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Evaluating the Impact of Rehabilitation and Maintenance Strategies on User Costs for Airport Runways in Egypt

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ABSTRACT

Cairo International Airport in Egypt ranks among the most significant aviation hubs in Africa and the Middle East, handling 69,739 annual aircraft movements in 2016. The airport operates three runways designated as 05C-23C, 05L-23R, and 05R-23L, each representing distinct air traffic movement patterns and varying pavement conditions. This variation in runway characteristics necessitates the development of maintenance strategies that effectively incorporate life cycle cost analysis components to optimize operational efficiency and cost-effectiveness.

In 2016, deterioration of pavement conditions was observed in both runways 05C-23C and 05L-23R, and the authority proposed two maintenance alternatives based on financial models rather than economic models. Moreover, One of the problems facing developing countries in airport management, particularly in cases of low daily aircraft movements (large spare runway capacities), is ignoring some elements of life cycle cost analysis, specifically user costs, which represent the loss in revenues, including fuel taxes, aircraft landing fees, passenger services, and others, as a result of runway closures for runway maintenance operations.

This study evaluated three runways with different pavement rehabilitation alternatives using life-cycle cost analysis, revealing that Alternative 3 (newly proposed) demonstrated superior economic performance with user cost reductions ranging from 213.0% to 369.5% compared to conventional alternatives across all runway configurations, validated through both NPV and EUAC methodologies. User costs as a percentage of total project costs exhibited a strong correlation with operational intensity, ranging from 10-14% for low-traffic runways to 43-53% for very high-traffic facilities, with maintenance frequency significantly influencing cost proportions. Probabilistic analysis incorporating uncertainty factors yielded 12.5% higher NPV estimates and 2.9% elevated EUAC values compared to deterministic approaches, with a combined 7.7% average increase, highlighting the importance of risk-based planning in airport pavement rehabilitation projects.

Keywords: Life Cycle Cost Analysis (LCCA), User Cost, AirCost LCCA Software, NPV and EUAC analyses.

1. INTRODUCTION AND LITERATURE REVIEW

Life-cycle cost analysis (LCCA) for airport maintenance has evolved beyond traditional direct costs. The Federal Aviation Administration requires that "life-cycle costs shall be considered in AIP procurement where specified in bidding documents" under Title 49, CFR, Part 18 [1]. A comprehensive airport pavement management system should consider indirect costs such as fuel, crew, passenger delay, aircraft maintenance, and loss of airport revenue [1]. Airport Revenue Reduction Cost (ARRC) and Airline Delay Cost (ADC) are considered critical indirect/user cost metrics in airport maintenance LCCA [2].

Significant research gaps exist for airport maintenance user-cost applications. Limited research addresses budget prioritization at airports, with studies mostly related to highways rather than aviation infrastructure [3]. Published works on airport financial performance are scarce, indicating an indisputable need for more research [4]. User costs were omitted from many whole-of-life cost analyses for airport pavements, creating a significant gap that may lead to suboptimal maintenance investment decisions [5]. The absence of systematic guidelines makes LCCA difficult for airports [6].

Airline user costs represent the most substantial component of airport maintenance-related user costs. In 2023, the average cost of aircraft block time for U.S. passenger airlines was $100.80 per minute [7]. Maintenance and overhaul constitute 46% of total aircraft operating expenses, while 15% of airline Direct Operating Costs originate from maintenance activities [8,9]. Airlines focus on the maintenance process during operation phases, where airport maintenance activities directly impact operational efficiency [10]. FAA/Nextor estimated annual delay costs at $33 billion in 2019, while passenger time is valued at $47 per hour [7]. The 487 U.S. commercial airports support 12.8 million jobs and produce $1.8 trillion annual output [11].

Current methodological approaches for incorporating user costs vary significantly in complexity. Probabilistic and deterministic LCCA can contrast direct versus indirect costs in airport pavement management [2]. Analysis should focus on both user travel costs and transportation service supply costs, including airport and airline costs [12]. However, traditional Cost-Benefit Analysis approaches may underestimate actual user cost impacts [13]. Advanced optimization approaches demonstrate that linear models can handle complete daily airport operations within minutes, suggesting potential 30% cost reductions during recovery operations [14]. Emerging technologies like BIM-based predictive maintenance could minimize user costs [15]. Industry experts acknowledge this remains "the first attempt to quantify the effect of ageing on maintenance costs," indicating comprehensive user cost frameworks require continued research and empirical validation [16].

Three runways were selected as a case study based on their previously mentioned characteristics. To accomplish these research objectives, a comprehensive experimental program was developed and executed. The subsequent section provides a detailed description of the study methodology. AIR COST Software represents a dedicated analytical platform designed for performing Life-Cycle Cost Analysis (LCCA) within the aviation sector.

2. STUDY METHODOLOGY

Figure 1 Runway 05C-23C
Location on Cairo airport in Cairo

To accomplish the research objectives, several sequential phases and activities were executed. Three runways (05C-23C, 05L-23R, and 05R-23L) at Cairo Airport were selected for conducting LCCA comparative analysis of alternatives, as illustrated in Figure 1.

