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Life-cycle cost analysis in evaluation of maintenance and rehabilitation strategies in airport pavement

Análise do custo do ciclo de vida na avaliação de estratégias de manutenção e reabilitação em pavimento aeroportuário

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ABSTRACT
The performance of airport pavements and the safety of takeoff and landing operations depend on the maintenance and rehabilitation (M&R) strategies selected by the Airport Pavement Management System. In this sense, this paper aims to analyze different M&R strategies on a runway of a Brazilian aerodrome. The functional performance of the pavement was evaluated with the International Roughness Index and the economic performance based on the Life-Cycle Cost Analysis and the Effectiveness/Cost Ratio. The analyses were effective in comparing the alternatives, in addition to highlighting the indispensability of M&R, since the application of maintenance, whether preventive or corrective, reduced total costs and offered a satisfactory performance to the pavement. It was found that keeping the pavement in proper condition reduces costs with M&R strategies and helps ensure operational safety.

RESUMO
O desempenho dos pavimentos aeroportuários e a segurança das operações de pousos e decolagens dependem das estratégias de manutenção e reabilitação (M&R) selecionadas pelo Sistema de Gerência de Pavimentos Aeroportuários. Nesse sentido, este trabalho tem o objetivo de analisar diferentes estratégias de M&R em uma pista de pouso e decolagem de um aeródromo brasileiro. O desempenho funcional do pavimento foi avaliado com o Índice de Irregularidade Internacional e o econômico com base na Análise do Custo do Ciclo de Vida e na Relação Efetividade/Custo. As análises apresentaram-se eficazes na comparação das alternativas, além de evidenciar a indispensabilidade das M&R, visto que a aplicação de manutenções, sejam preventivas ou corretivas, reduziram os custos totais e ofereceram um desempenho satisfatório ao pavimento. Constatou-se que manter o pavimento em condições adequadas reduz os custos com as estratégias de M&R e auxilia na garantia da segurança operacional.

1. INTRODUCTION

Air transport has become, in the last two decades, one of the most important alternatives for the movement of people and cargo, nationally and globally. As a result, and with the development of larger aircraft with greater payload, technical, economic and scientific interests related to the study of the aircraft-pavement interaction arose, in terms of its structural capacity and functional performance, which may interfere with the safety of landing operations and take-off.

Although pavements are one of the most important infrastructures of an airport complex and require frequent assessment, maintenance and rehabilitation (M&R) activities, decision-making is often characterized by the absence of analyzes that consider their performance and the resources allocated in the medium or long term. This context can result, in the worst-case scenario, in an unwise use of financial resources (FAA, 2014).

Life-Cycle Cost Analysis (LCCA) is an Engineering Economics tool that compares the economic viability of different alternatives (Walls and Smith, 1998). Thus, LCCA is an effective method to allocate available resources and facilitate decision-making in Airport Pavement Management Systems (APMS), contributing to the pavement preservation and, consequently, operational safety.

This paper aims to evaluate, through the LCCA and the Effectiveness/Cost Ratio (ECR), different M&R strategies for a Brazilian runway, correlating the costs and the functional performance, evaluated through roughness.

2. LITERATURE REVIEW

Degradation of pavements is one of the contributing factors to the occurrence of incidents and accidents involving aircraft (Oliveira, Almeida and Ramos, 2016). However, the decision to conserve airport pavements is hampered by insufficient resources. On the other hand, the non-completion or delay in maintenance and rehabilitation (M&R) applications, in addition to implying higher direct costs, may require interventions that significantly affect airport operations (Pittenger, 2011).

Therefore, Life-Cycle Cost Analysis (LCCA) is a procedure that compares economic effectiveness by identifying the alternative with the lowest cost over a life-cycle (Walls and Smith, 1998). LCCA requires comparing the costs and benefits of alternatives. Among the available methods for this comparison are the Net Present Value (NPV), the Befit-cost Ratio (BCR) and the Cost-Effectiveness Analysis (CEA).

The NPV converts benefits and costs to present values, while the BCR relates them, assigning them monetary values. The NPV can be determined by Equation 1.

$$NPV = \sum_{n=1}^{n} \frac{C_n}{(1+i)^n} \tag{1}$$

where:

C = Total cost for the period;

i = discount rate;

n = analysis period.

LCCA costs are usually divided into two categories: direct and indirect (operating costs, discomfort, and accident risks). Indirect costs or user costs are, however, complex to determine. Khurshid, Irfan and Labi (2009) state that the best way to express the costs of users can be qualitatively, by the benefit to users in relation to an alternative that does not perform M&R.

