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Comparative Life Cycle Cost Analysis of Proposed Pavement Evaluation Approach and Traditional Techniques at Cairo Airport, Egypt

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ABSTRACT

Cairo International Airport, located in Cairo, Egypt, is the second busiest airport in Africa, serving more than 16 million passengers and 69739 aircraft movements in 2016. Cairo Airport includes three Runways. Runway 05C-23C One of the crucial runways in the airport serves the maximum air traffic equal to 45383 aircraft movements.

In 2016, there was a noticeable rapid deterioration in the pavement condition of the 05C-23C runway due to the significant ageing of the pavement layer; the government decided to choose the traditional method for rehabilitation, which involves a long-term rehabilitation strategy lasting up to 14 years with minimal maintenance during only emergencies.

Deep investigations were conducted to choose the best rehabilitation or maintenance strategy due to life cycle cost analysis using AirCost LCCA software. This research identifies that the new proposed approach is more cost-effective, being on average 470% and 290% cheaper than the traditional methods (Governmental System and Experts System), respectively, in terms of Net Present Value (NPV) and Equivalent Uniform Annual Cost (EUAC), using both deterministic and probabilistic methods. Moreover, the traditional method is not economical, as user costs constitute 48.68%, 65.31%, and 49.52% of agency costs. Additionally, the traditional method incurs significantly higher agency costs than other methods, based on NPV and EUAC analyses.

Keywords: Life Cycle Cost Analysis (LCCA), Airport Pavement Design, AirCost LCCA Software, FAARFIELD Software.

1. INTRODUCTION AND LITERATURE REVIEW

The runway constitutes a fundamental element of every airport, meticulously engineered to ensure a smooth and safe all-weather riding surface capable of supporting an aircraft's weight. Airport runway pavement designs employ layered elastic methods to estimate loading strain, predict pavement lifespan, and collect empirical performance data from full-scale test pavements. This methodology has been validated by field experiments conducted by the National Airport Pavement Test Facility (NAPTF) [1].

Limited resources exacerbate the challenge of conserving airport pavements. Delays or failures in maintenance and rehabilitation (M&R) lead to higher direct costs and necessitate interventions that can significantly disrupt airport operations [2].

Consequently, life cycle cost analysis (LCCA) emerges as a critical procedure for comparing the economic effectiveness of alternatives by identifying those with the lowest life cycle costs. LCCA involves comparing the costs and benefits of alternatives using methods such as Net Present Value (NPV), Benefit-Cost Ratio

(BCR), and Cost-Effectiveness Analysis (CEA). For LCCA to be effective, the alternatives must provide similar levels of service, with selection based on cost minimization. However, the functional benefits of different M&R strategies are not equivalent, necessitating a performance analysis for each alternative [3].

LCCA costs are generally categorized into direct and indirect costs, which include operating costs, discomfort, and accident risks. Indirect costs, or user costs, are notably complex to determine. The most effective way to express user costs is qualitatively by evaluating the benefit to users relative to an alternative that does not undergo M&R [4].

Benefits are intrinsically linked to the concept of M&R effectiveness. To address the difficulties associated with monetizing these benefits, several studies apply to the CEA. For instance, a study evaluating four maintenance strategies for a runway, including reconstruction, identified priority maintenance areas and cost-effective strategies based on pavement surface conditions, as indicated by the Pavement Condition Index (PCI) [5].

The calculation of the area under the performance curve of an indicator and its acceptability limit stands out as a robust procedure for estimating effectiveness [6].

Variables such as discount rate, analysis period, and pavement section prioritization significantly influence LCCA outcomes. These variables must be considered to ensure data reliability, as fluctuations can reduce result accuracy. A stochastic LCCA is advantageous as it accommodates data variability through a probability density function rather than a single value [7].

The application of LCCA in airport pavement analysis remains sparse and relatively recent, with most studies emerging in the last decade. There is a notable lack of research addressing the programming of M&R strategies in airport pavements using LCCA [8].

Another study developed an algorithm to minimize M&R costs within an Airport Pavement Management System (APMS), examining nine options and achieving a 74% cost reduction compared to the initial alternative. Furthermore, the impact of delays in various M&R strategies on airport pavement was also studied, comparing four PCI-based alternatives. Results indicated that delaying preventive maintenance by one year increases deterministic costs by 16%. However, sensitivity analysis showed a cost reduction of over 10% when the discount rate increased by 1% [9].

1.1 Runway with Variable Cross-Section

Due to Federal Aviation Administration guidance [10].

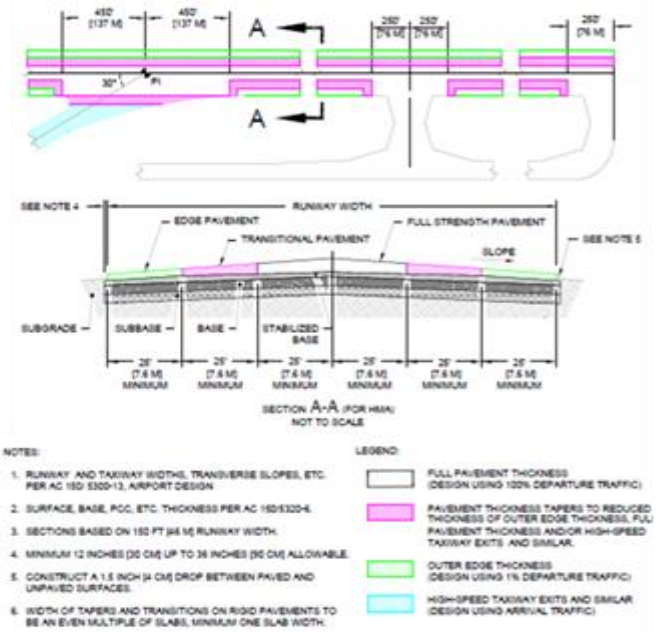

Figure 1 Runway with Variable Cross Section (FAA)

Runways may be constructed with a transversely variable section. Variable sections permit a reduction in the quantity of materials required for the upper pavement layers of the runway.
This typically includes the keel section of the runway, entrance taxiways, and aprons. The full-strength keel section is the center 50 feet (15 m) of wide runway. Furthermore, the pavement thickness is designed using arrival weights and estimated frequency for high-speed exits. Furthermore, along the extreme outer edges of the runway where pavement is required but traffic is unlikely, the pavement thickness is designed using the departure weights and 1 percent of estimated frequency. as shown in Figure (1).

