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THEMATIC SECTION | AIR TRANSPORTATION SYSTEMS: INFRASTRUCTURE, OPERATIONS, AND ENVIRONMENTAL INTEGRATION

Impact of Costs Related to International Roughness Index Variability on a Brazilian Runway

José Levi Chaves de Sousa[1,*], Rayssa de Sousa Carneiro[1], Sebastian Felipe Castellanos Buitrago[1], José Wémenson Rabelo Chaves[1], Francisco Heber Lacerda de Oliveira[1]

1. Universidade Federal do Ceará – Departamento de Engenharia de Transportes – Programa de Pós-Graduação em Engenharia de Transportes – Fortaleza/CE – Brazil.

*Correspondence author: levi.chaves@det.ufc.br

ABSTRACT

The functional quality of runways (RWY) is a critical factor for the safety and comfort of airport operations. One of the main indices used to assess this quality is the International Roughness Index (IRI). Maintaining IRI values within acceptable limits is essential to avoid operational problems, reduce aircraft maintenance costs, and ensure safety. In this context, the aim of this article is to analyze whether there is variability in the IRI with maintenance and rehabilitation (M&R) costs on a RWY. The research method used data provided by the National Agency for Civil Aviation (Agência Nacional de Aviação Civil [ANAC]) for the years 2020, 2021, and 2023, collected by a laser profilometer. The results show that the interventions carried out in 2020 reduced the IRI values in 2021, improving the pavement condition. However, an increase in the IRI values was observed in 2023, indicating the onset of deterioration. The financial analysis showed that the most expensive interventions occurred in 2020 due to the need for pavement reconstruction, while in 2021, costs were lower due to preventive maintenance. In 2023, costs increased again, highlighting the importance of continuous M&R. In conclusion, fair M&R interventions are essential to maintain RWY quality and safety, prevent degradation, and avoid high future costs.

Keywords: IRI; Airport costs; Maintenance and rehabilitation; Runway.

INTRODUCTION

The functional quality of runways (RWY) is imperative to ensure the safety and comfort of airport operations, as the infrastructure plays a pivotal role in mitigating risks and ensuring safe operations (Rodrigues *et al.* 2022). One of the primary indicators utilized to assess this quality is the International Roughness Index (IRI). The National Civil Aviation Authority of Brazil (Agência Nacional de Aviação Civil [ANAC]) has established specific limits for the IRI on Brazilian airport RWY, with the maximum recommended value set at 2.5 m/km (ANAC 2023). Nevertheless, the variability of IRI values over time can be defined by various factors, including the quality of the paving, climatic conditions, and the maintenance practices adopted.

Therefore, it is imperative to maintain IRI values within acceptable limits to prevent operational issues and minimize aircraft maintenance expenditures. According to the findings of the Federal Aviation Administration (FAA 2009), longitudinal irregularities have the potential to directly impact the directional control of aircraft and augment the fatigue of their components, consequently leading to elevated operating costs. Furthermore, Leite *et al.* (2023) emphasize that the rehabilitation of RWYs can enhance IRI values, thereby promoting optimal functional and operational conditions.

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From this, it becomes important to maintain the IRI values within acceptable limits to avoid operational issues and reduce costs related to aircraft maintenance as well as the maintenance and rehabilitation (M&R) of pavements. It is noteworthy that the concession process influences the management of airport pavements. Regulatory agencies set limits and frequencies for M&R, which concessionaires must comply with. Consequently, to reduce costs and optimize resources, concessionaires may prioritize frequent and preventive maintenance to avoid high expenses from emergency repairs and ensure the quality and safety of the pavements.

Given this context, this study aims to analyze whether there is variability in the IRI in a Brazilian RWY. Based on this analysis, M&R solutions will be proposed, including an estimate of the associated costs.

LITERATURE REVIEW

The quality of a pavement's ride comfort is directly related to the defects and irregularities of its surface. At airports, although care is also taken to ensure passenger comfort, there is a greater focus on the safety of landing and take-off operations, given the particularities of aircraft traffic (Chen and Chou 2004). Oliveira (2009) adds that airport pavement must provide their users with a high level of service, complying with the necessary operating, safety and quality conditions, contributing to reducing risks during landings and take-offs and mitigating possible occurrences of aircraft accidents and/or incidents.