The alternatives of an LCCA must provide similar levels of service, being the selection based on the minimization of costs (Walls and Smith, 1998). Contradictorily, the functional benefit of different M&R strategies is not the same, and a performance analysis needs to be included for each alternative.

Benefits are directly associated to the concept of M&R effectiveness. As for its determination, several studies apply the CEA to avoid difficulties associated with its monetization (Irfan et al., 2015). The calculation of the area delimited by the indicator's performance curve and its acceptability limit seems to stand out compared to other existing procedures for estimating effectiveness (Khurshid, Irfan and Labi, 2011).

Variables such as discount rate, period of analysis and prioritization of pavement sections influence the LCCA. These influences should be taken into account, since the data fluctuation reduces the results' reliability. According to Bagdatli (2018), a stochastic LCCA contributes to the consideration of these uncertainties, because it allows input data to vary as a function of a probability density rather than the adoption of a single value.

2.1. The costs of roughness

Roughness is a critical feature in the functional evaluation of airport pavements. When excessive, it can affect users' safety and comfort, cause wear and tear on vehicles and increase vehicles operating costs (VOC). In addition, fuel consumption increases as well as traffic speed decreases, causing an increase in travel time. International Roughness Index (IRI) is one of the main methods of measuring roughness in pavements.

Wang and Wang (2017) developed a model to quantify the impact of road M&R on agency cost and VOC. The benefit for the pavement in poor condition was greater compared to the pavement in good condition. In addition, the initial value of IRI exerted more influence on the benefits to the operating costs of the vehicles than on the benefit on the agency cost.

Kalan et al. (2020) considered the roughness of a highway to assess the loss of capacity due to lack of maintenance. The authors concluded that M&R activities, when applied in the appropriate period, can lead to savings in travel time, avoiding the increase in IRI and the decrease in traffic capacity.

Thus, roughness is understood as one of the main parameters available to identify and correlate the costs and benefits of M&R strategies in LCCA. However, there is a lack of studies that relate M&R costs with roughness in airport pavements.

According to Emery, Hefer and Horak (2015), the analysis of roughness in airport pavements, in terms of passenger discomfort, is not significant, since the tire-pavement interaction time is limited to the short duration of takeoffs and landings. On the other hand, there is concern about excessive vertical acceleration, which can impair the reading of equipment in the cockpit, increase both stopping distance and the probability of landing gear failure in emergency operations, cause damage or fatigue to aircraft structure and raise landing gear maintenance cycles.

Although widely accepted for road pavements, the use of IRI for airport pavement analysis is contested (Stet, 2006; Loprencipe and Zoccali, 2019). In this sense, Boeing (2002) presented the Boeing Bump method, which takes into account the effect of roughness on the aircraft structure. The method was developed based on the observation of aircraft traveling over isolated events of vertical deviations (bumps). Subsequently, FAA (2009) summarized the method developed by Boeing and presented the Boeing Bump Index (BBI), which corresponds to the highest value for the ratio between the height of the bump and its maximum acceptable height. The BBI value will be acceptable if it is less than 1.0, while higher values may be classified as excessive or unacceptable. Although it was developed specifically for airport pavements, the BBI has limitations in its use, such as the failure to consider cyclic, harmonic or successive events, in addition to the speed and aircraft physical characteristics.

Sousa, Carneiro and Oliveira (2022) verified a weak correlation between IRI and BBI values, especially if only their average values are considered. Thus, the authors understood that the index selected for the roughness survey and its different forms of interpretation can lead to different conclusions about decision-making regarding M&R activities.

From this perspective, Magalhães and Oliveira (2022) analyzed the correlation between IRI and the Runway Roughness Index (RRI), an index that considers the weighted root mean square (WtRMS) of vertical acceleration in the cockpit (VACP). The authors analyzed values for different gravity conditions of roughness and distinct aircraft's speed and observed a weak correlation between IRI and RRI, evidencing a deficiency of IRI in explaining the VACP variations. On the other hand, Merighi, Pereira and Schiavon (2022) consider that the RRI has the limitation of not identifying the location of the vertical deviation, indicating that it should be considered as an acceleration indicator and not an index for pavement condition. Thus, the authors recommend the complementary use of RRI and BBI, since the first contributes to the interpretation of acceleration due to the condition of the pavement and the second to the interpretation of defects in the pavement.