The first phase encompasses three activities: initially, air traffic data and growth rate collection; secondly, existing pavement data acquisition, including runway paving history, current pavement sections, and critical defects affecting pavement conditions; and thirdly, LCCA and financial data compilation. The second phase involved proposing pavement maintenance and rehabilitation approaches comprising three alternative techniques and six maintenance and rehabilitation strategies, followed by conducting a life cycle cost analysis using both deterministic and probabilistic methodologies. The final phase consisted of data analysis and discussion to derive study conclusions and recommendations, as depicted in Figure 2.

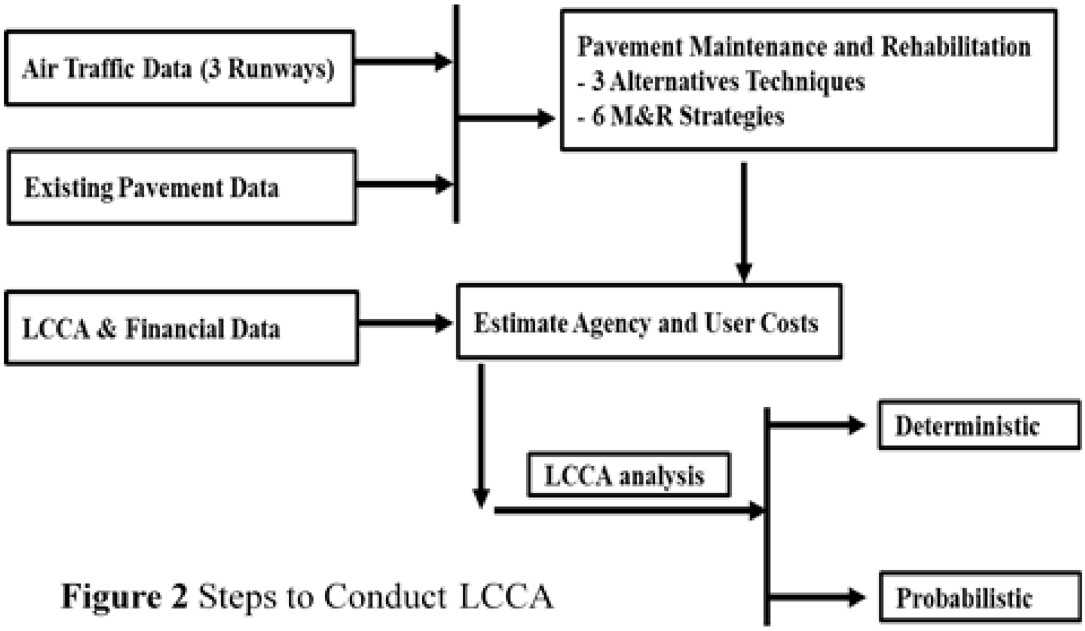

Figure 2 Steps to Conduct LCCA

Table (1) discount rates historical data in Egypt

Discount Rates	
Date	Discount Rate (%)
22/01/2002	10.00
22/01/2006	9.00
21/09/2008	11.50
15/02/2009	10.50
28/11/2011	9.50
24/03/2013	10.25
20/07/2014	9.75
27/12/2015	9.75
03/11/2016	15.25

2.1 Air Traffic Data

Cairo Airport operates three runways with varying traffic volumes: 05C-23C handles the highest annual air traffic with 45,383 movements, 05L-23R managing moderate traffic with 16,069 movements, and 05R-23L accommodating the lowest traffic with 8,287 movements in 2016, as demonstrated in Table 1, where runway 05R-23L consistently maintained the lowest annual traffic across most years. Additionally, Cairo Airport Company (CAC) provided air traffic mix data spanning 2008 to 2016, with a 10% growth factor applied based on CAC's future projections, as presented in Table 2 and Figure 3.

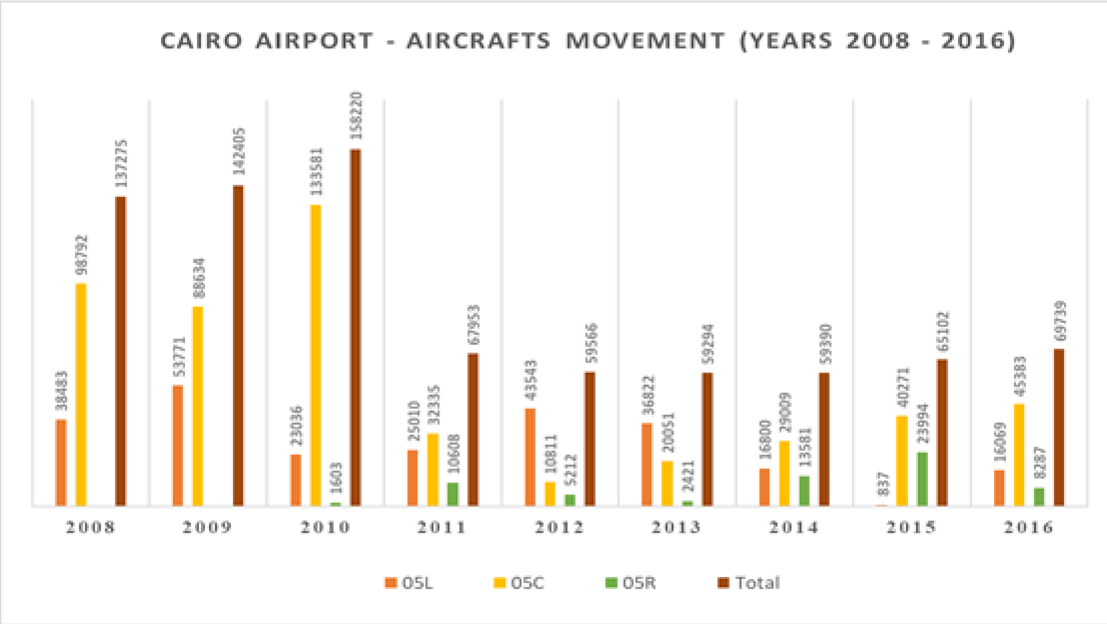

Figure 3 Cairo airport runways - air traffic movement (2008-2016)

