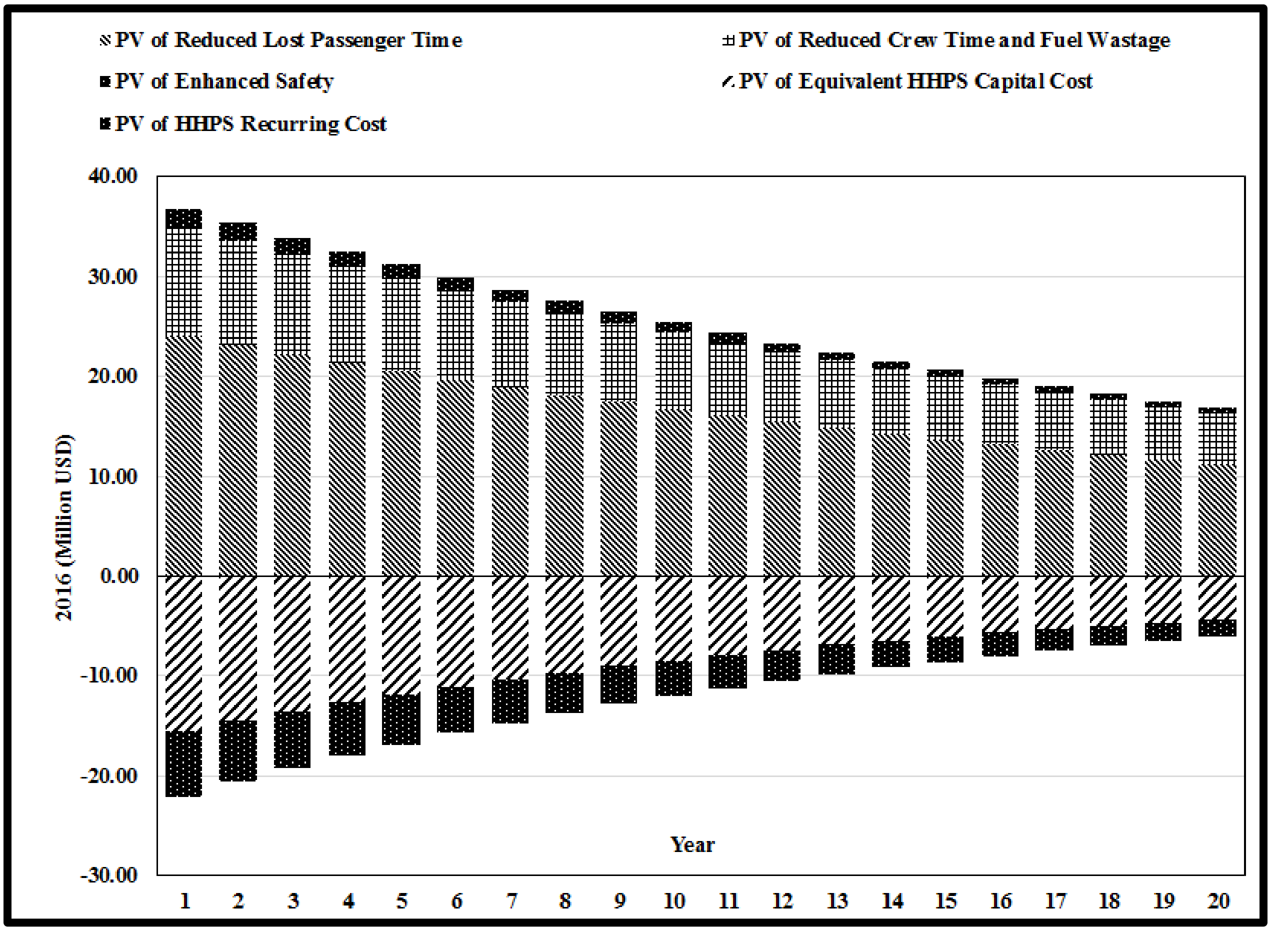


Figure E-11. Various Costs and Benefits Cash Flow of Using HHPS to Clear Snow From Sheet 7 “Cash Flow” of the Economic Analysis Tool

E.7 SUMMARY.

This appendix aims to serve as a user manual for the economic analysis tool developed for examining the feasibility of HHPS. This appendix should be reviewed along with the main report to envisage the methodology adopted to conduct the analysis. The developed tool can be used to overcome the limitations due to data unavailability listed in the report. Airport managers have access to accurate data for their airport and have the ability to establish more reasonable assumptions specific to their airport. The report focuses on the HHPS installation at aprons, but the tool can be used to investigate the feasibility at any airport.

E.8 REFERENCES.

E-1. Federal Aviation Administration (FAA), Office of Airport Safety and Standards, “Airport Winter Safety and Operations,” Advisory Circular (AC) 150/5200-30D, December 9, 2008 (updated 07/29/2016).

E-2. United States (U.S.) Bureau of Labor Statistics (BLS) Reports, “Nonfatal Occupational Injuries and Illnesses Requiring Days Away From Work, 2015,” available at https://www.bls.gov/news.release/osh2.toc.htm (date last visited 05/17/2017)

E-3. U.S. Department of Transportation, Trottenberg, P., and Rivkin, R. S., Memorandum, “Guidance on Treatment of the Economic Value of a Statistical Life in U.S. Department of Transportation Analyses,” Revised departmental guidance 2013 (date last visited 03/24/2017).

E-4. American Society of Heating, Refrigeration and Air-Conditioning Engineers (ASHRAE), “*The 2015 ASHRAE Handbook — HVAC Applications*,” 2015, pp. 51.1 – 51.20.