Despite the existence of alternative indexes such as BBI and RRI, ANAC (2019) requires that roughness at Brazilian aerodromes should be monitored by IRI values. The minimum frequency for measurement is determined according to the number of landing operations at the aerodrome. The acceptability limit is 2.5 m/km every 200 m and the survey is done at 3m and/or 6m from the centerline, once on each side.

The acceptability threshold considered for the IRI affects the results of cost analyses, given its influence on considering the need for repair. Cossío Durán and Fernandes Jr. (2020) demonstrated this when comparing three different IRI limits: (i) 2.0 m/km (Sayers, Gillespie and Queiroz, 1986); (ii) 2.5 m/km (ANAC, 2019) and (iii) 3.7 m/km (vertical acceleration). The authors concluded that decision-making regarding M&R strategies is different, depending on the selected threshold. The vertical acceleration limit reduced the number of sections in a "Very Poor" state, which may contribute to the reduction of unnecessary M&R.

Sousa and Oliveira (2020) performed a concordance analysis of the IRI's acceptability parameters and critical vertical acceleration in the cockpit. The analysis was based on the limit value of 0.40g for vertical acceleration and different limits for the IRI, ranging from 2.0 to 4.0 m/km. The authors concluded that the use of different IRI acceptability limits for each third of the runway had advantages in the selection of M&R strategies in relation to the use of a single limit for its entire length.

Rahman and Tarefder (2012) correlated IRI data and accident rates at airfields in New Mexico. It was possible to identify that, for the evaluated cases, the accidents depend more on the operation and the length of the runway than on the pavement's roughness. It is inferred, therefore, that the impact of roughness on user maintenance costs may be unequal for road and airport pavements.

2.2. Cost analysis for airport pavements

Although used in road pavements, the application of LCCA in airport pavements analysis is still scarce and recent, and the studies described in this section date from the last decade. For Babashamsi et al. (2022), there is a lack of studies that deal with the programming of M&R strategies in airport pavements using the LCCA.

Rahman and Tarefder (2012) performed a functional, environmental, and economic comparison analysis between maintenance types on an airport pavement. They conducted a probabilistic LCCA of the variation in the discount rate and PCI levels. In any case, preventive maintenance is more efficient than corrective maintenance.

Irfan et al. (2015) conducted a study to evaluate four maintenance strategies for a runway, including reconstruction. The results identified the maintenance areas to be prioritized and the lowest cost strategies, considering the pavement surface conditions, expressed by PCI.

On the national scene, Cossío Durán (2015) contributes to the development of an APMS for the Araquara State Airport, in São Paulo. For a 20-year project period, five PCI-based M&R strategies were designed and compared using the BCR. The lowest cost strategy presented adequate conditions for airport operations.

An algorithm aimed at minimizing the cost of M&R in an APMS was developed by Balinho do Ó and Picado-Santos (2017). The study looked at nine options, including not repair, and was able to achieve a 74% lower cost compared to the initial alternative considered.

Babashamsi et al. (2022) studied the significance of delay in various M&R strategies on airport pavement, opposing four PCI-based alternatives. The results show that delaying preventive maintenance for one year increases the deterministic cost by 16%. However, with the sensitivity analysis performed, the cost reduced more than 10% because the discount rate increased by 1%.

3. METHODS

3.1. Longitudinal profile analysis

Using the ProFAA software, version 3.0.0, the longitudinal profile of a 3,300 m length runway at a Brazilian airport was analyzed. For the analysis of roughness, the IRI obtained by an inertial laser profilometer was used. The result was adopted as the initial value of the IRI, that is, in Year 0 of the analysis. The runway was divided into 200 m sections, resulting in 17 sections. The IRI was evaluated globally and by runaway thirds in accordance with the ANAC (2019) recommended tolerance level of 2.5 m/km every 200 m.

3.2. IRI progression model

The progression of the IRI was estimated from the analysis of technical reports of the IRI survey of a Brazilian aerodrome's runway, between the years 2014 and 2020 (ENGEVIAS, 2014; FRAPORT, 2018; 2020a; 2020b). The IRI variation over the years was determined for each section, estimating the annual percentage increase, as if it occurred uniformly. For this annual increase, a growth rate of 10% was estimated and considered.

The progression model also needed to consider the IRI performance increase after applying the M&R. These values were estimated considering the mentioned IRI survey, since the 2020 data refer to measurements obtained before and after the rehabilitation of the runway (milling and recomposition of the asphalt coating). As for this analysis, a relationship similar to that of Wang and Wang (2017) was verified, since the benefit for the pavement in poor condition was greater compared to that for the pavement in good condition. The results were taken to weigh predictions related to the pavement's condition after similar interventions.