1.2 USING GLASS GRID

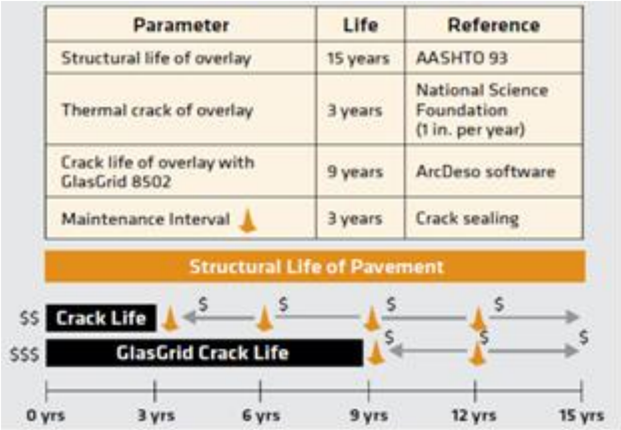

Figure 2. Life Cycle Cost Savings

The use of GlassGrid (Tensile strength 115 ±5 kN/m) for asphalt reinforcement is a material employed to strengthen pavement, enhance its performance and lifespan, and reduce maintenance intervals. This grid is made from high-strength glass fibers combined with polymer materials, characterized by its high resistance to tension and bending. [11]. as shown in Figure (2).

1.2 Using Software

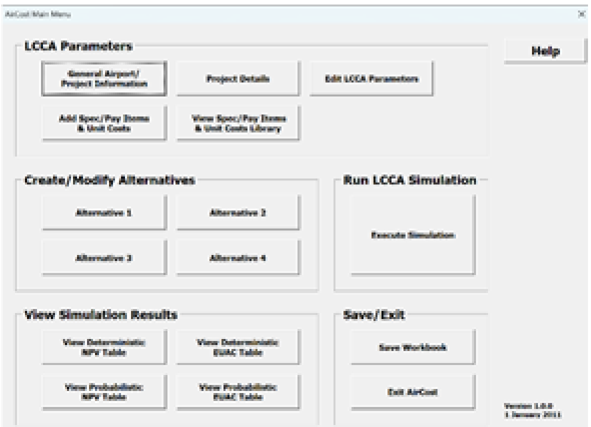

Figure 3 AIRCOST Software interface

AIRCOST Software is a specialized tool for conducting Life-Cycle Cost Analysis (LCCA) in the aviation industry. This Software is beneficial for analyzing the total Cost of ownership and operation of aviation assets over their entire life span, providing insights that can help make informed decisions regarding maintenance, rehabilitation, and replacement strategies. AIRCOST Software interface is shown in Figure (3).

Figure 4 FAARFIELD Software interface

FAARFIELD Software is a sophisticated engineering tool developed by the Federal Aviation Administration (FAA) to design and analyze airport pavements. It ensures that new and rehabilitated airport pavements are structurally adequate to support the expected aircraft loads over their intended lifespan. The FAARFIELD Software interface is shown in Figure (4).

The main objectives of this study are to conduct a new pavement evaluation Approach for runway and compare Egyptian Traditional Techniques in life cycle cost analysis in terms of Net Present Value (NPV) and Equivalent Uniform Annual Cost (EUAC), using deterministic and probabilistic methods.

Runway 05C-23C was selected as a case study due to its aforementioned characteristics. To achieve these objectives, a comprehensive experimental program was designed and implemented. The following section presents a thorough explanation of the study methodology.

2. STUDY METHODOLOGY

Figure 5 Runway 05C-23C Location on Cairo airport in Cairo city, Egypt

To achieve the objectives of this paper, several successive activities were performed.

The first activity was selecting an airport.

Runway 05C-23C in Cairo airport was selected to be studied to conduct LCCA comparison for alternatives, which Runway 05C-23C contains 4000m length and 85m total width (60m main width+25m shoulder) as shown in Figure (5).

The second activity was data collection, which included the paving history of Runway 05C-23C, air traffic movement and growth rate, existing pavement sections, key defects impacting pavement Conditions, and LCCA governmental data.

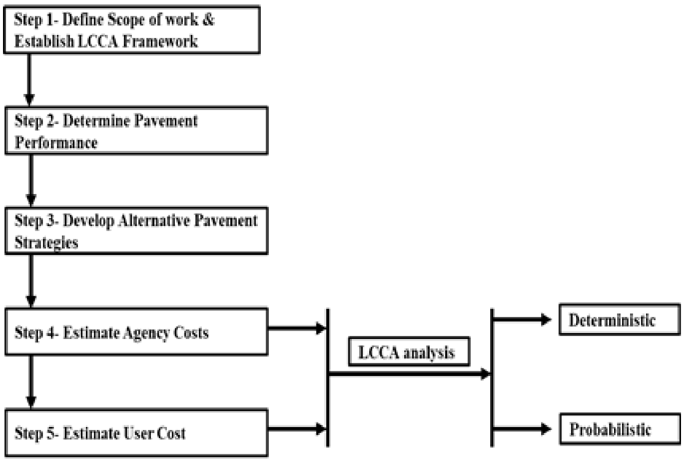

Figure 6 Steps to Conduct LCCA

The third activity was Proposing the LCCA pavement evaluation approach, which was conducted and compared by traditional method and expert method presented in a 5-step. as shown in Figure 6.

. The last stage of work was discussion and analysis of collecting data to get study conclusions and recommendations.

2.1 Paving History of The Runway 05C-23C

The development and enhancement of the paved areas of the 05C-23C airfield runway were undertaken approximately 28 years ago. as shown in Figure (7).

In 1982. The runway was constructed as a Second parallel Runway (4,000m length / 60m width). 45m width and 7.5m Shoulders. The runway body was a base course layer (40 cm) depth covered with (30cm) asphalt layers.

In 1996. using polymer-modified asphalt layers with a thickness of 12 cm (milling and covering the existing pavement). During this period, the runway was widened from both sides to a width of 60 meters instead of 45 meters, and the existing taxiways were expanded to a width of 30 meters instead of 23 meters. This included Runway extension of 12 cm polymer-modified asphalt above a 15 cm stabilized bituminous base and 30 cm base layer and removing and reconstructing the shoulders with a 6 cm polymer-modified asphalt layer above a 7 cm asphalt-stabilized base layer and a 20 cm stone base layer.

