sustainability

Article

A Comparative Study of Probabilistic and Deterministic Methods for the Direct and Indirect Costs in Life-Cycle Cost Analysis for Airport Pavements

Peyman Babashamsi [1,2], Shabir Hussain Khahro [3,*], Hend Ali Omar [4], Sri Atmaja P. Rosyidi [5], Abdulnaser M Al-Sabaeei [1], Abdalrhman Milad [6], Munder Bilema [7], Muslich Hartadi Sutanto [8] and Nur Izzi Md Yusoff [1,*]

1 Department of Civil Engineering, Universiti Kebangsaan Malaysia, Bangi 43600, Malaysia; peymenshams@yahoo.com (P.B.); abdulnaser_17005477@utp.edu.my (A.M.A.-S.)
2 Opus International (Malaysia) Berhad, Kuala Lumpur 58100, Malaysia
3 College of Engineering, Prince Sultan University, Riyadh 11586, Saudi Arabia
4 Department of Civil Engineering, University of Tripoli, Tripoli 22131, Libya; hend.omar@uot.edu.ly
5 Department of Civil Engineering, Universitas Muhammadiyah Yogyakarta, Yogyakarta 55183, Indonesia; atmaja_sri@umy.ac.id
6 Department of Civil and Environmental Engineering, College of Engineering and Architecture, University of Nizwa, Birkat-al-Mouz, Nizwa 616, Oman; a.milad@unizwa.edu.om
7 Department of Civil Engineering, University of Benghazi, Benghazi 1308, Libya; munderbilema@gmail.com
8 Department of Civil and Environmental Engineering, Universiti Teknologi Petronas, Seri Iskandar 32610, Malaysia; muslich.sutanto@utp.edu.my
* Correspondence: shkhahro@psu.edu.sa (S.H.K.); izzi@ukm.edu.my (N.I.M.Y.)

Citation: Babashamsi, P.; Khahro, S.H.; Omar, H.A.; Rosyidi, S.A.P.; M Al-Sabaeei, A.; Milad, A.; Bilema, M.; Sutanto, M.H.; Yusoff, N.I.M. A Comparative Study of Probabilistic and Deterministic Methods for the Direct and Indirect Costs in Life-Cycle Cost Analysis for Airport Pavements. *Sustainability* **2022**, *14*, 3819. https://doi.org/10.3390/su14073819

Academic Editors: Adelino Jorge Lopes Ferreira and João Santos

Received: 25 February 2022
Accepted: 19 March 2022
Published: 24 March 2022

Abstract: Airports play a critical role in transporting goods and passengers and supporting the growth of the world economy. Airports spend huge sums annually to maintain and improve pavement functions by expanding the runways, taxiways, and aprons, and perform routine maintenance and rehabilitation of the existing pavements. Besides the traditional direct costs, a comprehensive airport pavement management system should also consider indirect costs such as fuel, crew, passenger delay, aircraft maintenance, and loss of airport revenue when conducting a life-cycle cost analysis (LCCA). Engineers, managers, and stakeholders can make better decisions on the appropriate pavement maintenance and rehabilitation strategies by performing economic analyses of the direct and indirect costs. This study performed probabilistic and deterministic LCCA to contrast the effect of direct costs vis-a-vis indirect costs in airport pavement management. A case study found that indirect costs could contribute up to 20% of the total costs when using Portland cement concrete (PCC), hot mixed asphalt (HMA), and crack seat overlay (CSOL). Previous research did not give much attention to maintenance since the researchers believed that routine maintenance makes up only an insignificant percentage of the LCCA. However, routine maintenance of HMA and CSOL makes up 10.2% and 14.2% of the total cost. The rehabilitation cost of PCC makes up 16.3% of the total cost, and the rehabilitation cost for HMA and CSOL makes up 25.4% and 35.2% of the total cost.

Keywords: life-cycle cost analysis; direct cost; indirect cost; airport revenue reduction cost; airline delay costs and airport pavement management system

1. Introduction

The Federal Highway Administration (FHWA) introduced the life-cycle cost analysis (LCCA) to help decision-makers determine the best maintenance and rehabilitation (M&R) strategy during the pavement life-cycle [1,2]. Initially, it recommended considering the life-cycle cost in pavement management when designing a pavement [3]. The budget for future projects should include maintenance and rehabilitation (M&R) and traffic delay costs [4]. According to the Transportation Equity Act for the 21st Century (TEA-21), LCCA is "… a process for evaluating the total economic worth of a usable project segment by analyzing initial costs and discounted future costs, such as maintenance, user costs, reconstruction, rehabilitation, restoring, and resurfacing costs, over the life of the project segment" [2].

Pavement engineers use the Caltrans Highway Design Manual (HDM) Topics 612 and 619 to evaluate the cost-effectiveness of employing alternative pavement designs to construct, reconstruct, and rehabilitate new highways [5]. FHWA developed an LCCA software tool, Real Cost (version 2.5), in 2004 to provide support to those performing LCCA for highway projects [6].

The first step in LCCA is determining the schedule for the first and upcoming activities for implementing a particular option and estimating the cost of the activities. The projected life-cycle cost stream consists of the predicted time frame for each activity and its associated costs. Discounting is an economic analysis technique for converting all projected costs into the present dollar and summing the costs to obtain the net present value (NPV) or converting them into future cost prices and summing them to determine the net future value (NFV). When considering several comparable options for the same life-cycle period, the total benefits or costs are scrutinized to assess the most cost-effective option. [7–14] have published a comprehensive discussion on LCCA.

Because of the significantly reduced allocation for all projects, some airports depend on LCCA to make decisions [15]. The absence of systematic guidelines makes it very difficult to conduct LCCA for airports. As a result, the analysis should quantify operational delays by considering the indirect costs (user costs) [15,16]. The size of an airport, the hour of the day, pavement location, and sequence of pavement construction are among the factors influencing user costs, and the consequences could be substantial. According to Duval [17], closing one of the two runways at a medium-sized airport for reconstruction may result in airlines, incurring an operational cost of $30,000 per hour. The LCCA must consider this cost because it may influence the selection of pavement rehabilitation with a long construction period. The operational and societal analyses could demonstrate the importance of accelerated construction techniques over traditional strategies, even though they might be more expensive [18].

The Federal Aviation Administration (FAA) introduced AirCost, a probabilistic LCCA spreadsheet program, in 2011. Since then, many state airport management agencies have adopted and utilized this program [16]. Other airports have their spreadsheet programs. These programs are written to meet the agencies' specific needs, and most do not consider the indirect costs. The disadvantage of using the AirCost program is that it ignores the insufficient probabilistic model by considering airport revenue reduction cost only as an indirect cost of the program.

LCCA was initially based on the cost–benefit analysis (CBA) of the 1950s that is considered when choosing a pavement design. The American Association of State Highway Officials (AASHO) Red Book 1960 established the economic evaluation of highway improvement at the planning level by introducing CBA in highway investment decisions. It significantly improved the LCCA by including the data for vehicle operating costs in a format that decision-makers could use to perform life-cycle cost analysis [19].

In 1977, FHWA instructed all agencies to evaluate the cost-effectiveness of pavement design [20]. Different versions of the AASHTO Pavement Design Guide [21,22] recommended using the life-cycle costing and discussed the fundamental reasons for including these costs in LCCA. The Long-Term Pavement Program (LTPP) and Strategic Highway Report Program (SHRP) were established in 1984 to develop an in-depth understanding of pavement behavior and an efficient system for managing highway infrastructures that do not require significant funding [23–25]. Carvetti and Owusu-Ababio [26] used the principles of LCCA to evaluate the pavement design alternatives for the Wisconsin DOT.

The focus of early research on pavement LCCA is qualified appraisals in various applications. The life cycle costs investigation by Fagen and Phares [27] focused on steel beam precast, concrete beam precast, and continuous concrete slab bridge deck for a low-volume roadway. Embacher and Snyder [28] focused on asphalt concrete and concrete for low-volume roads, while Zimmerman and Peshkin [29] employed LCCA to determine the optimal time for preventive maintenance. Huang et al. [30] designed a supportive decision network to identify the optimal concrete deck maintenance method. The primary input in LCCA is effective pavement maintenance or rehabilitation. It could be a short-term analysis of effective treatment, such as a slower rate of deterioration or improved performance, or a long-term assessment or evaluation of effective preservation [31].

The drawback of most previous research is treating the information parameters as deterministic qualities. The research focus in the past decade is to construct probabilistic approaches for dealing with uncertainties. Tighe [32], for example, collected empirical data to determine the cost and variation in pavement thickness. Generally, the log-normal distribution can explain the uncertainties when running a chi-square best-fit test. Salem et al. [33] used Weibull distribution to characterize uncertainties in the age of pavement failure. Osman [34] used Weibull distribution to develop a risk-based technique that only considers the uncertainties for pavement performance. Li and Madanu [35] described the cost uncertainty to demonstrate the life-cycle cost/benefit using, an eleven-year historical bid data from Indiana to characterize the unit cost of construction and maintenance activities using a Beta distribution. Even though these LCCA studies contributed significantly to the probabilistic LCCA, there is still a dearth of studies investigating the various input uncertainties.