A classification into five categories was created as a reference for determining the moment of application of the M&R strategies (Table 1). For each category, an activity or set of activities was recommended, considering the practice observed in the national scenario. This step was based on the observations of Cossío Durán (2019). Due to technical particularities, it was assumed that the Reconstruction reduces the IRI to a value limited to 1.5m/km, as reaching lower values would be costly or even impractical.

Table 1: M&R rating and recommended strategies for IRI correction

IRI range	Pavement conditions	M&R	Post-intervention IRI (improvement)
<1.5	Very Good	Not necessary a	-
1.5 to 2.0	Good	Preventive b	15%
2.0 to 2.5	Fair	Corrective c	30%
2.5 to 3.0	Poor	Reinforcement d	45%
>3.0	Very Poor	Reconstruction e	Up to 1.5m/km

(a) Do-nothing; (b) Cracks sealing and surface repairs; (c) Reprofiling; (d) Milling, and recomposition (5cm); (e) Demolition and reconstruction (12 cm).

3.3. M&R strategies costs

Data from DNIT (2022), with reference to April/2022, were used to define the unit cost compositions. Only direct costs were estimated. Planning, administration, and mobilization costs have been excluded, but it is believed that these will assume similar or insignificant values. For indirect costs, a value was defined for Benefits and Indirect Costs, according to DNIT (2022) at 26.28% for services and 15.0% for asphalt inputs.

3.4. Definition of alternatives and Life-Cycle Cost Analysis (LCCA)

Four different M&R strategies were evaluated over a 20-year analysis period. Two approaches were considered, deterministic and probabilistic. The evaluated alternatives are summarized in Table 2.

Table 2: Summary of evaluated M&R strategies

Alternative	Description
A	Do-nothing
B	Preventive maintenance application
C	Corrective maintenance application
D	Application of preventive and corrective maintenance

For each section, alternative and year of the analysis, it was decided between: (i) performing the proposed M&R and considering the IRI improvement, according to the definitions presented in Table 1 and (ii) not performing the M&R, with IRI progression.

The deterministic analysis followed the elaborated compositions and the value of 7% per year for the discount rate. The probabilistic analysis considered the variability of unit costs of the services that make up the M&R strategies and the discount rate; the variability of the IRI values and the model proposed in Table 1 were not considered. The probabilistic analysis was modeled by stochastic values, attributed by a normal probability distribution, with average (elaborated composition) and standard deviation (15% of the average), performing 5,000 Monte Carlo simulation iterations for the NPV. Table 3 shows the input parameters of the LCCA performed.

Table 3: LCCA input parameters

Parameter (cost or unit fee)	Average	Standard Deviation
Crack sealing (BRL/m)	3.45	0.52
Surface patch (BRL/m^3)	313.34	47.00
Priming (BRL/m^2)	7.28	1.09
Primer Coat (BRL/m^2)	1.93	0.29
Milling (BRL/m^3)	84.05	12.61
Hot Mix Asphalt - HMA (BRL/m^3)	517.82	77.67
Discount rate (% per year)	7.00	1.00

3.5. Effectiveness analysis

It was also determined the Effectiveness/Cost Ratio (ECR). Effectiveness was not monetarily represented, but estimated by performance in relation to roughness. The area bounded by the IRI progression curve and its acceptability limit were used to estimate effectiveness. Costs were analyzed with deterministic NPV and the benefit is negative when the IRI is above the acceptability threshold.

4. RESULTS AND DISCUSSIONS

Table 4 presents the survey and classification of the runway roughness, with IRI values for the 200 m segments, as well as the average value and standard deviation of the respective thirds.

It can be seen from Table 4 that four sections do not meet the IRI acceptability limit, 2.5 m/km, recommended by ANAC (2019), which indicates the need for M&R to recover runway’s functional conditions. These four sections are located near the headboards, which may be due to the aircraft's touchdown zone during landing operations and the acceleration effort during takeoffs. Such conditions tend to request more intensely the 1st and 3rd thirds, when compared to the 2nd third. It was considered, in determining the costs of each alternative, the realization of repairs in these sections at the beginning of the analysis.