In 2009, regular maintenance work on the 05C-23C runway pavement began, involving the filling of surface cracks with hot material, repairing potholes with epoxy materials, and enhancing the efficiency of navigational markings' paint.

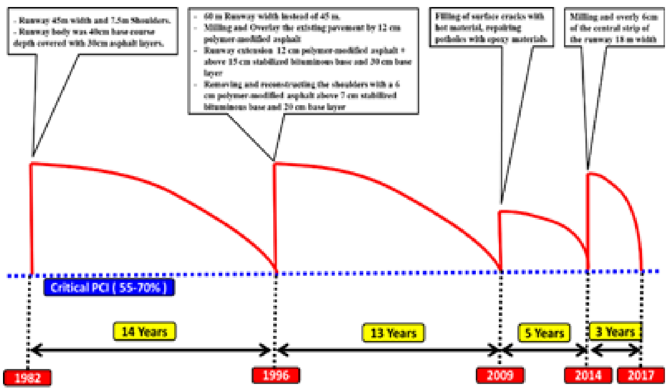

Figure 7 Pavement survival curve of the Runway 05C-23C

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In 2014, alongside the commencement of runway development work, urgent and temporary maintenance was performed on scattered sections of the central strip of the runway within a 9-meter scope around the runway axis on both sides. This involved milling and overlaying with a 6 cm layer without treating the remaining deep cracks after milling.

In 2016, there was a noticeable rapid deterioration in the pavement condition of the 05C-23C runway due to the significant ageing of the pavement layers.

2.2 Air Traffic Movement and Growth Rate

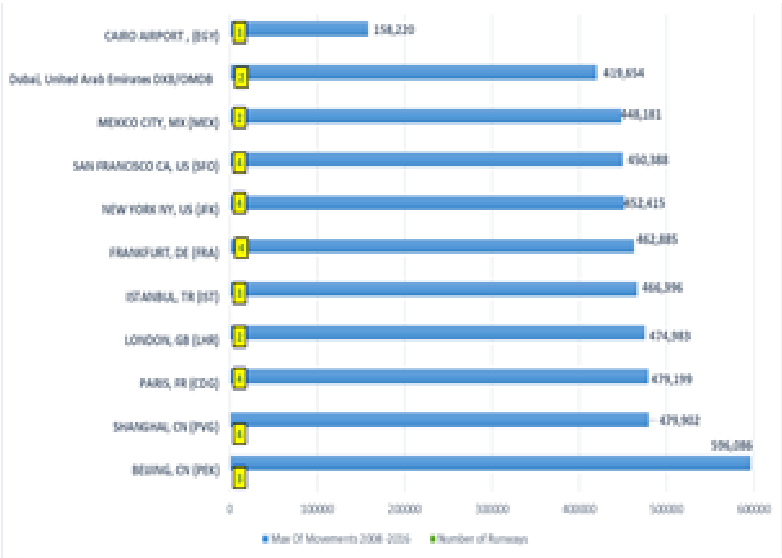

Figure 8 No of runways vs air traffic movement (max of years 2008-2016)

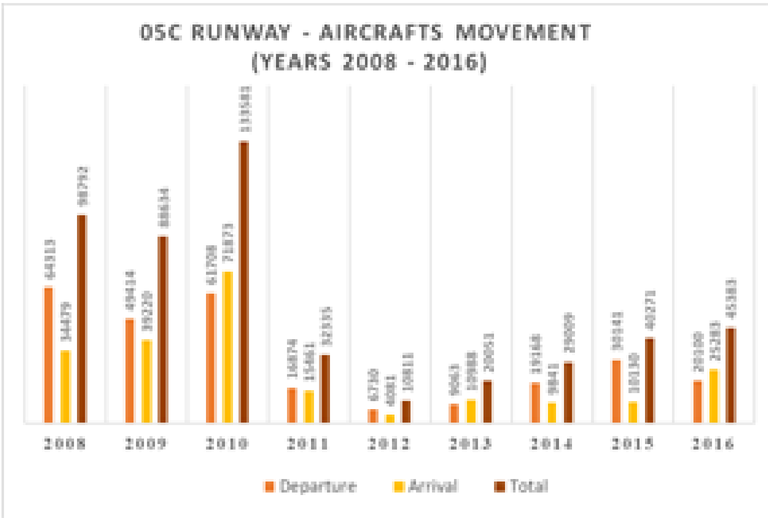

Figure 9 Cairo airport (05C) - air traffic movement (2008-2016)

Cairo Airport has the lowest air traffic mix and maximum number of runways compared to international airports due to ACI releasing 2016 world airport traffic rankings, which led to excessive spare capacity, as shown in Figure (8). Furthermore, Cairo Airport air traffic mix was given by Cairo Airport Company (CAC) from the year 2008 to 2016, and a 10% growth factor was selected due to CAC future expectations, as shown in Table (1) and Figure (9).

Table (1) Runway 05C-23C air traffic Mix 2016

Id	Aircraft	Annual Departures	Traffic Mix Share (%)	Id	Aircraft	Annual Departures	Traffic Mix Share (%)
1	A320-200 std	6787	36.31%	**18**	B767-200	160	0.86%
2	DHC-7	2193	11.73%	**19**	G-V/G500	139	0.74%
3	B777-300	1800	9.63%	**20**	A300-B4/C4	134	0.72%
4	A330-300 std	1468	7.85%	**21**	Fokker 50	128	0.68%
5	A321-200 std	1435	7.68%	**22**	Gulfstream-G-IV	98	0.52%
6	B737-400	1417	7.58%	**23**	HS125	64	0.34%
7	A310-200	615	3.29%	**24**	TU-134A	58	0.31%
8	CRJ900	568	3.04%	**25**	An-124	48	0.26%
9	B747-200/300	369	1.97%	**26**	B757-200	43	0.23%
10	A319-100 std	368	1.97%	**27**	Learjet 45/55B	33	0.18%
11	A340-200	343	1.84%	**28**	C-130	31	0.17%
12	C550/551	323	1.73%	**29**	ERJ-135	28	0.15%
13	MD-11	227	1.21%	**30**	C-123	26	0.14%
14	B787-8	222	1.19%	**31**	IL-76T	26	0.14%
15	EMB-170 STD	191	1.02%	**32**	C-17A	19	0.10%
16	EMB-190 STD	184	0.98%	**33**	Others	373	2.00%
17	CL-604/605	182	0.97%	**TOTAL**		**20100**	**100%**

2.3 Existing Pavement Section

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 Figure (10).