These studies used Monte Carlo simulations to perform probabilistic LCCA because the final probability distribution can be assimilated from all iterations to describe the probability of an event [36]. Reigle and Zaniewski [37] used this approach to understand the risk of alternative investments. Risk is the potential disadvantage of investment that could lead to financial losses extensively discussed in finance literature [38]. The uncertainty in short-term and long-term costs of pavements suggests that the actual life-cycle costs for an alternative could be potentially higher (or lower) than expected.

Two important financial metrics for measuring the potential downside (or upside) of investment are the value at risk (VaR) and value at gain (VaG). According to De Neufville and Scholtes [38], VaR is the threshold value of an investment cost for a given probability.

The lowest cost alternative might not be the best option in every aspect since different factors, including the political and environmental concerns, available budget, risk, must be considered [8]. As a result, even though the data required for the decision-making process is gathered during the LCCA, it is not the end [39].

The critical assumption of all economic assessments of pavement projects is the constraints imposed by the allocated budget [40]. Some airports used LCCA as a decision-making tool due to the significant cut in the funding for all projects [15]. Agencies should assess their projects by considering the high potential savings achieved when adopting a cost-effective approach [41]. LCCA is one of the economic analyses employed by airports to evaluate pavement projects and reduce expenditure through prudent spending of the limited funds [42]. Decision-makers will be using LCCA more often as they practice the best asset management in the infrastructure life-cycle [43]. Using local pavement data to perform LCCA could give a more in-depth knowledge of pavement life-cycle performance and cost-effectiveness [37]. Implementing a cost-effective approach based on non-factual data could result in a poor outcome [44].

Although it is generally not easy to quantify operational and societal sustainability issues, it is possible when using the LCCA approach [15,16,44]. Because the lack of systematic guidelines makes it difficult to perform LCCA of airports, operational delays are quantified by including user costs in the analyses [15,16]. User costs are dependent on several factors, including airport size, the time during the day, pavement location, and the sequence of pavement construction; the impact of these factors could differ considerably.

Night-time construction or maintenance of non-essential segments (such as aprons) would probably cause a slight delay in the operating system. Because of this, the LCCA does not include user costs [45]. User cost is included in the LCCA when there is a significant operational delay because of the impact of selecting a pavement option with a long construction period.

The contribution of this study can be summarized by improving the indirect costs in the previous software by considering Airplane Delay Costs (ADC), which comprises fuel cost, crew cost, aircraft maintenance cost, passenger delay cost, and the compound and simple growth factor modes in the airport revenue reduction costs. It also improves the probabilistic model by including risk assessment in LCCA. Overall, it highlights the importance of indirect cost in airport pavement management.

In summary, LCCA could support and demonstrate the net benefits of selecting a particular option based on sustainability instead of opting for an option because of its lowest initial cost. It is essential to combine outputs with other elements, such as political and environmental concerns, risks, and the available budget resources [8]. The combined result of LCCA and LCA outputs provides pavement engineers with critical information on the impact of the pavement life cycle [46]. Therefore, this study aims to present a comprehensive LCCA in airport pavement management and prove the significance of indirect costs and maintenance activities in airport pavement management.

2. Methods

Airport pavement projects involve long periods of planning, designing, contracting, and construction. After the budget allocation, the initial design of airport pavements considers the project aims, requirements, and limitations based on the current information. The following stage focuses primarily on determining the type of pavement and M&R activities for the pavement project [47]. Agencies that do not have sufficient data should carry out probabilistic LCCA for each alternative. Otherwise, deterministic LCCA is performed with sensitivity analysis to determine the impacts of the various critical input data, such as discount rate and initial pavement service life.

Even though experience-based estimates can be used to quantify the LCCA inputs, it is essential to use all available, applicable, and reliable data in the analysis. The result of LCCA is only as good as the quality of the inputs. Figure 1 illustrates the process for carrying out LCCA for airport pavement LCCA using the AirCost program.

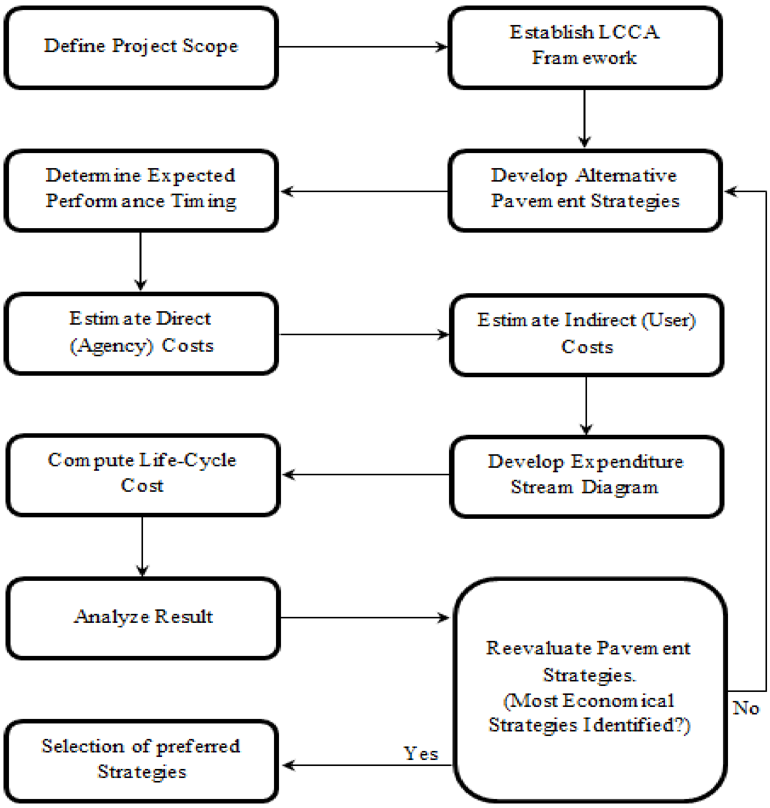

Figure 1. The process for conducting airport pavement LCCA.

2.1. Estimation of the Direct Costs

2.1.1. Physical Costs of Pavement Activities

The best way to evaluate physical costs is by identifying the adequate and trustworthy unit cost data for pay items that contribute to the initial construction and all M&R treatments. These data are available in the historical bid records of construction projects for recent years (ideally, the previous seven years). The unit cost data is also available at the local highway agencies. A better unit cost appraisal employs the unit price data from the lowest bid or the three lowest bids for the projects. Each unit price should be converted to the present day to represent the effect of inflation, and analysis should focus on filtering out biased costs in projects for out-of-range quantities of a specific pay item. The formula for direct cost is given by Equation (1). Rehabilitation comprises two parts, with salvage value and without salvage value.

$$\mathrm{NPV}_{\mathrm{Physical\ Cost}} = \sum\nolimits_1^K \mathrm{Cost}_{\mathrm{IC}} \frac{1}{[1+\mathrm{i}_{\mathrm{dis}}]^{\mathrm{n}}} + \sum\nolimits_1^k \mathrm{Cost}_{\mathrm{Mj}} \frac{1}{[1+\mathrm{i}_{\mathrm{dis}}]^{\mathrm{n}}} + \sum\nolimits_1^k \mathrm{Cost}_{\mathrm{NRj}} \frac{1}{[1+\mathrm{i}_{\mathrm{dis}}]^{\mathrm{n}}} + \sum\nolimits_1^k \mathrm{Cost}_{\mathrm{SRj}} \frac{1}{[1+\mathrm{i}_{\mathrm{dis}}]^{\mathrm{n}}} \quad (1)$$

where:

idis = Discount Rate
n = Year − Analysis Base Year
j = number of maintenances or rehabilitations
k = number of activities in each life-cycle event
$\mathrm{Cost}_{\mathrm{IC}}$ = Unit Costk × Quantityk (for initial construction)
$\mathrm{Cost}_{\mathrm{Mj}}$= Unit Costk × Quantityk (for each maintenance)
$\mathrm{Cost}_{\mathrm{NRj}}$= Unit Costk × Quantityk (for items with no salvage value)
$\mathrm{Cost}_{\mathrm{SRj}}$ = Unit Costk × Quantityk (for items with salvage value)

2.1.2. Salvage Value at the End of the Life-Cycle

The current FAA guideline recommends calculating salvage value based only on the serviceable life [16]. Figure 2 shows that the salvage value is the cost of the last rehabilitation activity multiplied by the ratio of the remaining pavement life divided by its total expected rehabilitation life, as given by Equation (2). The differential salvage value between pavement options is usually not significant, and when discounted over long periods, tends to have less impact on the LCCA output.