Table 4: Survey of the current roughness of the study runway pavement

Section	Runway stretch (m)	IRI (m/km)		Classification (according to Table 1)
1	0 - 200	4.21	1st third: $IRI_{average}$: 2.76 / Standard Deviation: 1.08	Very Poor
2	200 - 400	4.08		Very Poor
3	400 - 600	2.18		Fair
4	600 - 800	2.04		Fair
5	800 - 1000	1.98		Good
6	1000 - 1200	2.04		Fair
7	1200 - 1400	1.98	2nd third: $IRI_{average}$: 2.02 / Standard Deviation: 0.03	Good
8	1400 - 1600	2.06		Fair
9	1600 - 1800	2.01		Fair
10	1800 - 2000	2.02		Fair
11	2000 - 2200	2.01		Fair
12	2200 - 2400	1.90	3rd third: $IRI_{average}$: 2.53 / Standard Deviation: 0.88	Good
13	2400 - 2600	1.95		Good
14	2600 - 2800	1.96		Good
15	2800 - 3000	2.06		Fair
16	3200 - 3200	3.58		Very Poor
17	3200 - 3300	3.75		Very Poor

$IRI_{average}$ = 2.46 m/km / Standard Deviation: 0.84 m/km (all runway stretch).

4.1. Deterministic life-cycle cost analysis

Table 5 presents the results obtained for the Net Present Value (NPV) for each of the four evaluated M&R strategies.

Table 5: NPV of the appraised alternatives

Alternative	NPV (BRL)
A	14,426,940.18
B	6,168,217.28
C	11,675,673.07
D	6,248,565.88

Alternative A has the highest NPV and, consequently, is the costliest solution. “Do-nothing” implies an unlikely alternative, especially in the case of granted airfields, due to the loss of asset value over time. On the other hand, this alternative validates the APMS concepts, that “do-nothing” intensifies pavement damage, reduces performance and demands expensive interventions with greater impact on landing and takeoff operations.

In turn, the NPV of Alternative B has the lowest cost. In general, it is the alternative that has more interventions throughout the pavement life-cycle because it only considers preventive maintenance. The costliest option involving M&R is Alternative C, which is 89.3% more expensive than Alternative B, despite applying the M&R in a smaller amount.

Alternative D has the second lowest NPV, being 1.3% more expensive than Alternative B. This result contributes to the interpretation that corrective maintenance, despite increasing the total cost, is still a preferable solution to Reinforcement or Reconstruction.

4.2. Probabilistic life-cycle cost analysis

Table 6 presents the results of the 5,000 Monte Carlo simulations for the average, maximum and minimum NPV, as the respective standard deviations of each of the four M&R alternatives analyzed in this paper.

Table 6: Results for the probabilistic LCCA

Alternative	Minimum (BRL)	Average (BRL)	Maximum (BRL)	Standard Deviations (BRL)
A	8,085,010.83	14,498,824.50	21,662,292.64	1,826,483.33
B	3,508,871.86	6,174,936.21	8,914,277.57	729,205.25
C	5,507,462.19	11,885,941.20	18,671,361.37	1,775,396.12
D	3,161,146.73	6,285,269.48	9,507,778.39	855,727.29

The probabilistic NPV values for Alternatives B and D are the lowest. However, due to the standard deviation, the minimum value from Alternative D simulations is less than the minimum NPV from Alternative B. This result corroborates the interpretation that corrective maintenance activities increase cost variability and investment risks.

The most expensive alternatives, on the other hand, are A and C, with the minimum NPV of Alternative A being greater than the average NPV of alternatives B and D; the largest standard deviations are also present in these alternatives. The probabilistic interpretation results allows a conclusion similar to the deterministic ones and contributes to the understanding of the variability and sensitivity of costs in relation to the magnitude of the parameters.

The probability density function - Figure 1a - and the cumulative probability distribution - Figure 1b - show that 0.11% and 0.31% of the values obtained for Alternative A are lower than the maximum values of the alternatives B and D, respectively. Thus, Alternative A (Do-Nothing) is unlikely to assume advantageous values.

Uncertainty is directly proportional to the slope of the cumulative probability curve and a wider distribution of the density function represents greater variability. Thus, alternatives A and C have the greatest uncertainty and Alternative D is more uncertain than B, indicating that corrective maintenance increases uncertainty, with preventive maintenance being preferable.

Additionally, a sensitivity analysis was performed for all alternatives to complement the understanding of the influence of the variables' volatility. The range of values (Figure 2) was determined by adopting separately the values obtained by the simulations of each input data, verifying the impact on the NPV, while the other variables remained invariable (the average value was considered in this analysis).