- Data from 16 core samples indicate that the total asphalt pavement thickness of the runway 45m width is approximately 40 cm above 40 cm base layer. Furthermore, the Runway extension with a 7.5m width from the two sides includes 12 cm asphalt above 15 cm stabilized bituminous base and 30 cm base layer. Most visible cracks on the pavement surface extend only through the surface and binder layers up to 12 cm, with some limited cracks extending to greater depths.
- Data from 8 core samples show that the total asphalt pavement thickness of the runway shoulders ranges from 7 cm to 17 cm, with an average of 13 cm above the base layer 20 cm. Approximately 50% of visible cracks on the pavement surface extend only through the surface layer up to 6 cm, while the remaining cracks extend to greater depths, sometimes through the entire thickness of the asphalt pavement layers.
- Min 60-100cm Compacted subgrade was found with min CBR =10% and 95% compaction.

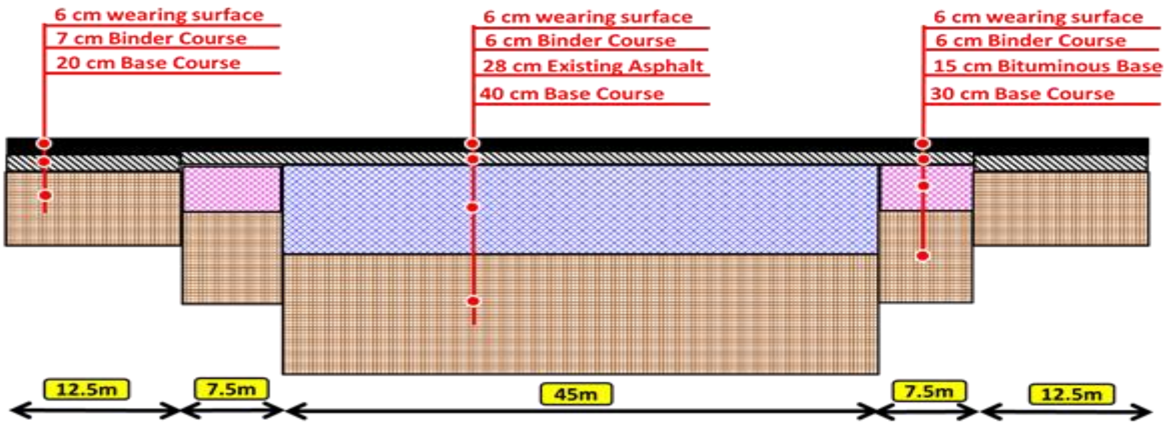

Figure 10 Existing Pavement Sections and layers

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2.4 Key Defects Impacting Pavement Condition

A visual assessment of the pavement condition index (PCI) and core sampling of all paved areas of the 05C-23R runway was conducted to identify the types of surface defects, the severity and extent of these defects, and to determine the number, thickness, type, and condition of existing pavement layers, as well as to identify crack characteristics, including their width and crack depth into the existing pavement cross-section. The assessment covered the existing pavement of the runway body and the paved shoulders.

2.4.1 Runway Body Pavement Condition

Figure 11 Site Pictures for Runway Body Pavement Condition

- Longitudinal and transverse cracks of moderate to high severity are prevalent along the entire runway length in the old pavement strips on both sides and the central strip at longitudinal joint areas, sometimes in the middle of the strips but less frequently. These cracks are more severe and frequent at intersections with taxiways. Some reflective cracks are present in the central strip, and some block cracks are scattered, particularly at the intersection with a taxiway. as shown in Figure (11).
- Medium severity weathering and ravelling, more widespread in the old pavement strips on both sides of the runway axis, sometimes leading to the formation of potholes.
- Polished aggregates in the central strip outside repaired areas are negatively impacting skid resistance.
- Recurrent disintegration and detachment of epoxy materials used to repair severe cracks and surface conduits for cables and embedded lighting units.
- Uneven pavement surface at transverse and sometimes longitudinal joints in repair areas

2.4.2 Runway Shoulders Pavement Condition:

- Some longitudinal cracks at band joints are of low to moderate severity, and some transverse cracks are of low to moderate severity, with grass and weeds emerging in crack areas and surface conduits for lighting cables. The pavement condition is generally acceptable, as shown in Figure (12).

Figure 12 Site Pictures for Runway Shoulders Pavement Condition

2.5 LCCA Governmental Data

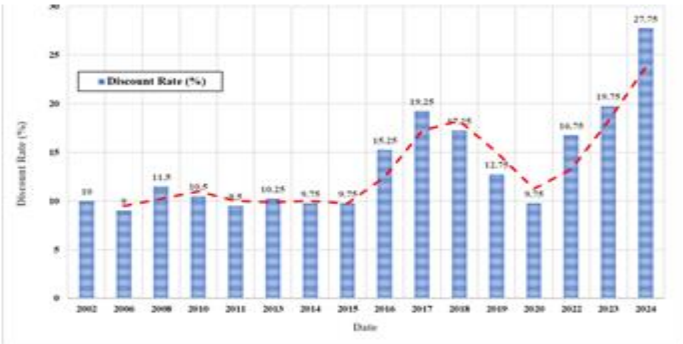

Figure 13 discount rates historical data in Egypt

The two main elements impacting the probability statistics LCCA are discount rates and pay item unit costs. Figure (13) illustrates the historical data on discount rates in Egypt in reference to The Central Bank of Egypt's Discount Rates Statistics, in which the average number 10.5% was selected and 0.25 as the standard deviation.
Table (2) illustrates that pay item unit costs in reference to the unified priced assessment for the work of the Egyptian National Road Project Year 2017

Table (2). Pay item unit costs Egyptian pound (EGP) at 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 surface 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. LCCA FOR PROPOSED PAVEMENT EVALUATION APPROACH

3.1 Step 1- Define the Scope of work and Establish the LCCA Framework

The main difference between the New Approach and Egyptian Traditional Techniques in Step 1 is the type of the LCCA, while Egyptian Traditional Techniques use only the Deterministic method. as shown in Table (3).