$$\mathrm{NPV}_{\mathrm{Salvage\ Value}} = \mathrm{SV} \times \frac{1}{[1+\ \mathrm{i}_{\mathrm{dis}}]^{\mathrm{AP}+(\mathrm{Initial\ Construction\ Year}-\mathrm{Base\ Year})}} \quad (2)$$

where:

SV = Salvage Value
idis = Discount Rate
AP = Analysis Period

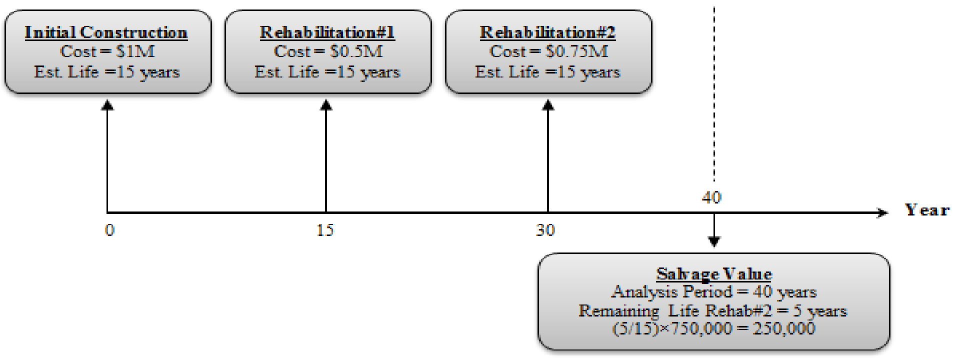

Figure 2. The remaining life salvage value.

2.1.3. Supplementary Costs

The evaluation of supplementary expenses is complex and time-consuming. However, an alternative method for determining supplementary costs is to consider them as a rate of the total project-level pavement costs (usually 5%).

2.2. Estimation of the Indirect Costs

Indirect costs are the highest costs incurred by most airport management systems. Some APMS only consider airport revenue reduction cost (ARRC) in simple growth rate and do not consider airplane delay cost (ADC). In 2007, airport delays cost the economy approximately $40.7 billion [48]. This study considers two specific user costs as the total cost borne by users during reconstruction and M&R activities. Although previous studies include users in airport revenue reduction, additional user costs, including fuel, crew, maintenance, and passenger delay costs, should be appropriately calculated in LCCA.

2.2.1. Airport Revenue Reduction Cost (ARRC)

Each option involves different construction activities (initial construction/rehabilitation and future M&R) during their life-cycle and could result in reduced daily revenue during the construction and rehabilitation activities.

It is worth noting that, as a primary element of an LCCA, it is essential to convert the revenue reduction costs related to future planned activities since all costs must be discounted to today's values. Equation (3) gives the user cost of ARRC for all options.

$$\mathrm{NPV_{ARRC}} = \mathrm{ARRC_{IC}} \times \frac{1}{[1+\mathrm{i_{dis}}]^{\mathrm{n}}} + \sum \mathrm{ARRC_{M_j}} \times \frac{1}{[1+\mathrm{i_{dis}}]^{\mathrm{n}}} + \sum \mathrm{ARRC_{R_j}} \times \frac{1}{[1+\mathrm{i_{dis}}]^{\mathrm{n}}} \tag{3}$$

where:

j = number of maintenance or rehabilitation

ARRC = Airport Revenue Reduction Cost

The analyzer can choose one of two growth modes, the simple mode given by Equation (4), or the compound mode given by Equation (5).

$$\mathrm{ARRC_{simple}} = \mathrm{AAR} \times (1 + \mathrm{ni_R}) \times \mathrm{RR} \times \frac{\text{Duration of Construction}}{365} \tag{4}$$

$$\mathrm{ARRC_{Compound}} = \mathrm{AAR} \times (1 + \mathrm{i_R})^{\mathrm{n}} \times \mathrm{RR} \times \frac{\text{Duration of Construction}}{365} \tag{5}$$

where:

AAR = Airport Annual Revenue ($)

n = Year – Analysis Base Year

$\mathrm{i_R}$ = Annual Revenue Growth Rate (e.g., 5% = 0.05)

RR = Revenue Reduction (%)

2.2.2. Airline Delay Cost (ADC)

The present study also considers airline delay costs. The EU and most American APMS use the tactical gate-to-gate delay when considering delay cost. The EU report classified delay as tactical delay (the delays that are longer than the announced schedule, which exceed the anticipated padding of the schedule) and strategic delay (the delay relative to an unpadded schedule). Another classification includes gate-to-gate delay (or single flight) and network-level delay [49].

Gate-to-gate delay is an environmental situation that causes an unexpected delay and may affect any flight.

Network delay is the impact of a single flight on the rest of the system.

This study only considers the direct costs of such delays on an individual airplane. The model proposed by Ferguson et al. [49] is the most comprehensive and is given by Equation (6); this model comprises two types of delays, short-time delay (15 min or less), and long-time delay (65 min or longer). Interpolation is used for delays of between 15 and 65 min. The ADC is calculated using Equation (7) and discounted using Equation (8).

$$C_{delay} = C_{fuel} \times FBR \times FP + C_{crew} \times CC \times (\text{No : of Crew}) + C_{maintenance} \times MC + C_{pax} \times PAX \times (\text{No : of seats}) + C_{other} \times OC \quad (6)$$

$$ADC = C_{delay} \times ADT \times (\text{No : of total flight per day}) \times DC \quad (7)$$

$$NPV_{ADC} = ADC_{IC} \times \frac{1}{[1+\ i_{dis}]^n} + \sum ADC_{M_j} \times \frac{1}{[1+\ i_{dis}]^n} + \sum ADC_{R_j} \times \frac{1}{[1+\ i_{dis}]^n} \quad (8)$$

where:

FBR = Fuel Burn Rate
FP = Fuel Price
CC = Crew Cost
MC = Maintenance Cost
PAX = Passenger Delay cost
OC = Other Costs
C_{fuel} = Coefficient of fuel cost
C_{crew} = Coefficient of crew cost
$C_{maintenance}$ = Coefficient of maintenance cost
C_{pax} = Coefficient of passenger delay cost
C_{other} = Coefficient of other costs
C_{delay} = Coefficient of delay
ADT = Airplane Delay Time
DC = Duration of construction

Ferguson et al. [49] included the imputed cost factor in their data to validate the cost factors. The researchers applied the formulas to the US data and noted a difference between the US and European frameworks. One difference is the result of the EU Passenger Bill of Rights, which makes the passenger payback costs borne by the airlines in the US much lower than those in the EU. Because airplanes in the US spend more time taxiing at airports than in Europe, air traffic management enforces more scheduled ground delays on airlines to ensure a short circling at the destination airport. According to the EU report, the duration of circling delay is greater than the taxiing delay for European airlines. Further scrutiny of the cost factors revealed the following costs:

Extra Fuel Cost: Each type of airplane is assigned a fuel burn rate based on arrival management (Gate-to-Gate), as shown in Table 1.

Table 1. The fuel burn rate and maintenance costs for different types of airplanes due to delay [49].

Airplane Model	No. of Seat	Fuel Burned (kg/h)	Fuel Burn Rate (gal/min)	BHDOC	Maintenance Cost (per min)
ATR 42	45	392	2.1	2510	376.5
ATR72	60	504	2.7	3100	465.0
B737-500	100	2530	13.8	4550	682.5
B737-300	125	2731	14.8	4950	742.5
B737-400	140	2588	14.1	5280	792.0
A320	155	2074	11.3	4790	718.5
A321	165	2625	14.2	5690	853.5
B737-800	175	2187	11.9	4040	606.0
B757-200	215	2789	15.2	5960	894.0
B767-300	240	3908	21.2	7590	1138.5

Extra Crew Cost: This is the additional expense paid to the cabin crew and flight attendants. Unforeseen delays may require the service of extra flight attendants and cabin crew or making an additional payment to the regular crews for the extra hours they have to work.

Extra Maintenance Cost: Maintenance cost is the expense of repairing the body kit and engine power. The additional upkeep costs incurred for each minute of delay is about 15% of the Block Hour Direct Operating Cost (BHDOC), as shown in Table 1.

Passenger Delay Cost (PAX): This cost is the payback portion of the ticket fees made by the airlines to travelers whose flights are delayed. The value ranges from 0.05 for a 15-min delay to 0.48 for a 65-min delay. Table 2 shows the coefficient of PAX for Europe and the US.

Table 2. The coefficients for various cost factors for the EU and US.

Cost Factor	Europe						The US					
	Gate		Taxi		En-Route		Gate		Taxi		En-Route	
	15	65	15	65	15	65	15	65	15	65	15	65
Fuel	0	0	1	1	1	1	0	0	1	1	1	1
Crew	0	0.85	0	0.85	0	0.85	0	0.85	0	0.85	0	0.85
Maintenance	0.02	0.05	0.02	0.05	0.02	0.05	0.02	0.05	0.02	0.05	0.02	0.05
PAX	1	1	1	1	1	1	0	0	0	0	0	0

This study uses the cost factors from the BTS P52 database (2014) (maintenance costs, crew costs, and extra fuel costs) and the industry white paper aircraft operating and delay cost per enplanement.