According to the FAA (2009), irregularities in airport pavements have the potential to induce vibrations in the aircraft cabin, to the extent that pilots may experience difficulties in maintaining concentration or in manipulating the controls during landing and take-off procedures. The longitudinal irregularities that manifest in airport pavements are attributed to deficiencies in the construction process or to subsequent adverse effects resulting from external factors, including traffic, weathering, and other variables (Buttlar and Islam 2012). Moreover, the longitudinal roughness of the pavement may vary over time due to factors such as functional and structural defects, traffic load, the age and wear of the surface, as well as parameters related to resistance and deformability (Bueno *et al.* 2023).

A variety of indices have been developed to classify pavement surface conditions, as these indicators can be used to functionally quantify its performance (Bidgoli *et al.* 2019; Zhao *et al.* 2018). Pinho (2019) posits that, contingent upon the evaluation method employed, a satisfactory evaluation of a pavement should enable the verification of its real maintenance or rehabilitation needs, thereby facilitating the more effective utilization of material and financial resources to address its deficiencies. One such index is the IRI, which measures the longitudinal irregularity of a road surface (Yu *et al.* 2006).

The FAA has indicated that, despite its dissemination and utilization, the IRI is not applicable to airport pavement. This is due to the fact that the pavement characteristics, the load conditions, and the structural dynamic response differ from those of roads. However, regulatory frameworks in several countries, including Brazil (ANAC 2023), Italy (Ente Nazionale per l'Aviazione Civile [ENAC 2015]), and Canada (Transport Canada 2016), employ the IRI as a metric to evaluate irregularities at airports or to formulate their own indices.

Magalhães (2023) posits that the formulation of effective M&R strategies for airport pavement needs the availability of comprehensive RWY surface data, a prerequisite for ensuring the safety of ground operations. Durán (2015) and Durán and Fernandes Júnior (2020) posit that longitudinal irregularity is the most salient parameter of the pavement surface, with the capacity to correlate with a multitude of factors, including aircraft operating costs, passenger comfort, safety, velocity, travel economy, drainage, and the risk of hydroplaning.

Carneiro *et al.* (2023) developed a classification that relates the IRI and the type of M&R strategy. For each IRI category, an activity or a set of activities was recommended, considering the practice observed in the Brazilian scenario.

A study conducted by Leite *et al.* (2023) revealed that the implementation of rehabilitation measures on the RWY led to enhanced IRI values when compared to the pre-intervention data. The analysis demonstrated a reduction of approximately 47%, thereby enhancing the operational functionality of the RWY. In turn, the analyses carried out by Carneiro *et al.* (2023) proved to be effective in comparing the alternatives and demonstrating the indispensability of M&R. The application of maintenance, whether preventive or corrective, reduced total costs and offered satisfactory pavement performance. Researchers also found that keeping the pavement in good condition reduces the costs of M&R strategies and helps to ensure operational safety.

METHODOLOGY

The research method for this article was organized into four stages: data collection, data tabulation, statistical analysis, and calculation of M&R costs. Initially, data was retrieved from the technical reports furnished by ANAC for the years 2020, 2021, and 2023 concerning the RWY under scrutiny. As for the year 2022, the reports were not provided by the regulatory agency.

The reports in question contain the RWY's IRI data, which was measured at intervals of 200 meters in the left and right lanes of the road, starting at the predominant RWY threshold. The measurements covered distances of 3 and 6 meters, with a total distance of 2.6 kilometers being covered. The measurements were obtained using a laser inertial profilometer.

In the subsequent stage, the data obtained was meticulously organized and tabulated in Microsoft Excel 365, thereby facilitating a systematic organization of the values and paving the way for subsequent analysis in other software. In the third stage, the tabulated data was imported into R software version 4.4.0 and then analyzed in R Studio 2024. In R Studio, a descriptive statistical analysis was carried out to identify patterns, trends, and variability in the RWY IRI. Furthermore, the implementation of visual elements, such as line graphs, was instrumental in facilitating the interpretation of the results.