Table (2) Runway 05C-23C air traffic Mix 2016

Id	Aircraft	Gross Taxi Weight (Ibs)	Main Landing Gear Width (m)	Annual Departures		
				05C	05L	05R
1	**A320-200 std**	162925	6	6787	6486	179
2	**DHC-7**	43799	4	2193	393	95
3	**B777-300**	662000	12	1800	1229	50
4	**A330-300 std**	509050	10	1468	927	41
5	**A321-200 std**	197100	6.5	1435	1036	55
6	**B737-400**	150500	5.5	1417	1177	23
7	**A310-200**	315041	7	615	72	17
8	**CRJ900**	85000	5	568	131	30
9	**B747-200/300**	836000	14	369	73	11
10	**A319-100 std**	141978	6	368	443	6
11	**A340-200**	575175	12	343	281	25
12	**C550/551**	15000	3.5	323	21	2
13	**MD-11**	633000	11	227	33	8
14	**B787-8**	503500	11	222	153	3
15	**EMB-170 STD**	79697	4.5	191	121	4
16	**EMB-190 STD**	105712	5.5	184	165	8
17	**CL-604/605**	48200	4	182	116	3
18	**B767-200**	368000	10	160	82	7
19	**G-V/G500/G550**	90900	5	139	146	3
20	**A300-B4/C4**	365747	9	134	0	5
21	**Fokker 50**	45900	3.5	128	38	2
22	**Gulfstream-G-IV**	75000	5	98	76	2
23	**HS125**	25000	4	64	32	0
24	**TU-134A**	108027	6	58	0	0
25	**An-124**	877430	14	48	0	0
26	**B757-200**	256000	9	43	0	0

27	**Learjet 45/55B**	21500	3.5	33	12	0
28	**C-130**	155000	8	31	51	2
29	**ERJ-135**	42108	4	28	19	0
30	**C-123**	60000	7	26	0	0
31	**IL-76T**	376990	13	26	53	0
32	**C-17A**	585000	14	19	21	3
33	**Others**			373	42	0
TOTAL				**20100**	**13429**	**584**

2.2 Existing Pavement Data

The structural integrity of the pavement cross-section is generally good, with no signs of structural failure. The current pavement surface levels and smoothness are acceptable. Furthermore, pavement layers were summarized as shown in as presented in Table 3 and Table 4.

Table (3) Paving History of The Runways

Runways	**Dimensions (m)**	**Pavement Surface**	**Pavement Works (Year)**				**PCN**
			Initial Constr.	**Existing M&R**		**Government Expected M&R**	
				History	**Latest**		
05C/23C	4000 x 60	Asphalt	1982	1996, 2009	2014	2017	100 FBWU
05L/23R	3300 x 60	Asphalt	1963	1993, 2010	2012	2015	100 FBWU
05R/23L	4000 x 60	Asphalt	2010	---	---	---	100 FBWT

Table (4) Existing Pavement Sections and Layers

PAVEMENT LAYERS	**05C-23C**		**05L-23R**		**05R-23L**	
	Main Width (60m)	**Shoulder Width (12.5m)**	**Main Width (60m)**	**Shoulder Width (12.5m)**	**Main Width (60m)**	**Shoulder Width (12.5m)**
ASPHALT LAYERS	12 cm	13 cm	12 cm	13 cm	12 cm	13 cm
EXISTING ASPHALT	28 cm	---	---	---	31 cm	---
BITUMINOUS BASE	---	---	18 cm	---	---	---
BASE COURSE	40 cm	20 cm	45 cm	20 cm	20 cm	20 cm
SUB-BASE COURSE	---	---	---	---	20 cm	---
SOIL CBR	10%		10%		10%	

- **Visual inspection**

Visual inspection for pavement condition index (PCI) was performed in 2016, encompassing 456 PCI samples for runway width and 114 PCI samples for runway shoulders, with average PCI results for all techniques presented in Table 5.