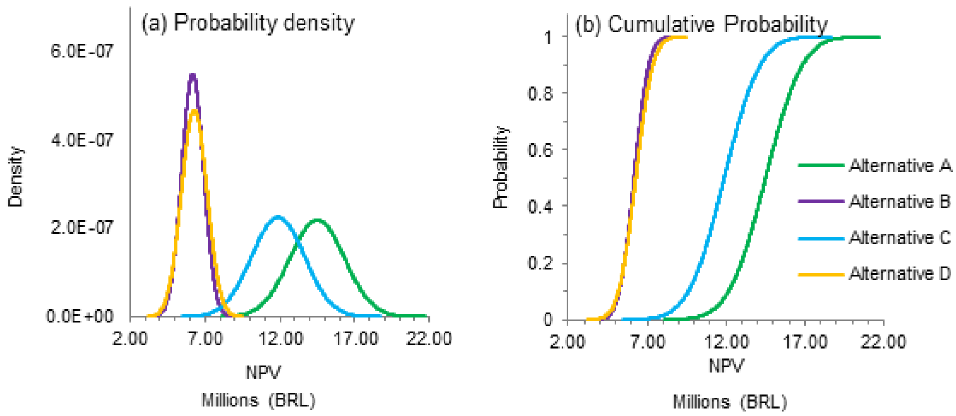

Figure 1. NPV probability distribution for each alternative

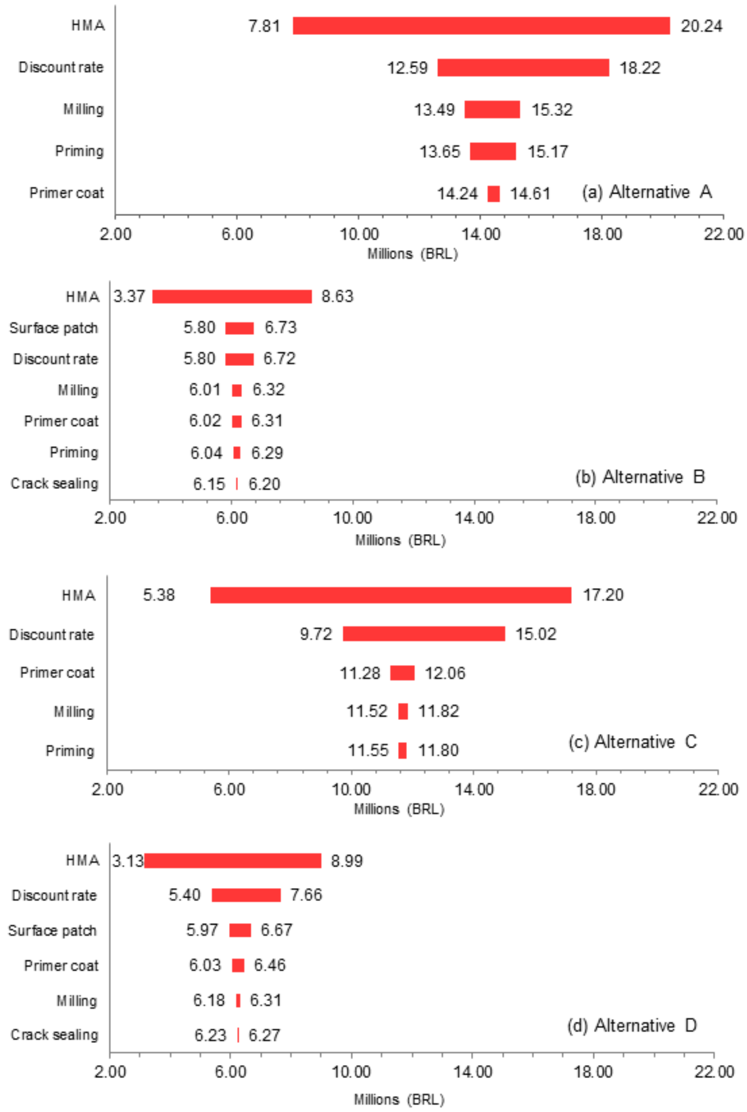

Figure 2. Sensitivity Analysis of NPV in relation to variables

It was observed, for Alternative B (Figure 2b), that the variation of R$ 100.00 in the unit cost of m^3 of HMA entails a variation of R$ 900,000.00 in NPV. Still for Alternative B, it was also found that, on average, the cost decreases by 2% as the discount rate increases by 1%. In general, HMA prices exert the greatest influence on NPV results, for all alternatives. The discount rate is the only one to show a negative correlation and is the second most influential, with the exception of Alternative B. In this case, the Superficial Patch promotes a larger range of NPV values, which can be explained by the high number of preventive maintenance applications.