In step four, after analyzing the statistical results, Microsoft Excel 365 was used to calculate the projected M&R costs for the reduction and maintenance of the IRI of the analyzed RWY. These calculations were based on the IRI classification proposed by Carneiro *et al.* (2023), which associates each IRI class with a specific M&R activity (Table 1). Thus, for each year analyzed, the application of an M&R strategy was considered for each section, according to the method defined by Carneiro *et al.* (2023), in order to estimate the hypothetical costs required to correct the longitudinal roughness, as if the M&R actions had been carried out.

Table 1. M&R strategies by classification.

IRI rate	Pavement condition	M&R code	M&R specific
< 1.5	Very good	DN	Do nothing
1.5 to 2.0	Good	PM	Crack sealing and micro-coating
2.0 to 2.5	Fair	CM	Resurfacing (5 cm)
2.5 to 3.0	Poor	RF	Milling and resurfacing (8 cm)
> 3.0	Very poor	RC	Demolition of the coating and its future reconstruction (12 cm)

Source: Adapted from Carneiro *et al.* (2023).

The objective of this study was to calculate the M&R costs. To this end, the price compositions contained in the Construction Reference Cost System (Sistema de Custos Referenciais de Obras [SICRO]) reports were taken into account, considering the average prices in force in the state of Ceará in the year each M&R was carried out (2020, 2021, and 2023). The distribution prices for asphalt products, as published by the National Petroleum, Natural Gas and Biofuels Agency (Agência Nacional do Petróleo, Gás Natural e Biocombustíveis [ANP]), were also considered in the composition of the unit prices for the M&R strategies.

RESULTS AND DISCUSSION

Table 2 shows a descriptive analysis of the annual results for the 2.6 km analyzed. The IRI averages have fluctuated over time, with elevated values observed in 2020 and a subsequent decline in 2021, attributable to the implementation of M&R initiatives in 2020. In 2023, a further increase was observed, although not to the same extent as in 2020. In 2020, the values exhibited relative constancy, with standard deviation values being considered, while in 2021, there was greater variation in the data, particularly to the left at 3 meters. In 2023, the standard deviation on the left side at 6 meters was the lowest for the period analyzed, indicating greater consistency in the data. As for kurtosis, a statistical measure that compares the distribution of sample data in relation to the normal distribution curve, it can be seen that the year 2023 has values closer to a normal distribution. Table 3 shows an interval analysis between the IRI values.

Table 2. Descriptive analysis of the IRI (in m/km).

IRI RWY	2020				2021				2023			
	Left		Right		Left		Right		Left		Right	
	3 m	6 m	3 m	6 m	3 m	6 m	3 m	6 m	3 m	6 m	3 m	6 m
Minimum	2.24	2.39	2.37	2.52	1.14	1.20	1.26	1.30	1.50	1.48	1.51	1.25
Maximum	3.50	3.42	3.76	3.88	3.11	2.85	2.71	2.57	2.81	2.33	2.84	2.76
Range	1.26	1.03	1.39	1.36	1.97	1.65	1.45	1.27	1.31	0.85	1.33	1.51
Average	2.89	2.89	2.99	3.02	1.65	1.68	1.64	1.62	1.94	1.78	1.96	1.90
Standard deviation	0.39	0.34	0.41	0.36	0.48	0.39	0.36	0.34	0.41	0.25	0.42	0.51
Median	2.80	2.85	2.99	2.95	1.58	1.63	1.55	1.53	1.90	1.75	1.83	1.67
P. 25%	2.66	2.63	2.77	2.80	1.45	1.46	1.43	1.41	1.63	1.58	1.71	1.52
P. 75%	3.14	3.19	3.18	3.25	1.66	1.74	1.71	1.72	2.06	1.81	2.00	2.28
Kurtosis	-1.34	-1.57	-0.93	0.00	3.74	3.44	2.96	2.13	-0.33	-0.49	-0.54	-1.26

Source: Elaborated by the authors.

Table 3. Analysis of IRI ranges (in m/km).