Table 5. PCI Results Comparison Between New Approach And Egyptian Traditional Techniques

Runway	**Pavement Condition Index (PCI)**				
	Egyptian Traditional Techniques		**New Approach**		
	ALTER (1) & ALTER (2)		**ALTER (3)**		
	Runway width (60m)	Runway shoulders (25m)	Main Runway width (15m)	Other Runway width (45m)	Runway shoulders (25m)
05C-23C	**64**	**71**	**59**	**80**	**73**
05L-23R	**78**	**82**	**71**	**85**	**84**
05R-23L	**91**	**87**	**90**	**93**	**89**

- **Structural design check**

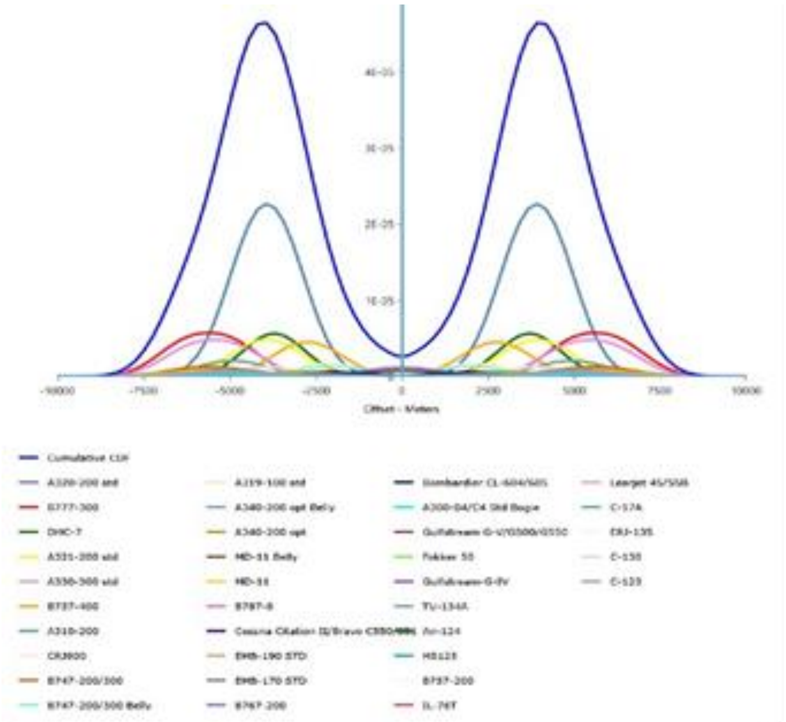

Figure 4 Calculated cumulative damage factor (CDF) using software FARFIELD

Structural design verification for existing pavement sections, minimum required thickness, and cumulative damage factor (CDF) were performed using FARFIELD 2.1.1 software, incorporating air traffic mix data, 10% growth factor, and 30-year design life parameters. The calculated service life for existing sections exceeded 30 years with a cumulative damage factor of 0.00005, as illustrated in Figure 4.

2.3 LCCA & Financial Data

The primary factors influencing probabilistic LCCA statistics are discount rates and unit costs for pay items. Table 6 presents historical LCCA data for Cairo Airport in Egypt based on Central Bank of Egypt statistics, while Table 2 displays unit costs for pay items referenced from the unified pricing assessment of the Egyptian National Road Project for 2017.

Table (6) LCCA historical data in Egypt

Items	LCCA Elements
Analysis Period	30 years
Discount Rates	-Deterministic (10.5%)
	-Normal Probabilistic (mean 10.5%, Std Dev 0.25)
Supplemental Costs	- Administrative Cost 2%
	- Engineering cost 5%
	- Ground traffic control 2%
Pay Item Unit Cost	Std Dev 0.25
Revenues growth rates	3%
Percentage of daily revenue reduction	15%

Table (7). Pay item unit costs Egyptian pounds (EGP) in the Year 2017

Item	Unit	Mean Unit Cost (EGP)	Std Dev Unit Cost (EGP)
Milling 5cm	Sq.m	12	3.0
Filling Cracks	Sq.m	22.5	5.6
Pavement Removal	Sq.m	45	11.3
Base Course	Sq.m	170	42.5
MC	Sq.m	18.5	4.6
RC	Sq.m	6	1.5
Stabilized base 13 cm	Sq.m	202	50.5
Binder Course 6 cm	Sq.m	91	22.8
Glass grid 120kN	Sq.m	40	10.0
Micro Surfacing	Sq.m	55	13.8
Wearing a surface of 5 cm	Sq.m	91	22.8
Marking Works	Sq.m	275	68.8
Lighting Works, including all electrical works	Lumb No.	25000	6250.0

3. Pavement Maintenance and Rehabilitation Techniques and Strategies

The primary distinction between the New Approach and Egyptian Traditional Techniques involves runway width segmentation based on anticipated damage areas, with Egyptian Traditional Techniques categorized into two alternatives. Alternative 1 (Governmental System) applies rehabilitation and maintenance strategies across the entire runway width (60m), Alternative 2 (Expert System) divides the runway width into 30m main and 30m secondary sections for targeted rehabilitation and maintenance strategies, and Alternative 3 (Proposed System) segments the runway width into 15m main and 45m secondary sections for specialized rehabilitation and maintenance approaches, as detailed in Tables 8 and 9. The proposed pavement interventions, rehabilitation and maintenance scheduling, and construction timeframes are presented in Table 10.

Table 8. Comparison Between New Approach and Egyptian Traditional Techniques

Elements	Egyptian Traditional Techniques	New Approach
Alternative Pavement Strategies	**Alter (1). Governmental System** Runway width (60m) + Runway shoulders (25m)	**Alter (3). Proposed System** Runway width (15m) + Other Runway width (45m)

	Alter (2). Experts System - Runway width (30m) + Other Runway width (30m) + Runway shoulders (25m)	+ Runway shoulders (25m)

Table 9. The proposed pavement works, rehabilitation and maintenance schedule time, and construction duration time.