Table 3. Step1- Comparison Between New Approach and Egyptian Traditional Techniques

Elements	**Egyptian Traditional Techniques**	**New Approach**
Airport element	Runway 05C-23C	Runway 05C-23C
Pavement Widening	No	No
Safety strips	No	No
Analysis Period	30 years	30 years
Discount Rates	Deterministic (10.5%)	-Deterministic -Probabilistic (mean 10.5%, std 0.25)
Pay Item Unit Costs	Deterministic	-Deterministic -Normal Probabilistic

3.4 Step 2- Determine Pavement Performance

The main difference between the New Approach and Egyptian Traditional Techniques in step 2 is the pavement condition index surveying technique, which Egyptian Traditional Techniques use only the traditional PCI method with limited samples compared to Fully detailed PCI samples for Runway width every 7.5m and Runway shoulder for also using Pavement survival curve and PCI deterioration curve as a guide for rehabilitation and maintenance strategy. as shown in Table (4).

Table 4. Step2- Comparison Between New Approach and Egyptian Traditional Techniques

Elements	**Egyptian Traditional Techniques**	**New Approach**
Visual inspection	limited PCI samples for Runway width and Runway shoulder	Whole detailed PCI samples for Runway width every 7.5m and Runway shoulder
Pavement Performance		- Pavement survival curve - PCI deterioration curve
Structural Pavement life	Structural design check	Structural design check

- **Visual inspection**

Visual inspection for pavement condition index (PCI) was conducted in 2016 for Runway width = 456 PCI sample and Runway shoulder = 114 PCI sample and average PCI results for all techniques shown in Table (6).

Table 6. PCI Results Comparison Between New Approach And Egyptian Traditional Techniques

ITEM	**Egyptian Traditional Techniques**		**New Approach**		
	Runway width (60m)	Runway shoulders (25m)	Main Runway width (15m)	Other Runway width (45m)	Runway shoulders (25m)
PCI	64%	71%	59%	80%	73%

- Pavement Performance

PCI deterioration curve has been conducted due to Visual inspection for pavement condition index (PCI) in the year 2016 and previous studies by Cairo Airport Company (CAC) as shown in Figure (14).

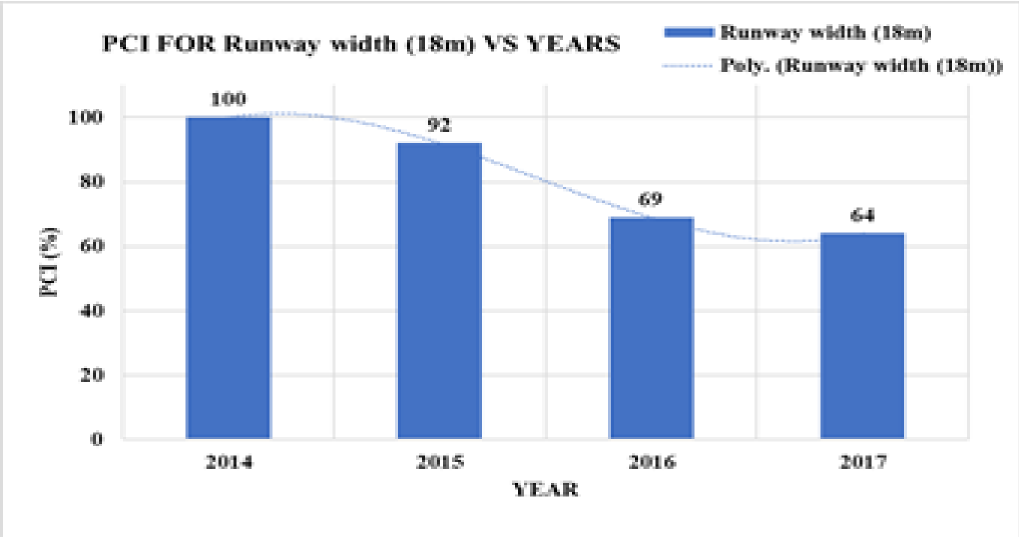

Figure 14 PCI deterioration curve of the Runway 05C-23C

- **Structural design check**

- Structural design check for existing pavement section, minimum required thickness, and cumulative damage factor (CDF) has been conducted using Software FARFIELD 2.1.1 due to air traffic mix, growth factor =10%, and design life = 30 years. the Calculate life for existing section = 5473 years and cumulative damage factor =0.00005 as shown in Figure (15). The minimum required thickness due to cumulative damage factor =1 was 11 cm asphalt layers, 12.7 cm stabilized base and 42.3 cm base course, as shown in Figure (16).

Figure 15 Calculated life span and cumulative damage factor (CDF) using software FARFIELD 2.1.1

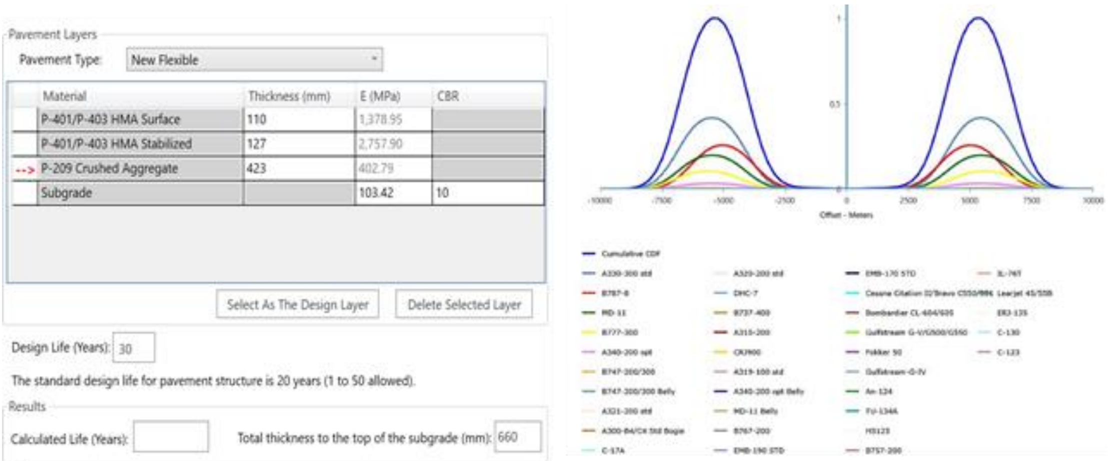

Figure 16 Minimum required thickness and cumulative damage factor (CDF) using software FARFIELD 2.1.1

3.4 Step 3- Develop Alternative Pavement Strategies

The main difference between the New Approach and Egyptian Traditional Techniques in step 3 is runway width divisions due to expected damage area, which Egyptian Traditional Techniques divided into two alternatives. Alternative (1) Governmental System which rehabilitation and maintenance strategy is used for total runway width (60m), alternative (2) expert system divided runway width to 30m main and 30m secondary for rehabilitation and maintenance strategy, and alternative (3) Proposed System divided runway width to 15m main and 45m secondary for rehabilitation and maintenance strategy. as shown in Table (5). The proposed pavement works, rehabilitation and maintenance schedule time, and construction duration time are shown in Table (6).