4.3. Roughness analysis in LCCA

As the functional benefits of the alternatives are different, it is necessary to evaluate the results in relation to the performance of the pavement, specifically regarding the IRI. Figure 3 shows the average IRI for each year.

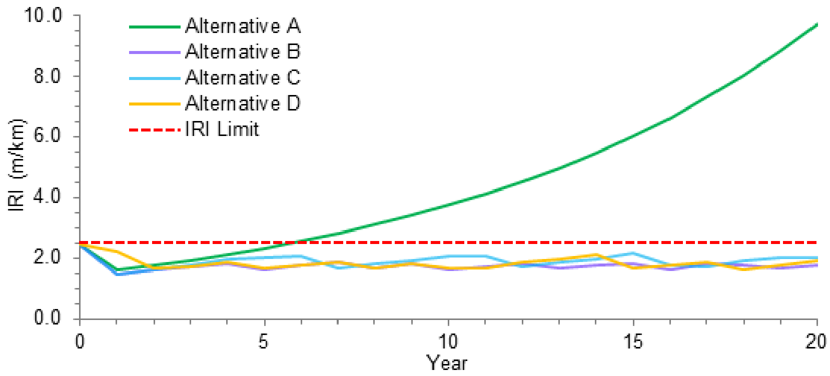

Figure 3. Average IRI of the runway over the analysis period

It can be seen from Figure 3 that the IRI does not reach the acceptability limit for alternatives B, C and D, with Alternative B (Preventive Maintenance) being the furthest away from the considered limit (2.5 m/km). Alternative A has the worst performance, showing, from the 6th year onwards, an average IRI higher than the acceptability limit and an IRI value of 9.71 m/km at the end of the analysis. Among the M&R strategies, Alternative C is the closest to the IRI acceptability limit, as corrective activities are applied when the IRI is higher.

The pavement's residual value, which represents the monetary value (benefit) attributed to the pavement at the end of analysis period, was not estimated. However, observing the IRI values, it is noted that Alternative B would have the highest residual value, followed by alternatives D and C. That is, the alternatives that have the lowest NPV also have the highest residual values and, consequently, the greatest benefits.

Table 7 shows the average IRI values, considering the analysis period, for the entire runway and its thirds.

It is observed in Table 7 that Alternative A stands out as the worst performing and Alternative B as the best. Alternative A has an average IRI value more than twice as high as that of the other alternatives, both for the entire length of the runway and for its thirds. Thus, in addition to offering the highest costs, not carrying out M&R activities implies lower benefits.

Table 7: Average IRI values (m/km) during the analysis period (20 years)

Alternative	Segment			
	Entire runway	1st third	2nd third	3rd third
A	5.00	5.24	4.73	5.00
B	1.71	1.72	1.71	1.69
C	1.87	1.88	1.87	1.87
D	1.83	1.83	1.84	1.82

With regard to the other alternatives, it can be seen from Table 7 that for the same strategy, it is not possible to identify considerable variations in the average IRI values between the thirds. Furthermore, it appears that the IRI does not vary significantly between alternatives C and D.

One of the elements that the APMS can implement is the prioritization of repair areas, in order to optimize the application of M&R strategies. Thus, the analysis by thirds was motivated and Figure 4 shows the functional performances of the thirds of the runway in relation to the IRI for all the alternatives, not by the average of the period, but annually.