RWY	2020				2021				2023			
	Left		Right		Left		Right		Left		Right	
	3 m	6 m	3 m	6 m	3 m	6 m	3 m	6 m	3 m	6 m	3 m	6 m
[0-200]	0.79	0.88	0.65	0.55	0.47	0.32	0.30	0.50	0.62	0.94	0.20	**1.42**
[200-400]	0.96	0.34	0.54	0.72	0.25	0.26	0.51	0.59	0.55	0.66	0.37	**1.15**
[400-600]	0.76	0.85	0.46	0.19	0.02	0.26	0.33	0.12	0.27	0.81	0.18	**1.32**
[600-800]	0.09	0.88	0.34	0.74	0.09	0.64	0.59	0.25	0.84	0.98	0.78	0.36
[800-1,00]	0.26	0.73	0.60	0.44	0.29	0.66	0.12	0.09	0.62	**1.45**	0.55	0.83
[1,000-1,200]	0.44	0.95	0.73	**1.32**	0.31	0.50	0.36	0.78	0.18	**1.64**	0.11	0.03
[1,200-1,400]	0.34	0.81	0.22	**1.40**	0.02	0.52	0.20	0.42	0.31	0.54	0.37	0.14
[1,400-1,600]	0.24	0.16	0.50	0.60	0.09	0.29	0.27	0.24	0.34	**1.02**	0.31	0.36
[1,600-1,800]	0.35	0.51	0.36	0.82	0.30	0.47	0.36	0.33	0.22	**1.22**	0.34	0.20
[1,800-2,000]	0.68	0.50	0.53	0.62	0.10	0.27	0.53	0.35	0.13	0.60	0.14	0.15
[2,000-2,200]	0.11	0.44	0.30	0.42	0.22	0.25	0.08	0.31	0.13	0.72	0.13	0.15
[2,200-2,400]	**1.08**	0.46	0.86	0.31	0.14	0.49	0.35	0.14	0.62	0.73	0.18	0.40
[2,400-2,600]	**1.05**	0.46	0.40	0.34	0.47	0.42	0.49	0.17	0.42	0.90	0.19	0.85

Source: Elaborated by the authors. Bolded values indicate ranges greater than 1 m/km.

As illustrated in Table 3, an analysis of the variation in the values between the maximum and minimum IRI intervals over four measurements for each segment of the RWY is presented. It is evident that the highlighted cells correspond to variations greater than 1 m/km, a criterion that has been established to identify segments characterized by significant variation, thereby resulting in different classifications for the same stretch. In 2020, the most significant variations were observed in the 1,000 to 1,400 meters segments in the right lane at 6 meters, with values of 1.32 and 1.40 m/km, respectively. In 2021, no values exceeded 1 m/km, indicating reduced variation between measurements and a RWY that was in better condition compared to the other years.

The analysis indicates an increase in variation across multiple segments in 2023, particularly within the [1,000-1,200] segment on the left at 6 meters, which exhibited the most significant variation, with a value of 1.64 m/km. This increase in variation, particularly on the left-hand side of the road, signifies a deterioration in the RWY over time. To address these concerns, M&R activities are recommended to mitigate and regulate the longitudinal irregularity of the RWY. Table 4 presents the standard deviation of the four measurements for each segment.