Table 5. Step3- 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) + Runway shoulders (25m)
	Alter (2). Experts System - Runway width (30m) + Other Runway width (30m) + Runway shoulders (25m)	

Table 6. The proposed pavement works, rehabilitation and maintenance schedule time, and construction duration time

Alternative		**Description**	**Works**	**Years After,**	**Construction Time (Day)**
Alter (1)	**Initial Construction & Rehabilitations**	Runway width (60m)	11 cm Asphalt,13 cm Stabilized base, and 30cm Base course	0,14, and28	180
		Runway shoulders (25m)	11 cm Asphalt and 20cm Base course		
Alter (2)	**Initial Construction**	Main Runway width (30m)	5cm Wearing ,6cm binder, and Maintenance	0,14, and28	90

		Other Runway width (30m)	5cm Wearing, and maintenance		
		Runway shoulders (25m)	Cracks Maintenance		
	Rehabilitations	Main Runway width (30m)	5cm Wearing, and Maintenance	7, and21	75
		Other Runway width (30m)	5cm Wearing and maintenance		
		Runway shoulders (25m)	Cracks Maintenance		
Alter (3)	**Initial Construction**	Main Runway width (15m)	5cm Wearing, Glass grid, and Maintenance	0,14, and28	30
		Other Runway width (45m)	Cracks Maintenance		
		Runway shoulders (25m)	Cracks Maintenance		
	Rehabilitations	Main Runway width (15m)	Micro Surfacing, and Maintenance	7, and21	15
		Other Runway width (45m)	Cracks Maintenance		
		Runway shoulders (25m)	Cracks Maintenance		

3.5 Step 4- Estimate Agency Costs

The main difference between the New Approach and Egyptian Traditional Techniques in step 4 is adding Supplemental Costs in the New Approach system containing Administrative Costs, Engineering Costs, and Ground traffic control costs. as shown in Table (7). Quantities for Egyptian Traditional Techniques (Alternative 1 and 2) and New Approach (alternative 3). as shown in Table (8).

Table 7. Step4- Comparison Between New Approach and Egyptian Traditional Techniques

Elements	**Egyptian Traditional Techniques**	**New Approach**
Physical Costs	- Paving Works - Marking Works - Lighting Works	- Paving Works - Marking Works - Lighting Works
Supplemental Costs		- Administrative Cost 2% - Engineering cost 5% - Ground traffic control 2%

Table 8. Quantities for Egyptian Traditional Techniques (Alternative 1 and 2) and New Approach (alternative 3)

Item	**Description**
Daily operations	125 (70 arrival flights and 55 departing flights)
Average number of passengers/flights	100
Daily total passengers	(125 × 100) = 12,500
Daily passenger enplanements (departure)	(55 × 100) = 5,500
Daily passenger deplanements (arrival)	(70 × 100) = 7,000
Average landing fee	25000 EGP /Aircraft
Landing fee daily revenue	**(70 aircraft x25000 EGP /aircraft) = 1,750,000 EGP**

Passenger facility charge	200 EGP /enplaned passenger
Passenger facilities charge daily revenue.	**(5,500 passengers x 200 EGP/enplaned passenger) =1,100,000 EGP**
Average aircraft fuel usage	320 gal/flight
Daily fuel flowage =	(320 × 55) = 17,600 gal. = 66623 Litre
Fuel flowage fee	2 EGP/Litre
Fuel flowage daily revenue	**(66623 Litre x 2 EGP/Litre) = 133,246 EGP**
Total daily revenue	**(1,750,000 + 1,100,000 + 133,246) = 2,983,246 EGP**
Percentage of daily revenues reduction	**15% for airports with 3 Runways**
Revenues growth rates	**3%**

3.6 Step 5- Estimate User Cost

The main difference between the New Approach and Egyptian Traditional Techniques in step 4 is adding user cost elements (Daily revenues, their percentage and Revenue growth rates) in the New Approach system. as shown in Table (9). Total daily revenue calculations. as shown in Table (10).

Table 9. Step5- Comparison Between New Approach and Egyptian Traditional Techniques

Elements	**Egyptian Traditional Techniques**	**New Approach**
Daily revenues		- Landing fee daily revenue - Passenger facility charges daily revenue - Fuel flowage daily revenue
Percentage of daily revenues reduction		- 3 Runways (15-20%) - 2 Runways (25-30%) - 1 Runway (45-60%)
Revenues growth rates		3% compound

Table 10. Total daily revenue calculations

Item	**Unit**	**QUANTITES Alter (1) Initial Const.**	**Rehab.**	**Alter (2) Initial Const.**	**Rehab.**	**Alter (3) Initial Const.**	**Rehab.**
Milling 5cm	Sq.m			580000	240000	110000	
Filling Cracks	Sq.m			25000	25000	59000	29,000
Pavement Removal	Sq.m	136,000	136,000				
Base Course	Sq.m	92,000	92,000				
MC	Sq.m	340,000	340000				
RC	Sq.m	820,000	820,000	360000	240000	110,000	
Stabilized base 13 cm	Sq.m	240,000	240000				
Binder Course 6 cm	Sq.m	340,000	340,000	153000			
Glass grid 120kN	Sq.m					110,000	
Micro Surfacing	Sq.m						110,000
Wearing surface 5 cm	Sq.m	340,000	340,000	240000	240000	110,000	
Marking Works	Sq.m	17,670	17,670	17670	17670	5,570	5,570
Lighting Works	Lumb No.	709.00	709.00	642	642	400.00	100.00

4. RESULTS AND DISCUSSION

4.1. Analysis Of Agency Cost

Table (11) illustrates for alternatives 1,2, and 3 that initial construction costs vary from 165.9, 66.35, and 29.25 million EGP, respectively. Furthermore, rehabilitation costs vary from 165.9, 47.63, and 10.73 million EGP respectively. This means there is an enormous significant cost difference between alter (3) new proposed approach compared to alter (1and2 and) traditional method, in which alter (3) is lower than alter 1 and 2 by 567.24%, 226.86% respectively, in the initial construction and by 1545.65%, 443.74% respectively.