3. Background of the Case Study

The basic data used in this case study is the serviceability data of a PCC pavement runway at the end of its service life. The functional unit is a 1-km (3280.84 ft) overlay system of the PCC runway pavement that is 61 m (200 ft) wide, making the pavement area 61,000 m^2 (72,954.7 yd^2). The PCC pavement comprises a 250-mm (10 in) PCC layer and 250-mm (10 in) crushed aggregate base course. The PCC layer is near the end of its useful life and requires rehabilitation to extend its service life. The base course is in good condition and does not require extensive maintenance work. The three reconstruction alternatives available are as follows.

I. Remove the existing pavement but retain the subgrade layers. Place a new layer of 300 mm (12 in) PCC.
II. Remove the present pavement but retain the existing base and subgrade layers. Place a layer of 250 mm (10 in) of HMA. This option uses mill-and-fill as periodic rehabilitation.
III. Crack, seat, and overlay (hereafter called CSOL). The existing PCC pavement is cracked and seated [50] and overlaid with 150 mm (6 in) of HMA. This option uses mill-and-fill as periodic rehabilitation.

The three pavements overlay designs follow the AASHTO pavement design guideline. Table 3 lists the structural design of the three overlay system options.

Table 3. Structural design of PCC, HMA, and CSOL for runway reconstruction.

PCC	HMA	CSOL
300 mm (12 in) PCC	250 mm (10 in) HMA	150 mm (6 in) HMA 250 mm (10 in) existing PCC

According to the Airport Cooperative Research Program (ACRP) [51], the rehabilitation of concrete slab is carried out every 18–20 years, and the diamond-grind surface has an average life of 16–20 years [5]. Thus, PCC rehabilitation activity is carried out every 20 years. The mill-and-fill activity for HMA and CSOL is carried out every 15 years [52,53]. The maintenance and rehabilitation schedule are adopted from the Jefferson County (Colorado) airport. Table 4 shows the maintenance and rehabilitation works, and Figure 3 shows the time frame. The three critical factors for this method are direct costs, indirect costs, and salvage value. Even though the base year for analysis is 2016, the construction began in 2018.

Table 4. Reconstruction and M&R activities for PCC, HMA, and CSOL.

PCC	**HMA**	**CSOL**
Reconstruction	**Reconstruction**	**Reconstruction**
Main 1: Crack and Joint sealing	Main 1: Crack sealing Main 2: Crack sealing Main 3: Seal coat Main 4: Crack sealing	Main 1: Crack sealing Main 2: Crack sealing Main 3: Seal coat Main 4: Crack sealing
Rehab 1: Crack and Joint sealing + Spall Repair + 50% slab replacement	Rehab 1: 150mm mill and new AC	Rehab 1: Full-depth mill and new AC
Main 1: Crack and Joint sealing	Main 1: Crack sealing Main 2: Crack sealing Main 3: Seal coat Main 5: Crack sealing	Main 1: Crack sealing Main 2: Crack sealing Main 3: Seal coat Main 5: Crack sealing
	Rehab 2: 150 mm mill and new AC	Rehab 2: Full-depth mill and new AC
	Main 1: Crack sealing Main 2: Crack sealing Main 3: Seal coat	Main 1: Crack sealing Main 2: Crack sealing Main 3: Seal coat

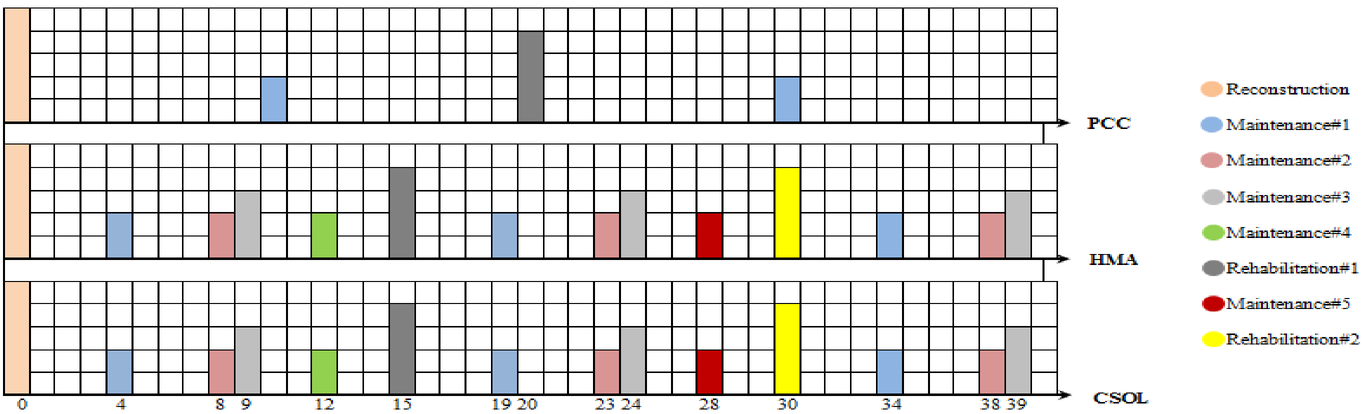

Figure 3. Reconstruction and M&R schedules for PCC, HMA, and CSOL.

3.1. Direct Cost Input Data

The analysis period is 40 years. The deterministic LCCA projects use the 4% typical discount rate for recent years. For the probabilistic LCCA, the mean discount rate is 4%, and the standard deviation is 1%. Table 5 shows the mean for pay item costs and the M&R schedule for all options. The probabilistic method considers a 10% standard deviation for each item cost variation.

The unit cost values are based on the mean cost of pay items at the Jefferson County airport system bid tabs between 2006 and 2016, and all values were converted to the 2016 costs. PCC does not have salvage value because of the 40 years analysis period and design life. However, the five-year residual value for HMA and CSOL was calculated. This study used Monte Carlo simulation to determine the best option.

Table 5. Initial and M&R unit costs for PCC, HMA, and CSOL.

PCC	HMA	CSOL
Cost for Initial Construction		
PCC removal, $11.00/m^2 PCC paving, $190.00/m^3 Electrical, $320,000.00/km Restripe, $12,000.00/km	PCC removal, $11.00/m^2 HMA paving, $140.00/m^3 41,640 L of tack coat, $0.25/L Geotextile, $1.80/m^2 Electrical, $320,000.00/km Restripe, $12,000.00/km	Crack and seat, $2.00/m^2 Surface preparation, $1.00/m^2 HMA Ppaving, $140.00/m^3 41,640 L of tack coat, $0.25/L Electrical, $320,000.00/km Restripe, $12,000.00/km
Cost of Maintenance		
Crack and joint sealing, $3.00/m^2	Crack sealing, $2.00/m^2 Seal coat, $1.00/m^2	Crack sealing, $2.00/m^2 Seal coat, $1.00/m^2
Cost of Rehabilitation		
Spall repair, $5.00/m^2 Slab replacement, $200/m^3 Restripe, $12,000.00/km	HMA removal, $5.00/m^2 HMA paving, $140.00/m^3 41,640 L of tack coat, $0.25/L Restripe, $12,000.00/km	HMA removal, $5.00/m^2 HMA paving, $140.00/m^2 41,640 L of tack coat, $0.25/L Restripe, $12,000.00/km

3.2. Indirect Costs Input Data

Each airport has two user costs, the airport revenue reduction cost (ARRC) that resulted from the total or partial closure of the runway, taxiway, or apron, and the airplane delay cost (ADC) that impact airlines as the primary airport user. Table 6 shows the other user costs, including revenue reduction, duration of construction, and airplane delay time information for all alternatives.

Table 6. User costs input data for PCC, HMA, and CSOL.

Alternatives	Events	Revenue Reduction (%)	Duration of Construction (Day)	Airplane Delay Time (min)
PCC	Reconstruction	25	7	15
	Maintenance 1	0	1	0
	Maintenance 2	0	1	0
	Rehabilitation 1	10	3	10
HMA	Reconstruction	15	4	10
	Maintenance 1	0	1	0
	Maintenance 2	0	1	0
	Maintenance 3	0	1	0
	Maintenance 4	0	1	0
	Rehabilitation 1	10	3	10
	Maintenance 5	0	1	0
	Rehabilitation 2	10	3	10
CSOL	Reconstruction	10	3	10
	Maintenance 1	0	1	0
	Maintenance 2	0	1	0
	Maintenance 3	0	1	0
	Maintenance 4	0	1	0
	Rehabilitation 1	10	3	10
	Maintenance 5	0	1	0
	Rehabilitation 2	10	3	10

The assumptions for the user cost analysis for the three options are as follows.