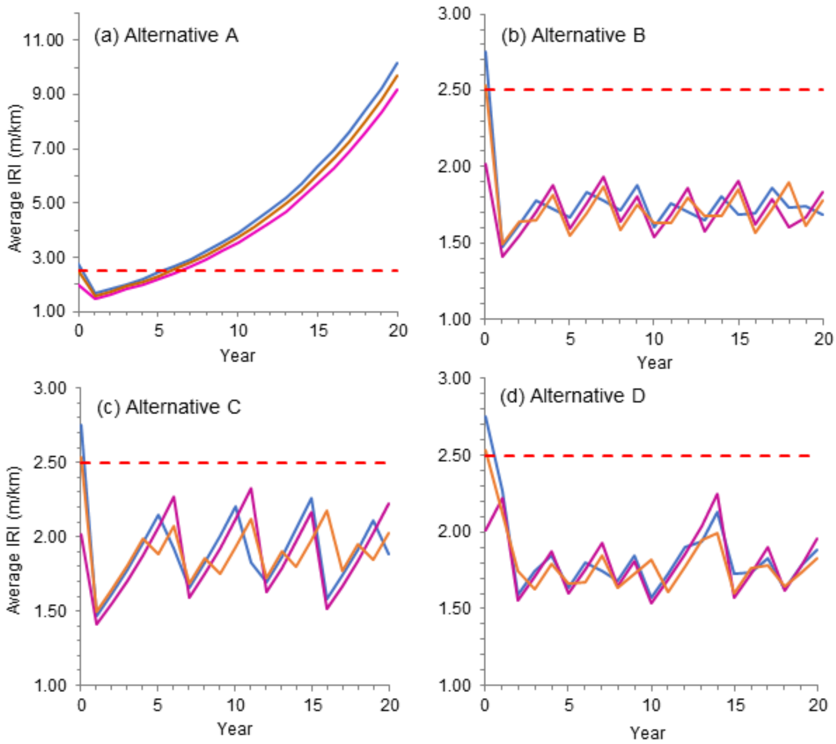

Figure 4. IRI progression on the runway's thirds through the analysis period

The graphs in Figure 4 show that performance by thirds is similar. However, it is observed that the 1st third has the highest IRI values and the 2nd third the lowest. The 2nd third presents, contradictorily, the maximum and minimum IRI values of the analysis (alternatives B, C and D). In addition, the sections receive, in general, the same number of interventions.

Table 8 presents the ECR of each alternative, the values were raised to the sixth power to facilitate their comparison.

Table 8: Cost-Effectiveness Analysis of evaluated strategies

Alternative	Effectiveness (IRI×year)	NPV (BRL)	Effectiveness/Cost ratio (IRI×year/BRL)
A	-45.93	11,665,648.35	-3.94
B	15.53	5,330,467.12	2.91
C	12.33	8,863,918.74	1.39
D	13.12	5,146,369.94	2.55

The data in Table 8 indicate that Alternative B presents the best ECR, confirming the effectiveness of preventive maintenance and allowing the IRI to distance itself from the acceptability limit. Therefore, corrective maintenance causes a reduction in ECR and the benefit to pavement performance, even if they provide immediate correction at better levels compared to preventive maintenance.

4.4. Final considerations on the analysis of results

The analysis carried out in this paper can be improved for its effective application. Issues related to restrictions on the operability of the aerodrome during the execution of M&R activities were not taken into account.

There is also opportunity for improvement regarding the IRI progression model. A reliable database and surveys, associated with an adequate APMS, would help in forecasting life-cycle investments, developing the progression model and analysis alternatives. Other aspects include: verification of different equations for the IRI and their influence on the total cost; evaluation of the influence of the variability of other parameters on the probabilistic LCCA, such as the period of analysis, the limit of acceptability of the IRI and the effectiveness adopted for the M&R activities.

The analyzes carried out depend on some factors. One is the activities considered and their unit costs. At another level, there is the influence of the progression model and the proposed classification for the IRI; as they directly influence the trigger moment for performing M&R. It is added that, for aerodrome operators, tangible results facilitate the process of incorporating new processes and analyses. In this sense, it is expected that this paper will contribute to the application of approaches to compare and select M&R activities, enabling the optimized allocation of resources with a view to promoting the adequate performance of airport pavements and the safety of their operations.

5. CONCLUSIONS

This paper found that “Do-Nothing” as a maintenance and rehabilitation (M&R) strategy for roughness conditions is not beneficial for the evaluated airport pavement. In addition to the need for a more expensive investment, a high roughness can affect the safety of landing and takeoff operations and impair the integrity of the aircraft. This interpretation is contained in the deterministic and probabilistic Life-Cycle Cost Analysis (LCCA), also presenting the worst performance and the worst Effectiveness/Cost Ratio (ECR).

For the other alternatives that proposed M&R strategies within the scope of this paper, the IRI does not reach the acceptability limit determined by the current Brazilian regulation. Therefore, in general, any one could be selected without compromising operational safety. In this sense, it is concluded that preventive maintenance is preferable to corrective maintenance, due to its lower cost and variability and, consequently, lower uncertainty and risk associated with investments. It has been shown that carrying out preventive maintenance is a rational solution to avoid costly services and increase the ECR.

LCCA proved to be effective for comparing M&R strategies on airport pavements. The LCCA, by itself, does not determine the most appropriate strategy. Its results can be used to support the decision making of aerodrome operators and the civil aviation authority. Allied to the LCCA, the analysis of the performance and the runways’ IRI enables a more rational decision-making regarding M&R strategies and the increase of operational safety at Brazilian aerodromes.

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