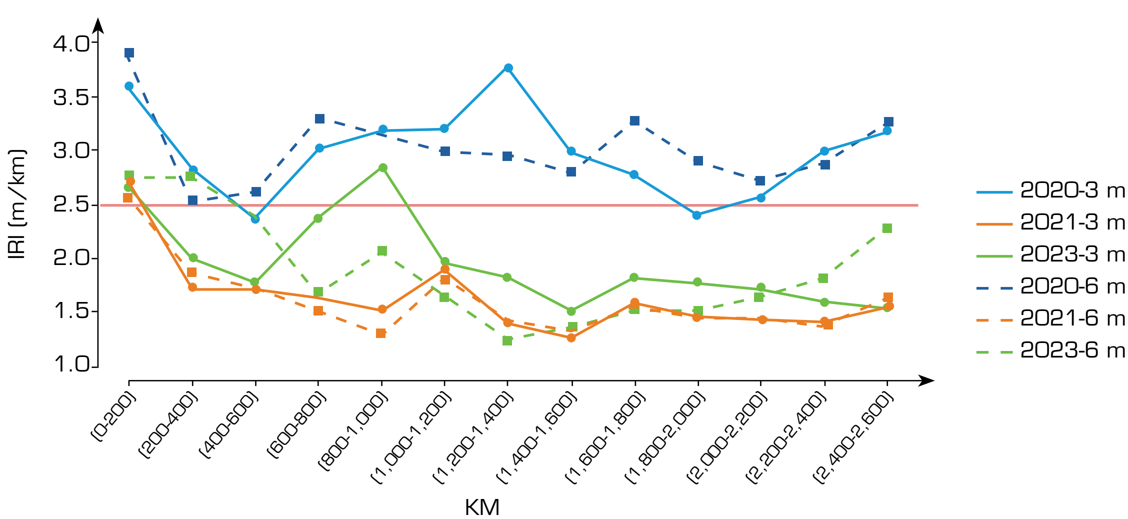
Table 4. IRI standard deviation analysis.

RWY	2020				2021				2023			
	Left		Right		Left		Right		Left		Right	
	3 m	6 m	3 m	6 m	3 m	6 m	3 m	6 m	3 m	6 m	3 m	6 m
[0-200]	0.42	0.38	0.28	0.26	0.21	0.15	0.15	0.21	0.26	0.43	0.09	**0.69**
[200-400]	0.43	0.14	0.23	0.34	0.12	0.12	0.24	0.28	0.23	0.29	0.16	**0.61**
[400-600]	0.36	0.41	0.20	0.08	0.01	0.12	0.16	0.05	0.12	0.35	0.08	**0.70**
[600-800]	0.04	0.39	0.16	0.34	0.04	0.31	0.29	0.13	0.48	0.41	0.37	0.16
[800-1,000]	0.13	0.31	0.28	0.18	0.14	0.35	0.05	0.05	0.33	**0.71**	0.23	0.45
[1,000-1,200]	0.18	0.41	0.34	**0.54**	0.16	0.27	0.16	0.36	0.08	**0.68**	0.05	0.01
[1,200-1,400]	0.16	0.34	0.12	**0.58**	0.01	0.23	0.09	0.19	0.17	0.23	0.16	0.06
[1,400-1,600]	0.10	0.07	0.26	0.26	0.04	0.14	0.15	0.11	0.18	0.43	0.13	0.20
[1,600-1,800]	0.15	0.21	0.17	0.34	0.14	0.24	0.18	0.19	0.12	**0.50**	0.15	0.09
[1,800-2,000]	0.38	0.21	0.26	0.26	0.04	0.13	0.26	0.15	0.06	0.28	0.06	0.08
[2,000-2,200]	0.05	0.23	0.13	0.18	0.11	0.14	0.03	0.16	0.06	0.32	0.05	0.07
[2,200-2,400]	**0.52**	0.23	0.38	0.15	0.06	0.27	0.19	0.06	0.29	0.33	0.07	0.21
[2,400-2,600]	**0.51**	0.19	0.21	0.14	0.22	0.19	0.20	0.07	0.22	0.38	0.09	0.39

Source: Elaborated by the authors. Bolded values indicate standard deviations greater than or equal to 0.5.

The cells that have been highlighted indicate standard deviations greater than 0.5, a critical value that has been established to identify segments with greater data dispersion. An analysis of the data from 2020 reveals that the segments ranging from 1,000 to 1,400 meters to the right and at 6 meters had standard deviations of 0.54 m/km and 0.58 m/km, respectively. This indicates variability in the measurement of RWY irregularity in these segments, suggesting the need for further investigation to understand the underlying causes.

The analysis conducted in 2023 indicates an augmentation in the standard deviation across multiple segments, particularly at 6 meters on both sides of the RWY. These findings imply an escalating degree of variability between the IRI measurements of the RWY, particularly during the initial and medial phases of the RWY. It can be seen that the results in Table 4 corroborate the results in Table 3, where the same segments with longer measurement intervals have standard deviations above 0.5. Figure 1 shows measurements of 3 and 6 meters of IRI in the years 2020, 2021, and 2023 for the right side of the RWY.