Maintenance & Rehabilitation Strategies			
A	**B**	**C**	**D**
11 cm Asphalt,13 cm Macadam, and 30cm Base course	**11 cm Asphalt, and 20cm Base course**	**5cm Wearing ,6cm binder (1) ,6cm binder (2), and Maintenance**	**5cm Wearing ,6cm binder, and Maintenance**
E	**F**	**G**	**H**
5cm Wearing and Maintenance	**5cm Wearing, Glass grid, and Maintenance**	**Micro Surfacing and Maintenance**	**Cracks Maintenance**

Table 10. The proposed pavement works, rehabilitation and maintenance schedule time, and construction duration time.

Alternative		Description	Works						Years After,
			05C-23C	**Time (Day)**	**05L-23R**	**Time (Day)**	**05R-23L**	**Time (Day)**	
Alter (1)	**Initial Construction & Rehabilitation**	**Runway width (60m)**	**A**	**180**	**C**	**150**	**D**	**120**	**0,14, and28**
		Runway shoulders (25m)	**B**		**D**		**E**		
Alter (2)	**Initial Construction**	**Main Runway width (30m)**	**D**	**90**	**D**	**90**	**D**	**90**	**0,14, and28**
		Other Runway width (30m)	**E**		**E**		**E**		
		Runway shoulders (25m)	**H**		**H**		**H**		
	Rehabilitation	**Main Runway width (30m)**	**E**	**75**	**E**	**75**	**E**	**75**	**7, and21**
		Other Runway width (30m)	**E**		**E**		**E**		
		Runway shoulders (25m)	**H**		**H**		**H**		
Alter (3)	**Initial Construction**	**Main Runway width (15m)**	**F**	**30**	**F**	**30**	**F**	**30**	**0,14, and28**
		Other Runway width (45m)	**H**		**H**		**H**		

		Runway shoulders (25m)	**H**		**H**		**H**		
		Main Runway width (15m)	**G**		**G**		**G**		
	rehabilitations	**Other Runway width (45m)**	**H**	**15**	**H**	**15**	**H**	**15**	**7, and21**
		Runway shoulders (25m)	**H**		**H**		**H**		

4. Estimate Agency Costs and User Costs

Total Agency costs contain Physical Costs (Paving Works, Marking Works, and Lighting Works and Supplemental Costs(Administrative Costs 2%, Engineering costs 5%, and Ground traffic control 2%, as presented in Table 11.

The main elements of user cost (loss of daily revenues, their percentage (15-20%) for airport consisting of 3 runways and Revenue growth rates 3% compound) which contain Landing fee daily revenue and Passenger facility charges daily revenue and Fuel flowage daily revenue as presented in Table 12.

4.1 Estimate Agency Costs

Table 11. Total Agency Costs in millions (EGP) for various runways in different alternatives

Item / Runway	05C-23C	05L-23R	05R-23L
Average number of passengers/flights		100	
Average landing fee (EGP /aircraft)		25000	
Passenger facility charge (EGP /enplaned (departure) passenger)		200	
Average aircraft fuel usage (Litre/flight)		1211	
Fuel flowage fee (EGP/Litre)		2	
Daily arrival (flights)	70	8	21
Daily passenger deplanements (arrival)	7000	800	2100
Daily departing (flights)	55	37	2
Daily passenger enplanements (dep)	5500	3700	200
Landing fee daily revenue (EGP)	**1,750,000**	**200,000**	**525,000**
Passenger facility charges daily revenue (EGP)	**1,100,000**	**740,000**	**40,000**
Fuel flowage daily revenue (EGP)	**133,246**	**89,638**	**4,845**
Total daily revenue (EGP)	**2,983,246**	**1,029,638**	**569,845**
Percentage of daily revenues reduction		**15%**	
Total daily revenue reduction (EGP)	**447,487**	**154,446**	**85,477**

4.2 Estimate User Costs

Table 12. Total daily revenue calculations for various runways

Runway	Total Agency Cost in millions (EGP)					
	Alter (1)		Alter (2)		Alter (3)	
	Initial Const.	Rehab.	Initial Const.	Rehab.	Initial Const.	Rehab.
05C-23C	164.47	164.47	60.71	47.63	29.25	10.73
05L-23R	100.45	100.45	50.09	39.30	24.13	8.86
05R-23L	84.69	84.69	60.71	47.63	29.25	10.73

5. RESULTS AND DISCUSSION

5.1. Evaluation of User Costs in Various Alternatives Techniques

Table (13) illustrates the net present value (NPV) for user costs across alternatives 1, 2, and 3. For runway 05C-23C, user costs vary from 121.91, 89.15, and 25.96 million EGP, respectively. For runway 05L-23R, user costs vary from 35.06, 30.77, and 8.96 million EGP respectively. For runway 05R-23L, user costs vary from 15.52, 17.03, and 4.96 million EGP respectively.