I. Generally, the exact annual revenue is confidential and dependent on the size of the airport and the number of flights and passengers. It is between $10–15 million for medium-sized international airports. A $12 million total annual revenue is assume.

II. The revenue growth is 5% in compound mode. Revenue growth should be higher than or equal to the discount rate, or else it is not feasible to implement the project.
III. Medium-sized international airports handle 300 flights per day, and each flight has 155 seats.
IV. The annual and monthly airplane fuel prices are available at 28 January 2021 http://www.transtats.bts.gov/fuel.asp. This study takes the 2016 annual fuel price as $0.37 per liter ($1.40 per gallon).
V. Unlike in Europe, US airlines do not pay PAX.
VI. Airplane crew cost varies depending on the level of responsibility. This study assumes a mean crew cost of $0.3 (30 cents) per minute, and each flight has ten crew members.
VII. Airplane maintenance cost is dependent on the selected type of airplane (mean number of seats). The analyzer can modify this value.

4. Results

4.1. LCCA Deterministic Outputs

In a conventional deterministic approach, the most critical factor when determining the appropriate method is the mean of the results (single value). Table 7 shows that the direct cost of PCC is $5,553,558, $5,055,028 for HMA, and $3,645,643 for CSOL. After deducting the salvage values, the cost for HMA and CSOL is $4,972,093 and $3,562,708. In terms of the mean NPV, the cost for CSOL is 35.8% and 28.3%, less than for PCC and HMA. Unlike earlier management software, it is essential to represent the user cost analysis in PAVECO comprehensively. Table 7 shows that CSOL has lower ARRC and ADC than the other options. The percentage of indirect cost for ADC for all options is higher than for ARC. HMA and CSOL have a higher ADC for rehabilitation, and the percentage for initial construction for PCC is higher than ADC.

Table 7. LCCA deterministic results for PCC, HMA, and CSOL ($1000).

Option	Activity	Direct Costs	Indirect Costs		Salvage Value
			ARRC	ADC	
PCC	Initial	4142	58.6	879.2	0.0
	Maintenance	166.5	0.0	0.0	
	Rehabilitation	980.6	12.2	114.6	
	Total	5553.6 [a]	70.8	993.8	
HMA	Initial	3012.9	20.1	334.9	82.9
	Maintenance	516.7	0.0	0.0	
	Rehabilitation	1284.7	25.0	217.0	
	Total	5055.0 [a]	45.1	551.9	
CSOL	Initial	1670.7	10.0	251.2	82.9
	Maintenance	516.7	0.00	0.0	
	Rehabilitation	1284.7	25.0	217.0	
	Total	3645.6 [a]	35.0	468.2	

Most previous research did not focus on maintenance since routine maintenance is considered less important in LCCA. However, Table 7 shows that the maintenance cost of HMA and CSOL makes up 10.2% and 14.2% of the total costs; the rehabilitation value in PCC is 16.3% of the total cost, and 25.4%, and 35.2% in HMA and CSOL. These percentages indicate that it is crucial to include routine maintenance in pavement airport management. The maintenance cost in HMA and CSOL does not affect user costs, since these activities do not affect the annual revenue and airplane delay costs because of its short duration of construction. Table 8 shows the direct costs and salvage values of all activities.

Table 8. Direct costs of PCC, HMA, and CSOL ($1000).

Alternative	Activity	Year	$\frac{1}{[1+i_{dis}]^n}$	Cost	NPV
PCC	Reconstruction	2	0.92	4480.0	4142.0
	Maintenance 1	12	0.62	183.0	114.3
	Rehabilitation	22	0.42	2324.0	976.1
	Maintenance 1	32	0.29	183.0	52.2
	Salvage Value	42	0.19	0.0	0.0
HMA	Reconstruction	2	0.92	3258.8	3012.9
	Maintenance 1	6	0.79	122.0	96.4
	Maintenance 2	10	0.68	122.0	82.4
	Maintenance 3	11	0.65	61.0	39.6
	Maintenance 4	14	0.58	122.0	70.5
	Rehabilitation 1	17	0.51	1609.0	826.0
	Maintenance 1	21	0.44	122.0	53.5
	Maintenance 2	25	0.38	122.0	45.8
	Maintenance 3	26	0.36	61.0	22.0
	Maintenance 5	29	0.32	122.0	39.1
	Rehabilitation 2	32	0.29	1609.0	458.7
	Maintenance 1	36	0.24	122.0	29.7
	Maintenance 2	40	0.21	122.0	25.4
	Maintenance 3	41	0.20	61.0	12.2
	Salvage Value	42	0.19	−1292.0	−829.4
CSOL	Reconstruction	2	0.92	1807.0	1670.7
	Maintenance 1	6	0.79	122.0	96.4
	Maintenance 2	10	0.68	122.0	82.4
	Maintenance 3	11	0.65	61.0	39.6
	Maintenance 4	14	0.58	122.0	70.5
	Rehabilitation 1	17	0.51	1609.0	826.0
	Maintenance 1	21	0.44	122.0	53.5
	Maintenance 2	25	0.38	122.0	45.8
	Maintenance 3	26	0.36	61.0	22.0
	Maintenance 4	29	0.32	122.0	39.1
	Rehabilitation 2	32	0.29	1609.0	458.7
	Maintenance 1	36	0.24	122.0	29.7
	Maintenance 2	40	0.21	122.0	25.4
	Maintenance 3	41	0.20	122.0	12.2
	Salvage Value	42	0.19	−1292.0	−829.4

It is worth noting that the present study considers the indirect costs in LCCA even though previous studies only include ARRC as the user cost. The present study has demonstrated the importance of ADC in LCCA. Table 7 shows that ADC is about 15 times higher than ARRC. Including ADC in the indirect costs increased the percentage to 19.1% of the total direct costs for all alternatives, which is why previous studies excluded indirect costs in airport pavement management. Including only ARRC in the direct cost does not have any significant impact compared to the high impact of the direct costs. Maintenance activities do not affect ADC because the short duration of the maintenance activities does not affect the flight schedule.

It is not practical to compare the procedures using special tools since the results depend on the different system boundaries, scopes, and measures. The difference in the employed tools could eclipse the distinctions in the procedures and distort the results. While using one single tool to analyze the options is the better choice, this approach has risks, including uncertainty and data quality. The data quantification method and the data selected for estimation and detail could influence the results when comparing analysis tools. It is essential to carefully weigh and verify the scope, system boundary, and data quality before conducting or using software output to ensure they are compatible with the projects' goals.

4.2. LCCA Probabilistic Outputs

The outcomes of risk analysis go beyond comparing the options to determine which option has the lowest average costs by expanding the probability analysis that any expected result will happen. There is no assumption that a specific option is beneficial. Risk analysis provides much more data than a basic deterministic approach. Table 9 shows the additional statistical values obtained from a simulation that revealed the hidden uncertainty associated with each option.

Table 9. The results of probabilistic LCCA for PCC, HMA, and CSOL ($1000).

Options	**Statistics**	**Direct Cost**	**Indirect Cost**		**Salvage Value**
			ARRC	**ADC**	
PCC	Mean	5606.2	71.4	999.2	0.0
	Std. dev.	460.0	5.1	56.6	0.0
	Min.	4918.8	63.7	63.7	0.0
	Max.	6501.1	81.2	81.2	0.0
HMA	Mean	5143.9	46.6	562.6	96.0
	Std. dev.	625.9	9.1	74.6	51.0
	Min.	4239.5	33.9	455.2	33.1
	Max.	6401.3	65.4	712.7	212.2
CSOL	Mean	3733.9	36.5	478.9	96.0
	Std. dev.	589.6	8.8	72.4	51.0
	Min.	2890.5	24.3	375.1	33.1
	Max.	4927.4	54.9	625.1	212.2

Figure 4 shows the range of possible outcomes displayed with the estimated probability of every occurrence. The highlighted standpoint of the histogram shows the variation of the probabilistic mean of each option. The graph with broader distribution has higher variation, indicating higher uncertainty. Figure 4 shows that HMA has the highest uncertainty.

Figure 4. Histogram of the NPV for PCC, HMA, and CSOL.

The slope of the cumulative curve represents the uncertainty for each option. A steep slope indicates a low variation, and a gradual slope indicates a high uncertainty. Figure 5 illustrates the risk profiles of the three options in a cumulative diagram. The steeper slope for PCC indicates its low uncertainty relative to HMA and CSOL. The up-side and down-side risk is a critical factor in interpreting a risk assessment. The downside risk for the total costs indicates the probability of financial failure (over-run). The upside risk of the total costs means that the total costs may be lower than the mean cost (under-run). In this study, the probability of upside risk (under-run) is about 65% for CSOL, 55% for HMA, and 45% for PCC.