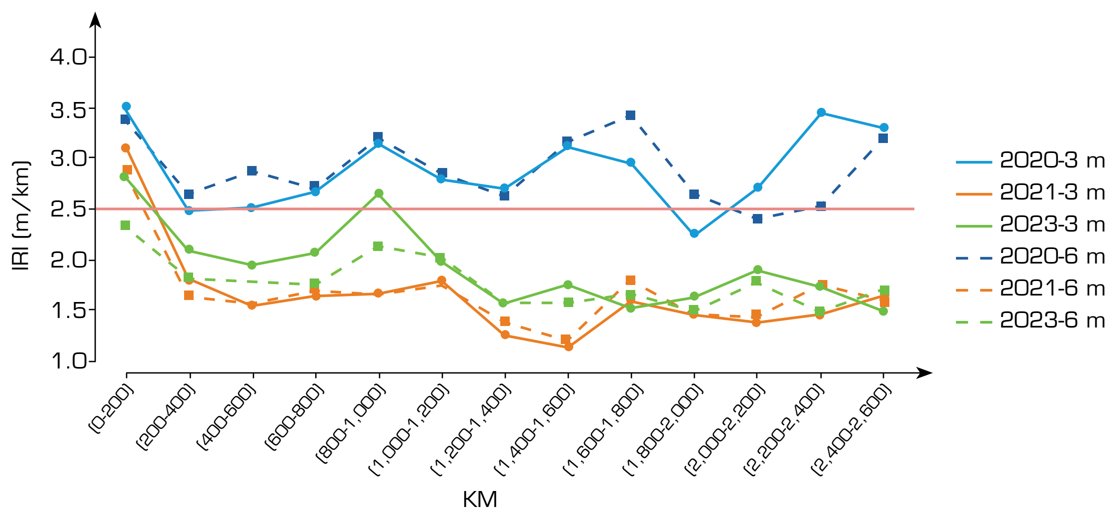


Source: Elaborated by the authors.

Figure 1. Line graph of the average IRI values on the right-hand side.

As demonstrated in Fig. 1, there is a clear variation in IRI along the RWY on the right-hand side. In 2020, the highest IRI peaks were observed, indicating greater unevenness in the roadway. In contrast, the 2021 data reveal a decline in longitudinal unevenness, manifesting as a decrease in IRI values and a concomitant enhancement in their stability. However, in 2023, the RWY demonstrated a deterioration in irregularity, particularly in the measurements at 3 meters. In both 2021 and 2023, measurements at 3 meters consistently exhibited higher values compared to those at 6 meters. However, a general tendency towards decrease was observed along the analyzed stretch.

In 2020, the majority of sections of the RWY, with the exception of two at 3 meters, exceeded the IRI limit value of 2.5 m/km (ANAC 2023), indicating a necessity for M&R. In 2021 and 2023, the majority of measurements fell below the established limit, with only sporadic instances of noncompliance observed in the [0-200] and [800-1,000] sections. These findings indicate a decline in the longitudinal irregularity of the RWY, in comparison to the data observed in 2020, thereby demonstrating adherence to the standards stipulated by ANAC. Although the highest IRI values observed over the years are concentrated in the first third and the aircraft touchdown zone, where the greatest impacts on the surface occur, it is important to note that this is not the only area with elevated IRI values. Figure 2 presents the IRI measurements at 3 and 6 meters for the years 2020, 2021, and 2023 on the left side of the RWY.



Source: Elaborated by the authors.

Figure 2. Line graph of the average IRI values on the left side.

As illustrated in Fig. 2, there is a demonstrable variation in IRI along the RWY on the left-hand side. In 2020, the highest IRI peaks were observed, indicating greater irregularity, especially at the beginning of the survey in the [0-200] segment, with only three sections not exceeding the 2.5 m/km limit. In 2021, a decline in longitudinal irregularity is evident, contrasting with a resurgence in IRI values in 2023, signifying a deterioration in RWY.