Table 13. NPV Costs distribution for various runways in different alternatives

NPV Costs in Millions (EGP)									
Cost Item	05C-23C			05L-23R			05R-23L		
	Alt.1	Alt.2	Alt.3	Alt.1	Alt.2	Alt.3	Alt.1	Alt.2	Alt.3
Agency Costs	219.91	113.41	46.37	134.33	93.58	38.26	113.26	113.41	46.37
User Costs	121.91	89.15	25.96	35.06	30.77	8.96	15.52	17.03	4.96
TOTAL	334.40	200.36	71.23	165.12	122.53	46.32	125.15	128.24	50.24

Table (14) illustrates the equivalent uniform annual costs (EUAC) for user costs across alternatives 1, 2, and 3. For runway 05C-23C, user costs vary from 13.47, 9.85, and 2.87 million EGP, respectively. For runway 05L-23R, user costs vary from 3.88, 3.40, and 0.99 million EGP respectively. For runway 05R-23L, user costs vary from 1.72, 1.88, and 0.55 million EGP respectively.

Table 14. EUAC Costs distribution for various runways in different alternatives

EUAC Costs in Millions (EGP)									
Cost Item	05C-23C			05L-23R			05R-23L		
	Alt.1	Alt.2	Alt.3	Alt.1	Alt.2	Alt.3	Alt.1	Alt.2	Alt.3
Agency Costs	24.31	12.54	5.12	14.85	10.34	4.23	12.52	12.54	5.12
User Costs	13.47	9.85	2.87	3.88	3.40	0.99	1.72	1.88	0.55
TOTAL	36.96	22.15	7.87	18.25	13.54	5.12	13.83	14.17	5.55

Figure (5,6) illustrates Alternative 3 demonstrates a substantially significant user cost advantage when compared to the conventional alternatives 1 and 2 approaches. In NPV analysis, alternative 3 achieves user cost reductions of 369.5% and 243.4% compared to alternatives 1 and 2, respectively, for the highest-impact runway (05C-23C). For the lowest-impact runway (05R-23L), alternative 3 maintains cost reductions of 213.0% and 243.5% compared to alternatives 1 and 2, respectively. The EUAC evaluation confirms these findings, with alternative 3 showing user cost reductions of 369.4% and 243.2% compared to alternatives 1 and 2, respectively, for runway 05C-23C.

These results establish that the innovative alternative three approach represents the most economically efficient pavement rehabilitation solution for user cost minimization across all runway configurations evaluated. The analysis consistently demonstrates that alternative 3 delivers superior user cost performance compared to traditional methodologies, establishing it as the optimal selection for projects prioritizing user impact reduction in airport pavement rehabilitation initiatives.

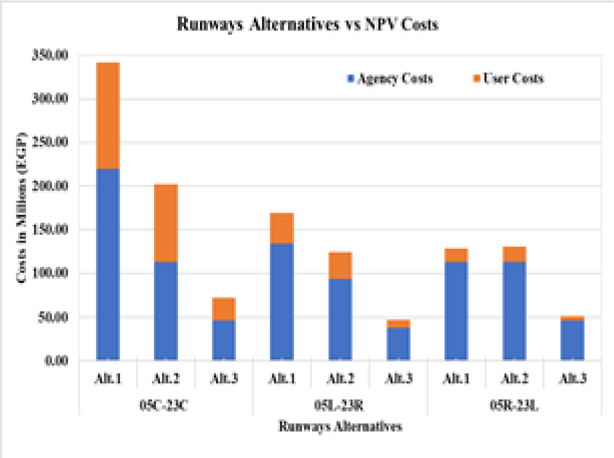

Figure 5 NPV Costs distribution for various runways in different alternatives.

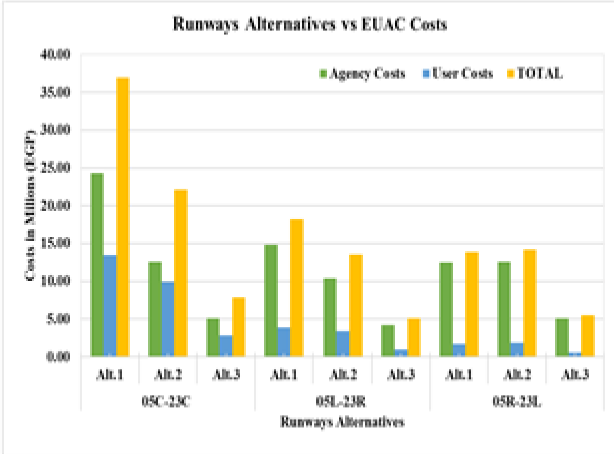

Figure 6 EUAC Costs distribution for various runways in different alternatives.

5.2. Analysis of User Costs to Total Cost in different runway types

Table (15) illustrates the user cost percentage and maintenance rehabilitation (M&R) duration across alternatives 1, 2, and 3. For runway 05C-23C, with 125 daily operations, user costs as a percentage of the total cost vary from 36.46%, 44.49%, and 36.44%, respectively. Furthermore, M&R total days vary from 540, 420, and 120 days respectively. For runway 05L-23R with 45 daily operations, user costs as a percentage of the total cost vary from 21.24%, 25.11%, and 19.34%, respectively. Furthermore, M&R total days vary from 450, 420, and 120 days respectively. For runway 05R-23L, with 23 daily operations, user costs as a percentage of the total cost vary from 12.41%, 13.28%, and 9.87%, respectively. Furthermore, M&R total days vary from 360, 420, and 120 days respectively.