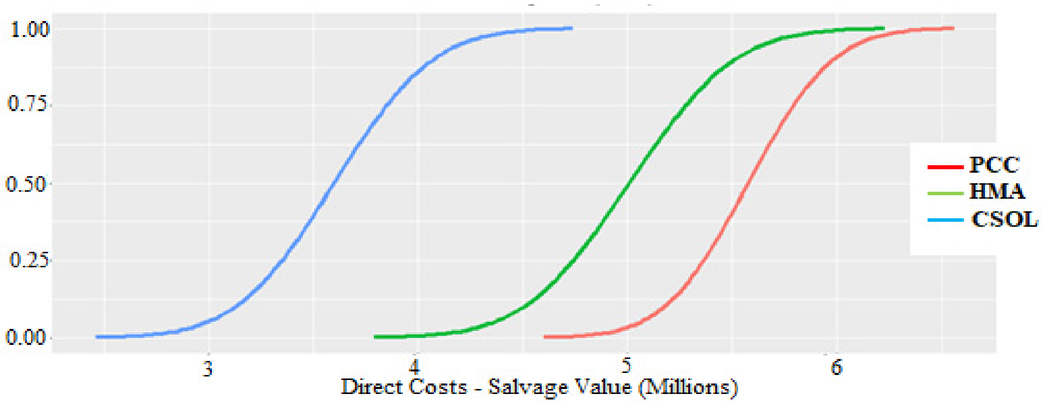

Figure 5. The cumulative risk profile of NPV for PCC, HMA, and CSOL.

Figures 6 and 7 show the uncertainty for two components of indirect costs, namely the airport reduction revenue costs (ARRC) and airplane delay costs (ADC).

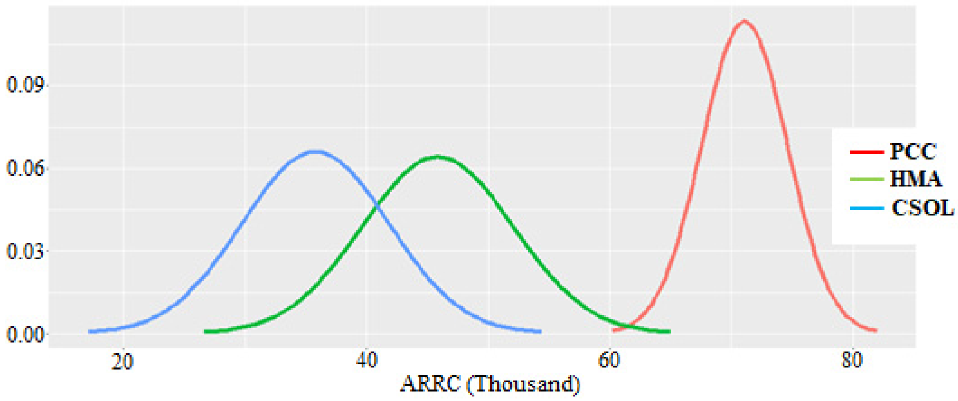

Figure 6. Histogram curve for the airport revenue reduction cost.

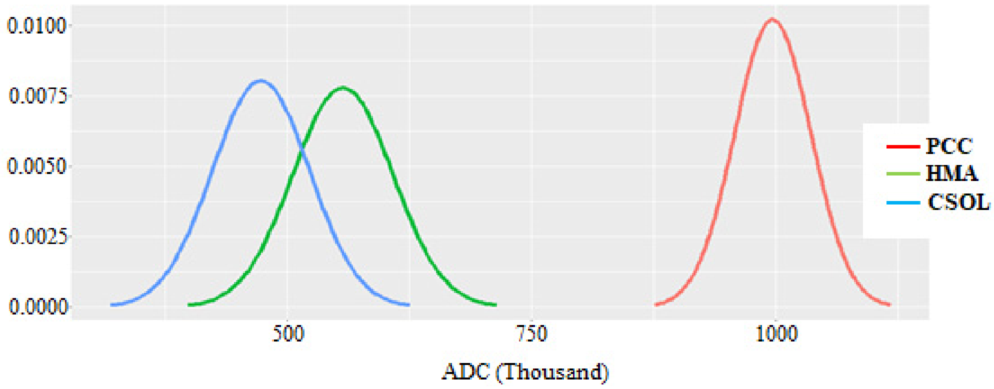

Figure 7. Histogram curve for the airplane delay cost.

4.3. LCCA Sensitivity Analysis

Sensitivity analysis can complement risk assessment. The sensitivity analysis of the simulation outputs can identify the input variables required to determine the resulting distributions. A high correlation coefficient indicates the higher significance of an input variable. All tornado plots in Figure 8 use a rank-order correlation that considers the assumption about the correlation between the input and output variables. A correlation coefficient less than 0.6 is generally insignificant [14].

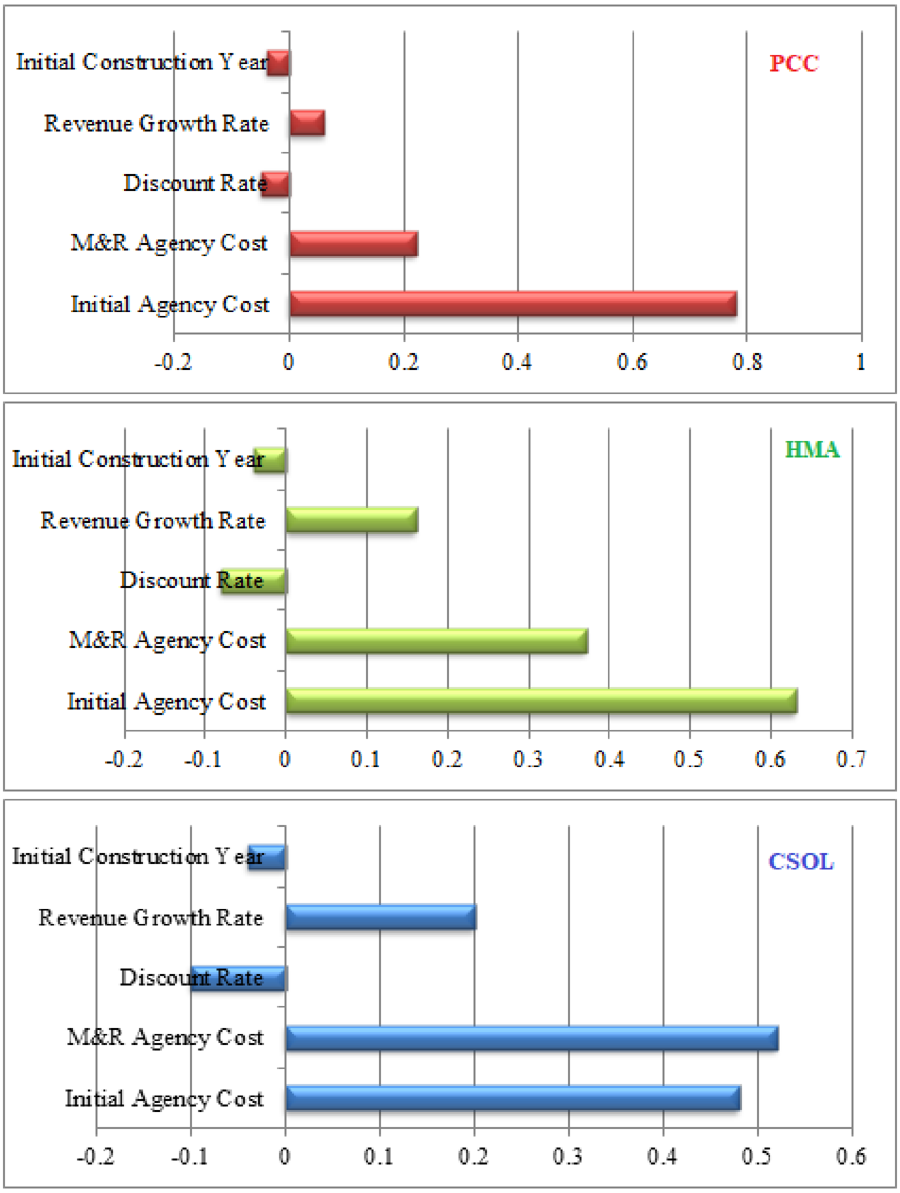

Figure 8. Correlation sensitivity plot for the NPVs for all options.

The correlation coefficient for initial agency costs in PCC and HMA is high, but is less than 0.6 for CSOL. The correlation coefficient for the M&R agency cost is high for all options, but not significant. An increase of one unit in the initial construction year and the discount year has a negative effect on LCCA. Postponing the project for a year or increasing the discount rate by 1% reduced the NPV by 4 to 10%. A 1% increase in revenue growth rate results in a 6 to 10% growth in the NPV for all options, whereas a 2% increase in the revenue growth rate could result in a 45% growth because of the compounded revenue growth mode.

Future studies can improve the LCCA for airports by investigating or developing methods that consider network delay in the system and expanding the probabilistic analysis of the delay costs. Another way to improve airport LCCA is by separately expanding the methods for quantifying the initial construction, maintenance, and rehabilitation and presenting them clearly in the results. Finally, researchers could use a dynamic programming algorithm to optimize the maintenance schedule.