Table 11. Agency cost (initial construction and rehabilitation) in different alternatives

Works	**Alter (1) Cost**		**Alter (2) Cost**		**Alter (3) Cost**	
	Initial Const.	**Rehab.**	**Initial Const.**	**Rehab.**	**Initial Const.**	**Rehab.**
Paving works	143.33	143.33	45.45	26.72	17.72	6.70
Marking Works	4.86	4.86	4.86	4.86	1.53	1.53
Lighting Works	17.73	17.73	16.05	16.05	10.00	2.50
Total Cost in millions (EGP)	165.91	165.91	66.35	47.63	29.25	10.73

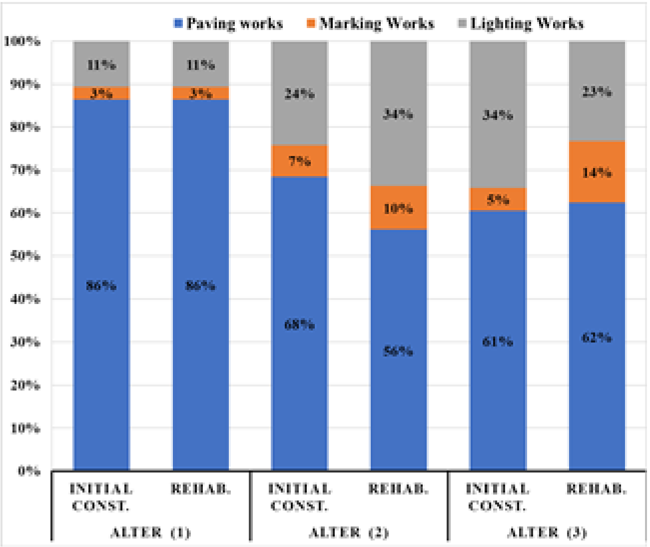

Figure 17 Cost distribution percentage of work types in different alternatives.

Figure (17) illustrates that the cost distribution percentage of marking and lighting works for alternatives 1,2 and 3 in initial construction costs varies from 14%, 31%, and 39%, respectively. Furthermore, rehabilitation costs vary from 14%, 44%, and 37%, respectively. This means there is an enormously significant cost difference between alter (1 or 2) and alter (1) traditional methods.

4.2. LCCA for Alternatives NPV, EUAC (Deterministic)

Figure (18,19) illustrates the net present value (NPV) for alternatives 1,2, and 3, that agency costs vary from 222.02, 120.99, and 46.47 million EGP, respectively. Furthermore, user costs vary from 108.07, 79.03, and 23.01 million EGP respectively. Furthermore, total costs vary from 322.61, 197.70, and 68.39 million EGP respectively.

Figure (20,21) illustrates the equivalent uniform annual costs (EUAC) for alternatives 1,2 and 3. Agency costs vary from 24.54, 13.37, and 5.14 million EGP respectively. Furthermore, user costs vary from 11.95, 8.73, and 2.54 million EGP respectively. Furthermore, total costs vary from 35.66, 21.85, and 7.56 million EGP respectively.

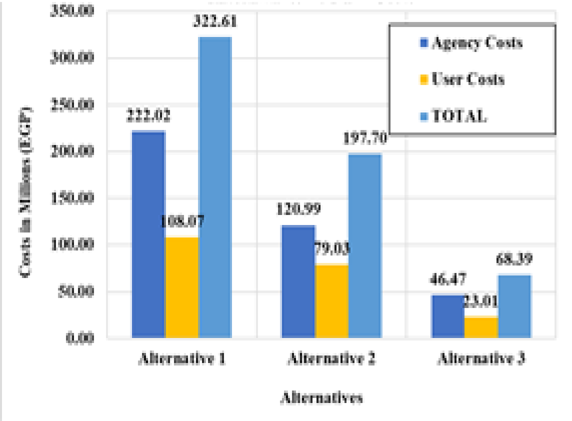

Figure 18 Alternatives vs NPV Costs.

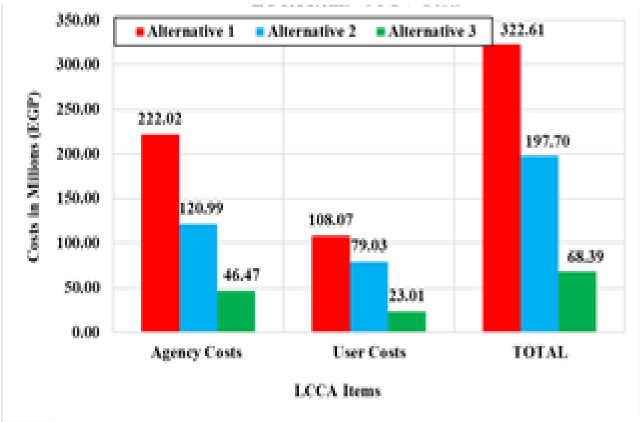

Figure 19 LCCA Items vs NPV Costs.

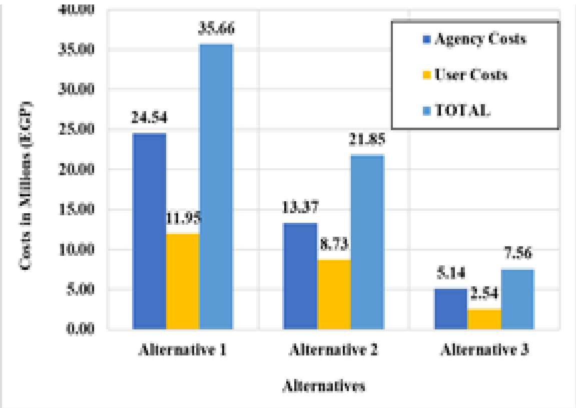

Figure 20 Alternatives vs EUAC

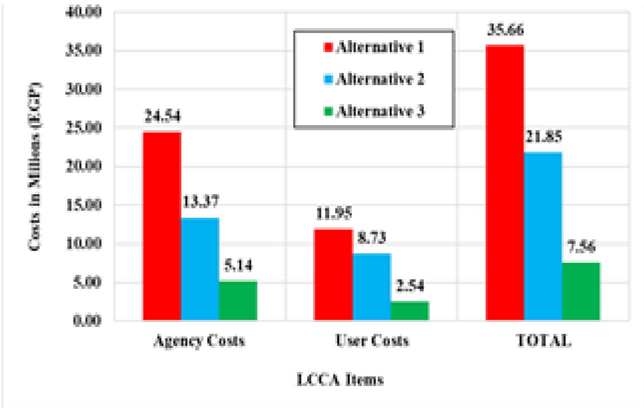

Figure 21 LCCA Items vs EUAC

There is an enormous significant total cost difference between the alter (3) new proposed approach compared by alter (1and2 and) traditional method, in which alter (3) is lower in Cost than alter 1 and 2 by 471.76%, 289.10%, respectively in NPV and EUAC. This means the new proposed approach alter (3) is the most cost-effective pavement alternative option, based on the NPV and

4.3. LCCA for Alternatives NPV, EUAC (Probabilistic)

1000 iterations have been conducted to evaluate alternatives due to variations in discount rates and Pay item unit costs

Table (12) illustrates the net present value (NPV) for alternatives 1,2 and 3. The mean values for total costs vary from 347.39, 214.36, and 73.97 million EGP, respectively.