Table 15. Daily Operation (movement) vs % of User Costs to Total Cost for various runways in different alternatives

Runways	Daily Operation (movement)	Alt.1		Alt.2		Alt.3	
		% OF User Costs to Total Cost	M&R total days	% OF User Costs to Total Cost	M&R total days	% OF User Costs to Total Cost	M&R total days
05C-23C	**125**	**36.46%**	**540**	**44.49%**	**420**	**36.44%**	**120**
05L-23R	**45**	**21.24%**	**450**	**25.11%**	**420**	**19.34%**	**120**
05R-23L	**23**	**12.41%**	**360**	**13.28%**	**420**	**9.87%**	**120**

Alternative 3 demonstrates substantially superior performance in minimizing both user cost impact and project duration compared to alternative 1 and 2 traditional approaches. In terms of user cost percentage, alternative 3 achieves the lowest proportion across all runways, ranging from 9.87% to 36.44%. In terms of project duration, alternative 3 is consistently 200% to 350% faster than alternatives 1 and 2, completing M&R activities in 120 days compared to 360-540 days for conventional methods.

Figure (7) illustrates that user costs as a percentage of total project costs vary significantly based on daily operational volume. For low-traffic runways with approximately 25 daily operations, user costs represent between 10% to 14% of total project costs. Medium-traffic runways experiencing around 50 daily operations show user costs ranging from 16% to 22% of total costs. High-traffic runways with 100 daily operations demonstrate user costs comprising 30% to 37% of total project expenditures. Very high-traffic runways handling 150 daily operations exhibit user costs accounting for 43% to 53% of total project costs.

The higher user costs percentage of total project costs observed for alternative 2 (25.11%) compared to alternative 1 (21.24%) on runway 05L-23R may be attributed to different growth rates in operational costs over time. Alternative 2, with its more frequent 7-year maintenance cycles, is more susceptible to escalating user costs. These cumulative growth effects compound with each maintenance cycle, causing user costs to represent a progressively larger percentage of total project costs.

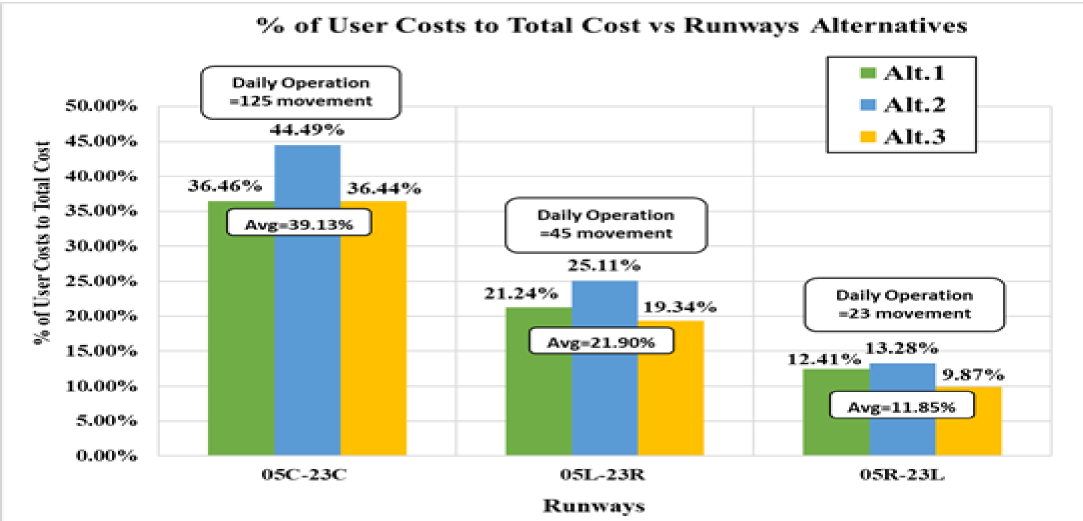

Figure (7) % of User Costs to Total Cost for various runways in different alternatives

5.3. Variation in User Costs due to LCCA Simulation Using NPV and EUAC analyses

Table (16) illustrates NPV Analysis illustrates the user costs across alternatives 1, 2, and 3 under deterministic and probabilistic conditions. For runway 05C-23C, deterministic user costs vary from 121.91, 89.15, and 25.96 million EGP, respectively. Furthermore, probabilistic user costs vary from 136.97, 101.44, and 28.87 million EGP, respectively. For runway 05L-23R, deterministic user costs vary from 35.06, 30.77, and 8.96 million EGP, respectively. Furthermore, probabilistic user costs vary from 39.39, 35.01, and 9.96 million EGP respectively. For runway 05R-23L, deterministic user costs vary from 15.52, 17.03, and 4.96 million EGP, respectively. Furthermore, probabilistic user costs vary from 17.44, 19.38, and 5.51 million EGP, respectively.

The EUAC Analysis illustrates the equivalent uniform annual costs under deterministic and probabilistic conditions. For runway 05C-23C, deterministic user costs vary from 13.47, 9.85, and 2.87 million EGP, respectively. Furthermore, probabilistic user costs vary from 13.91, 10.14, and 2.96 million EGP, respectively. For runway 05L-23R, deterministic user costs vary from 3.88, 3.40, and 0.99 million EGP, respectively. Furthermore, probabilistic user costs vary from 4.00, 3.50, and 1.02 million EGP respectively. For runway 05R-23L, deterministic user costs vary from 1.72, 1.88, and 0.55 million EGP, respectively. Furthermore, probabilistic user costs vary from 1.77, 1.94, and 0.56 million EGP, respectively.