4.4. Verification of the Results Using Different Software

In 2011, the ARA consultant developed the AirCost software for performing the LCCA of airport pavements. Table 10 shows a comparison of the programs in terms of LCCA scope and output.

Table 10. Comparison of the scope and analysis of LCCA.

Tool	Scope			Analysis	Output
	Direct Costs	Indirect Costs	Salvage Value		
PAVECO	Agency Costs Supplementary Costs	Airport Revenue Reduction Cost Fuel Delay Cost Crew Delay Cost Passenger Delay Cost Airplane Delay Maintenance Cost	Residual Value	Risk Assessment Probabilistic	Table Curve Histogram Cumulative Graph
AirCost	Agency Costs Supplementary Costs	Airport Revenue Reduction Cost	Residual Value	Limit Probabilistic	Table

The present study discusses the LCCA results in terms of the data sources, data range, input variation, and probabilistic analysis, and compares the tools used in a project. The results indicate that analysts should be cautious of the system boundary, data sources, and limitations when using the software to compare alternatives. Table 11 presents the results of cost analysis using different software.

Table 11. Comparison of the LCCA output ($1000).

Tool	Option	Scope			
		Direct Costs	Indirect Costs		Salvage Value
			ARRC	ADC	
PAVECO	PCC	5554	71	994	0.0
	HMA	5055	45	552	83
	CSOL	3646	35	468	83
AirCost	PCC	5458	64	N/A	0.0
	HMA	5033	42	N/A	87
	CSOL	3697	33	N/A	87

Figure 9 shows a screenshot of the results from AirCost that used the limited probabilistic method to compare four user-selected points. The AirCost results in the table do not present the considered risk assessment of the alternatives. The most significant difference between the outputs of the two programs is user cost, where PAVECO analyzed ARRC and ADC, whereas AirCost only considered ARRC. The difference in the ARRC is because the duration of maintenance activities in AirCost is dependent on the primary initial or rehabilitation activity. However, the maintenance in PAVECO could have differing revenue reductions and durations because it considers maintenance the primary, independent activity. Since the direct costs and salvage value are similar for both analyses, they could validate the PAVECO outputs.

Total NPV (in $1,000's)

	Statistic	Alternative 1	Alternative 2	Alternative 3	Alternative 4
Agency Costs	Mean	$5,458	$5,033	$3,697	
	Standard Deviation	$459	$474	$445	
	Minimum	$3,927	$3,849	$2,553	
	Maximum	$7,151	$6,825	$5,377	
	Percentile 1 (5%)	$4,755	$4,331	$3,044	
	Percentile 2 (50%)	$5,432	$4,997	$3,638	
	Percentile 3 (75%)	$5,733	$5,316	$3,959	
	Percentile 4 (95%)	$6,274	$5,839	$4,533	
User Costs	Mean	$64	$42	$33	
	Standard Deviation	$3	$6	$6	
	Minimum	$55	$29	$20	
	Maximum	$77	$66	$55	
	Percentile 1 (5%)	$59	$33	$24	
	Percentile 2 (50%)	$64	$41	$32	
	Percentile 3 (75%)	$67	$45	$36	
	Percentile 4 (95%)	$70	$53	$45	
Total Costs	Mean	$5,523	$5,075	$3,730	
	Standard Deviation	$461	$480	$451	
	Minimum	$3,988	$3,878	$2,573	
	Maximum	$7,225	$6,891	$5,432	
	Percentile 1 (5%)	$4,816	$4,367	$3,070	
	Percentile 2 (50%)	$5,496	$5,037	$3,671	
	Percentile 3 (75%)	$5,797	$5,361	$3,996	
	Percentile 4 (95%)	$6,343	$5,887	$4,574	
	Convergence Reached?	900	1000	1000	
	Iterations with repeated events?	0	0	0	

View Probabilistic EUAC Results | Print Results | Done

Figure 9. AirCost probabilistic results for PCC, HMA, and CSOL.

5. Conclusions

This study performed probabilistic and deterministic life-cycle cost analysis (LCCA) to contrast the effect of direct costs vis-à-vis indirect costs in airport pavement management. In this comprehensive model, the direct costs comprise the physical cost, salvage value, and supplementary costs, and the indirect costs are airport revenue reduction cost (ARRC) and airplane delay costs (ADC). The primary indirect cost in the previous pavement management systems is ADC as the primary user in the airports. ADC consists of the delay items related to fuel, crew, passenger, and maintenance delay costs in the system.

The results showed that ADC is a significant user cost and is usually higher than ARRC (more than 15 times) during the pavement life-cycle. The indirect costs for all three alternatives that include ADC in the calculation indicate the importance of including user costs in LCCA to managers, engineers, and stakeholders. Even though decision-makers often ignore indirect costs, this case study has shown that indirect costs make up

19.1, 12.1%, and 14.2% of the total direct costs in Portland cement concrete (PCC), hot mixed asphalt (HMA), and crack seat overlay (CSOL). The analysis also showed that PCC has higher ARRC and ADC. The LCCA method can separately analyze the direct and indirect costs of the initial construction, maintenance, and rehabilitation to illustrate the financial impact of each activity in the project framework. Most previous research did not consider maintenance cost, since routine maintenance makes up a small percentage of LCCA. However, maintenance cost makes up 10.2% and 14.2% of the total cost in HMA and CSOL, while the rehabilitation cost for PCC, HMA, and CSOL is 16.3%, 25.4%, and 35.2% of the total costs. These percentages underscore the importance of considering routine maintenance in airport pavement management. This study found a 35% probability of downside risk (overrun) for CSOL, 45% for HMA, and 55% for PCC. Future research could investigate network-level delays and the subsequent economic costs on different industries and businesses.

Author Contributions: Conceptualization, writing—original draft preparation and methodology, P.B.; Validation and review S.H.K.; Software, H.A.O.; Formal analysis, S.A.P.R.; Investigation and resources, A.M.A.-S.; data curation, A.M.; Visualization, M.B.; project administration, M.H.S.; Supervision and writing—review and editing, N.I.M.Y. All authors have read and agreed to the published version of the manuscript.

Funding: The authors would like to express their gratitude to Universiti Kebangsaan Malaysia for providing financial support for this work (DIP-2020-003).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data can be provided on request from corresponding authors.

Acknowledgments: The authors would like to acknowledge the support of Prince Sultan University for expert support and paying the Article Processing Charges (APC) of this publication.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Babashamsi, P.; Yusoff, N.I.; Ceylan, H.; Nor, N.G.; Salarzadeh Jenatabadi, H. Sustainable Development Factors in Pavement Life-Cycle: Highway/Airport Review. *Sustainability* **2016**, *8*, 248. [CrossRef]
2. FHWA. *Towards Sustainable Pavement Systems: A Reference Document, FHWA-HIF-15-002*; Federal Highway Administration: Washington, DC, USA, 2015.
3. Akbarian, M.; Swei, O.; Kirchain, R.; Gregory, J. Probabilistic Characterization of Life-Cycle Agency and User Costs: Case Study of Minnesota. *J. Transp. Res. Rec.* **2017**, *2639*, 93–101. [CrossRef]
4. Zaki, B.M.; Babashamsi, P.; Shahrir, A.H.; Milad, A.; Abdullah, N.H.; Hassan, N.A.; Yusoff, N.I.M. The impact of economic analysis methods on project decision-making in airport pavement management. *J. Teknol.* **2021**, *83*, 11–19. [CrossRef]
5. Caltrans. *Annual Average Daily Truck Traffic on the California State Highway System*; California Department of Transportation: Los Angeles, CA, USA, 2010.
6. FHWA. *Life-Cycle Cost Analysis: RealCost User Manual Version 2.5*; Federal Highway Administration: Washington, DC, USA, 2010.
7. ACPA. *Life-Cycle Cost Analysis: A Tool for Better Pavement Investment and Engineering Decisions, Engineering Bulletin EB011*; American Concrete Pavement Association: Rosemont, IL, USA, 2011.
8. FHWA. *Life-Cycle Cost Analysis Primer, FHWA-IF-02-047*; Federal Highway Administration: Washington, DC, USA, 2002.
9. FHWA. *Life-Cycle Cost Analysis for INDOT Pavement Design Procedures, FHWA/IN/JTRP-2004/28*; Project No. C-36-63Q, File No. 9-7-18, SPR-2712; Federal Highway Administration: Washington, DC, USA, 2004.
10. NHI. *Fundamentals of Life-Cycle Cost Analysis, National Highway Institute Course No. 13113, Participant Workbook, FHWA-NHI-09-024*; National Highway Institute: Arlington, VA, USA, 2008.
11. Riggs, J.L.; West, T.M. *Essentials of Engineering Economics*, 3rd ed.; McGraw-Hill Publishing: New York, NY, USA, 2008.
12. Di Mascio, P.; Antonini, A.; Narciso, P.; Greto, A.; Cipriani, M.; Moretti, L. Proposal and Implementation of a Heliport Pavement Management System: Technical and Economic Comparison of Maintenance Strategies. *Sustainability* **2021**, *13*, 9201. [CrossRef]
13. Swei, O.; Gregory, J.; Kirchain, R. Construction cost estimation: A parametric approach for better estimates of expected cost and variation. *Transp. Res. B-Meth.* **2017**, *101*, 295–305. [CrossRef]
14. Walls, J.; Smith, M.R. *Life Cycle Cost Analysis in Pavement Design-Interim Technical Bulletin*; The United States. Federal Highway Administration: Washington, DC, USA, 1998.