Table (13) illustrates the equivalent uniform annual costs (EUAC) for alternatives 1,2 and 3. The mean values for total costs vary from 36.50, 22.37, and 7.72 million EGP, respectively.

There is an enormous significant total cost difference between the alter (3) new proposed approach compared by alter (1and2 and) traditional method, in which alter (3) is lower in Cost than alter 1 and 2 by 469.61%, 289.78%, respectively in NPV and EUAC. The new proposed approach, alter (3), is the most cost-effective pavement alternative option based on the NPV and EUAC (Probabilistic Method).

Figure (22,23) illustrates that alter (3) new proposed approach is the most cost-effective pavement alternative option from the Bell Curve of Total Cost in NPV and EUAC, but the only nearest alternative Cost is alternative (2) in case of aggressive variation in discount rates and Pay item unit costs.

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Table 12. NPV Total Costs Probabilistic data in different alternatives

	Statistic	Alter. 1	Alter. 2	Alter. 3
NPV Total Costs	**Mean**	347.39	214.36	73.97
	Standard Deviation	79.61	67.33	19.79
	Min.	226.20	114.82	44.31
	P.1 (5%)	260.75	141.82	52.17
	P.2 (50%)	326.67	195.85	69.09
	P.3 (75%)	378.27	241.49	81.90
	P.4 (95%)	506.76	348.58	116.60
	Max.	690.77	549.13	158.12

Table 13. EUAC Total Costs Probabilistic data in different alternatives

	Statistic	Alter. 1	Alter. 2	Alter. 3
EUAC Total Costs	**Mean**	**36.50**	**22.37**	**7.72**
	Standard Deviation	**7.10**	**2.81**	**1.25**
	Min.	**23.14**	**16.90**	**5.47**
	P.1 (5%)	**26.35**	**18.45**	**6.09**
	P.2 (50%)	**35.70**	**21.96**	**7.50**
	P.3 (75%)	**41.06**	**24.00**	**8.45**
	P.4 (95%)	**49.06**	**27.56**	**10.09**
	Max.	**62.60**	**34.27**	**12.33**

5. CONCLUSIONS AND RECOMMENDATIONS

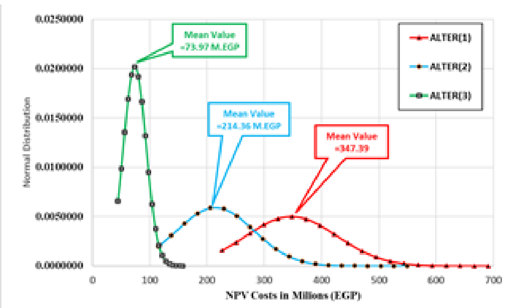

Figure 22 The NPVs Bell Curve of Total Cost

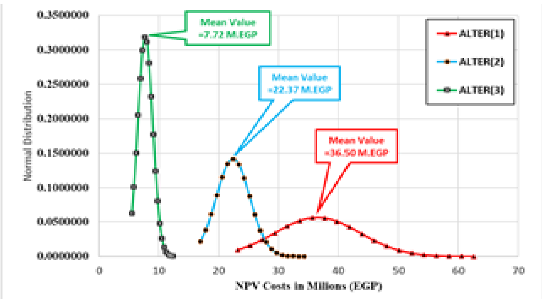

Figure 23 The EUACs Bell Curve of Total Cost

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

- The newly proposed strategy, which divides the runway width into a 15-meter main segment and a 45-meter secondary segment for rehabilitation and maintenance, proves to be more practical than traditional techniques for several reasons:

- The maximum cumulative damage factor (CDF) is located 5 meters from the runway centerline, with damage extending up to 7.5 meters from the centerline.

- The main landing gear width for the critical aircraft A320-200, which constitutes 33.77% of the air traffic mix, is 6 meters. The maximum landing gear width is 14 meters for aircraft such as the B747-200/300 and An-124, which comprise 1.84%, 0.24%, and 0.09% of the air traffic mix, respectively.

- A Pavement Condition Index (PCI) visual inspection survey for the new approach revealed significant differences between this section and the rest of the runway. Specifically, the PCI for the main runway width (15m) is 59%, for the other runway width (45m) is 80%, and for the runway shoulders (25m) is

73%.

- A visual assessment of the pavement and a core sampling of all paved areas indicated that significant impacts, such as tyre rubber accumulation, were primarily located in the main section.

- The approach aligns with the FAA typical section guidance (AC 150/5320-6G - Airport Pavement Design and Evaluation).

- There is a significant difference between the new proposed approach (Alternative 3) and the traditional methods (Governmental System - Alternative 1 and Experts System - Alternative 2). Alternative 3 is more cost-effective, being on average 470% and 290% cheaper than Alternatives 1 and 2, respectively, regarding Net Present Value (NPV) and Equivalent Uniform Annual Cost (EUAC), using deterministic and probabilistic methods.

- The traditional method used in Egyptian airports, notably Cairo Airport, involves a long-term rehabilitation strategy lasting up to 14 years with minimal maintenance during emergencies. Concerns over airport closures and user costs drive this method. However, this research demonstrates that the traditional method is not economical, as user costs constitute 48.68%, 65.31%, and 49.52% of agency costs. Additionally, the traditional method incurs significantly higher agency costs than other methods, based on NPV and EUAC analyses.

- The findings of this study are anticipated to assist the Civil Aviation Authority of Egypt in making informed decisions regarding potential developments. Furthermore, the study provides researchers with more advanced results that can inform future research and policy-making in airport pavement management.

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