Table 16. NPV and EUAC User Costs distribution in Millions (EGP) for various runways in different alternatives (Deterministic vs Probabilistic Analysis)

LCCA Analysis		05C-23C			05L-23R			05R-23L		
		Alt.1	**Alt.2**	**Alt.3**	**Alt.1**	**Alt.2**	**Alt.3**	**Alt.1**	**Alt.2**	**Alt.3**
NPV	**Deterministic**	**121.91**	**89.15**	**25.96**	**35.06**	**30.77**	**8.96**	**15.52**	**17.03**	**4.96**
	Probabilistic	**136.97**	**101.44**	**28.87**	**39.39**	**35.01**	**9.96**	**17.44**	**19.38**	**5.51**
EUAC	**Deterministic**	**13.47**	**9.85**	**2.87**	**3.88**	**3.40**	**0.99**	**1.72**	**1.88**	**0.55**
	Probabilistic	**13.91**	**10.14**	**2.96**	**4.00**	**3.50**	**1.02**	**1.77**	**1.94**	**0.56**

Figure (8,9) illustrates the Risk Assessment Results demonstrate that incorporating uncertainty factors into the life cycle cost analysis yields consistently higher cost estimates compared to deterministic approaches. The probabilistic analysis reveals an overall average increase of 12.5% in Net Present Value calculations over deterministic estimates when evaluating all alternatives and runway configurations. Similarly, the Equivalent Uniform Annual Cost methodology shows an overall average increase of 2.9% in probabilistic estimates compared to deterministic values across all evaluated scenarios. When integrating both NPV and EUAC analytical frameworks, the probabilistic approach exhibits an overall average increase of 7.7% compared to deterministic analysis across all alternatives and runway combinations, indicating that uncertainty considerations add a significant cost premium that must be factored into comprehensive airport pavement rehabilitation project planning and decision-making processes.

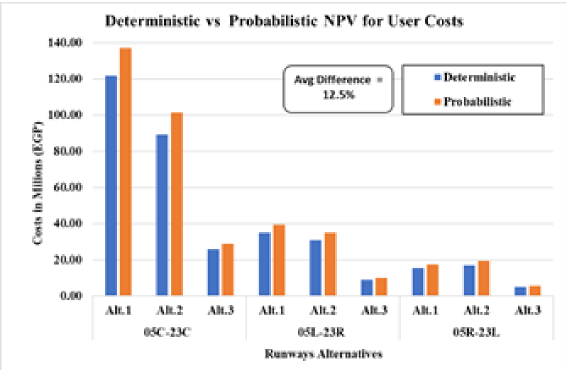

Figure (8) NPV User Costs distribution in Millions (EGP) for various runways in different alternatives (LCCA Analysis)

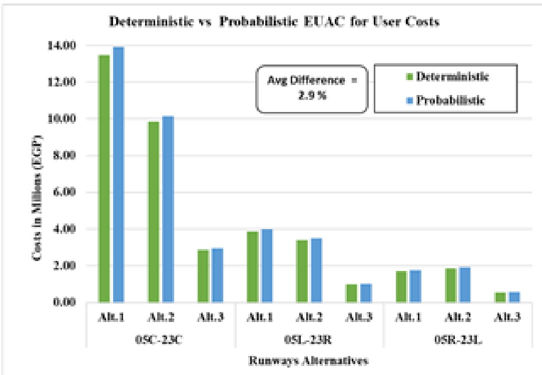

Figure (9) EUAC User Costs distribution in Millions (EGP) for various runways in different alternatives (LCCA Analysis)

1. CONCLUSIONS AND RECOMMENDATIONS

Based on the analysis of the study results, the following conclusions and recommendations can be summarized:

- Alternative 3 demonstrates substantial user cost advantages over conventional alternatives 1 and 2. NPV analysis shows alternative 3 achieves cost reductions of 369.5% and 243.4% compared to alternatives 1 and 2 for runway 05C-23C and 213.0% and 243.5% for runway 05R-23L. EUAC evaluation confirms these findings with 369.4% and 243.2% reductions for runway 05C-23C.
- User costs as a percentage of total project costs vary with operational volume: low-traffic runways (25 operations) show 10-14%, medium-traffic (50 operations) show 16-22%, high-traffic (100 operations) show 30-37%, and very high-traffic runways (150 operations) exhibit 43-53%. Alternative 2's a higher

percentage (25.11% vs 21.24% for alternative 1) on runway 05L-23R results from frequent 7-year maintenance cycles creating cumulative cost escalation.

- Probabilistic analysis reveals a 12.5% average increase in NPV calculations and a 2.9% increase in EUAC estimates over deterministic approaches. Combined analysis shows a 7.7% average increase, indicating uncertainty factors add significant cost premiums requiring consideration in airport pavement rehabilitation planning.
- One of the most important points of the research is the necessity of paying attention to the impact of user cost on total costs, even under conditions of low air traffic or even multiple runways at the airport. Also, airport management authorities must be required to select the optimal maintenance system that integrates with the maintenance duration so as not to cause a reduction in airport revenues and, consequently, the user cost and total cost.

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