15. Pittenger, D. Evaluate airport pavement maintenance/preservation treatment sustainability using life-cycle cost, raw material consumption and 'greenroads' standards. *J. Transp. Res. Rec.* **2011**, *2206*, 61–68. [CrossRef]
16. ARA. *Life Cycle Cost Analysis for Airport Pavements, Airfield Asphalt Pavement Technology Program (AAPTP) Report 06-06*; Applied Research Associates: Auburn, AL, USA, 2011.
17. Duval, J. Asphalt keeps aircraft flying at Boeing field. *Asphalt* **2007**, *22*, 22–25.
18. Peshkin, D.G.; Hoerner, T.E.; Zimmerman, K.A. *Optimal Timing of Pavement Preventive Maintenance Treatment Applications*; Transportation Research Board: Downers Grove, IL, USA, 2004.
19. Winfrey, R.E. *Motor Vehicle Running Costs for Highway Economy Studies*; Winfrey: Washington, DC, USA, 1963.
20. Anderson, D.; Peterson, D.; Sheppard, L.; Sy, C. *Pavement Design Rehabilitation Strategies*; Project FHWA/UT-79-6, Utah DOT; Government Publications Clearinghouse: Springfield, VA, USA, 1979.
21. AASHTO. *Guide for Design of Pavement Structures*; American Association of State Highway and Transportation Officials: Washington, DC, USA, 1986.
22. AASHTO. *Guide for Design of Pavement Structures Part 1, Chapter 3, Life Cycle Cost Analysis for Pavements*; American Association of State Highway and Transportation Officials: Washington, DC, USA, 1993.
23. Hadley, W.O. *SHRP-LTPP General Pavement Studies: A Five-Year Report*; Texas Research and Development Foundation: Texas, TX, USA, 1994.
24. Hanna, A.N.; Tayabji, S.D.; Miller, J.S. *SHRP-LTPP Specific Pavement Studies: Five-Year Report*; National Academy of Sciences: Washington, DC, USA, 1994.
25. Smith, R.; Freeman, T.; Pendleton, O. *Pavement Maintenance Effectiveness*; Strategic Highway Research Program, National Research Council: Washington, DC, USA, 1993.
26. Crovetti, J.A.; Owusu-Ababio, S. *Investigation of Feasible Pavement Design Alternatives for WisDOT. The Unit*; Marquette University: Milwaukee, WI, USA, 1999.
27. Fagen, M.; Phares, B. Life-cycle cost analysis of a low-volume road bridge alternative. *J. Transp. Res. Rec.* **2000**, *1696*, 8–13. [CrossRef]
28. Embacher, R.A.; Snyder, M.B. Life-cycle cost comparison of asphalt and concrete pavements on low-volume roads; case study comparisons. *J. Transp. Res. Rec.* **2001**, *1749*, 28–37. [CrossRef]
29. Zimmerman, K.A.; Peshkin, D.G. Applying pavement preservation concepts to low-volume roads. *J. Transp. Res. Rec.* **2003**, *1819*, 81–87. [CrossRef]
30. Huang, Y.H.; Adams, T.M.; Pincheira, J.A. Analysis of life-cycle maintenance strategies for concrete bridge decks. *J. Bridge Eng.* **2004**, *9*, 250–258. [CrossRef]
31. Prarche, S. Infrastructure management and the use of public-private partnerships. In Proceedings of the CSCE Annual General Meeting and Conference, Yellowknife, NT, Canada, 15 November 2007.
32. Tighe, S. Guidelines for probabilistic pavement life cycle cost analysis. *J. Transp. Res. Rec.* **2001**, *1769*, 28–38. [CrossRef]
33. Salem, O.; AbouRizk, S.; Ariaratnam, S. Risk-based life-cycle costing of infrastructure rehabilitation and construction alternatives. *J. Infrastruct. Syst.* **2003**, *9*, 6–15. [CrossRef]
34. Osman, H. Risk-based life-cycle cost analysis of privatized infrastructure. *Transp. Res. Rec.* **2005**, *1924*, 192–196. [CrossRef]
35. Li, Z.; Madanu, S. Highway project level life-cycle benefit/cost analysis under certainty, risk, and uncertainty: Methodology with the case study. *J. Transp. Eng.* **2009**, *135*, 516–526. [CrossRef]
36. Wang, H.; Wang, Z. Deterministic and probabilistic life-cycle cost analysis of pavement overlays with different pre-overlay conditions. *Road Mater. Pavement Des.* **2017**, *20*, 58–73. [CrossRef]
37. Reigle, J.A.; Zaniewski, J.P. Risk-based life-cycle cost analysis for project-level pavement management. *J. Transp. Res. Rec.* **2002**, *1816*, 34–42. [CrossRef]
38. De Neufville, R.; Scholtes, S. *Flexibility in Engineering Design*; MIT Press: Cambridge, MA, USA, 2011.
39. Liu, R.; Smartz, B.W.; Descheneaux, B. LCCA and environmental LCA for highway pavement selection in Colorado. *Int. J. Sustain. Eng.* **2015**, *8*, 102–110. [CrossRef]
40. Sinha, K.C.; Labi, S. *Transportation Decision Making: Principles of Project Evaluation and Programming*; John Wiley & Sons: Hoboken, NJ, USA, 2011.
41. Peshkin, D.G.; Bruinsma, J.E.; Wade, M.J.; Delatte, N.J. *Accelerated Practices for Airfield Concrete Pavement construction. Volume I: Planning Guide, Report IPRF-01-G-002-02*; National Academy of Sciences: Skokie, IL, USA, 2006.
42. Pasupathy, R.; Labi, S.; Sinha, K.C. Optimal reconstruction periods for stochastically deteriorating infrastructures. *Comput.-Aided Civ. Infrastruct. Eng.* **2007**, *22*, 389–399. [CrossRef]
43. Ozbay, K.; Jawad, D.; Parker, N.A.; Hussain, S. Life-cycle cost analysis: State of the practice versus state of the art. *J. Transp. Res. Rec.* **2004**, *1864*, 62–70. [CrossRef]
44. Bilal, K.M.; Irfan, M.; Labi, S. Comparison of methods for evaluating pavement interventions: Evaluation and case study. *J. Transp. Res. Rec.* **2009**, *2108*, 25–36.
45. Gransberg, D.D.; Scheepbouwer, E. Infrastructure asset life cycle cost analysis issues. *Transactions* **2010**, *3*.
46. Rangan, G.K.; Thompson, M.R. Severity effects of dual-tandem and dual-tridem repeated heavier aircraft gear loading on pavement rutting performance. *Int. J. Pavement Eng.* **2006**, *7*, 179–190.

47. APA. American rides on us asphalt. In *Life Cycle Cost Analysis: A Position Paper, APA. IM 53*; Asphalt Pavement Alliance: Lanham, MD, USA, 2001.
48. Schumer, C.E.; Maloney, C.B. *Your Flight Has Been Delayed Again: Flight Delays Cost Passengers, Airlines, and the US Economy Billions*; The US Senate Joint Economic Committee, 2008.
49. Ferguson, J.; Kara, A.Q.; Hoffman, K.; Sherry, L. Estimating domestic US airline cost of delay based on the European model. *Transp. Res. Part C Emerg. Technol.* **2013**, *33*, 311–323. [CrossRef]
50. Halil, C.; Coree, B.J.; Gopalakrishnan, K.; Mathews, R.; Kota, T. *Rehabilitation of Concrete Pavements Utilizing Rubblization and Crack and Seat Methods*; CTRE Project 02-106; Iowa State University: Ames, IA, USA, 2005.
51. Hajek, J.J. *Common Airport Pavement Maintenance Practices*; Transportation Research Board: Washington, DC, USA, 2011.
52. Weiland, C.; Muench, S.T. Life-cycle assessment of reconstruction options for interstate highway pavement in Seattle, Washington. *J. Transp. Res. Rec.* **2010**, *2170*, 18–27. [CrossRef]
53. Zhang, H.; Keoleian, G.A.; Lepech, M.D.; Kendall, A. Life-cycle optimization of pavement overlay systems. *J. Infrastruct. Syst.* **2010**, *16*, 310–322. [CrossRef]