With the exception of 2023, measurements at 6 meters exhibited higher IRI values compared to measurements at 3 meters, while the reverse was observed on the right side. In 2021 and 2023, the majority of measurements were below the limit, indicating a reduction in longitudinal irregularity. This improvement was consistent with the right side of the RWY, suggesting a uniform pattern across the array. It is important to acknowledge that while the IRI values decreased in 2023, the potential for a resurgence to the 2020 levels persists in subsequent years in the absence of M&R. To calculate the M&R costs required for the RWY, each segment of the RWY was classified. Similar to Fig. 1, Fig.2 also shows elevated IRI values in the aircraft touchdown zone, although it is not the only region to record high IRI values. The classification of the functional condition of the RWY sections in relation to the IRI values is illustrated in Table 5, with consideration given to the criteria outlined in Table 1.

As illustrated in Table 5, the ratings of the RWY segments exhibited an upward trend from 2020 to 2023. A marked enhancement in the surface conditions of the RWY was observed from 2020 to 2021, a development that followed the reconstruction of its lining.

Table 5. Classification of RWY conditions.

Year	2020		2021		2023	
Section	Condition	M&R	Condition	M&R	Condition	M&R
[0-200]	Very Poor	RC	Poor	RF	Poor	RF
[200-400]	Poor	RF	Good	PM	Fair	CM
[400-600]	Poor	RF	Good	PM	Good	MP
[600-800]	Very Poor	RC	Good	PM	Fair	CM
[800-1,000]	Very Poor	RC	Good	PM	Poor	RF
[1,000-1,200]	Poor	RF	Good	PM	Good	PM
[1,200-1,400]	Poor	RF	Very Good	DN	Good	PM
[1,400-1,600]	Very Poor	RC	Very Good	DN	Good	PM
[1,600-1,800]	Very Poor	RC	Good	PM	Good	PM
[1,800-2,000]	Poor	RF	Very Good	DN	Good	PM
[2,000-2,200]	Poor	RF	Very Good	DN	Good	PM
[2,200-2,400]	Poor	RF	Very Good	DN	Good	PM
[2,400-2,600]	Very Poor	RC	Good	PM	Good	PM

Source: Elaborated by the authors.

In 2020, the majority of segments received a rating of "poor" (54%) or "very poor" (46%), indicating a substandard state. However, in 2021, a notable shift was observed, with 54% of the segments classified as "good" and 38% as "very good." A notable observation is the condition of segment [0-200], which has not undergone rehabilitation and is the sole segment to receive a poor rating in 2021. In 2023, a further deterioration is observed, particularly within the initial 1,000 meters, indicative of the cumulative impact of weathering and aircraft traffic over time.

The definition of unit prices was derived from the average annual price indicated by SICRO for the services related to the application of the M&R proposed in Table 1. The unit prices defined for the items, for each of the years analyzed, are shown in Table 6. These prices also take into account the purchase price of the asphalt inputs.

Table 6. Average annual unit prices for services related to M&R strategies.

Code	Service	Unity	Average unit price in R$ (with inputs)		
			2020	2021	2023
4915626	Mechanized crack sealing on flexible pavement with emulsion – Commercial sand	m	2.33	2.43	2.90
4011408	Cold micro-coating with 0.8 cm polymer-modified emulsion – Band II – Commercial gravel	m²	5.16	6.59	8.11
4915663	Discontinuous milling of asphalt surfacing – 5 cm thickness	m³	50.62	57.10	69.60
4915666	Discontinuous milling of asphalt surfacing – 8 cm thick	m³	50.62	57.10	59.78
4011353	Bonding paint	m²	0.92	1.19	1.39
4011351	Priming with diluted asphalt	m²	4.64	5.41	5.68
4011463	Asphalt concrete – Range C – Commercial sand and gravel	t	272.83	329.95	425.78
4915667	Mechanized removal of asphalt coating	m³	8.48	8.85	12.42

Source: Retrieved from DNIT (2020; 2021; 2023).

The calculation of the annual costs per RWY segment was performed by utilizing the unit prices from the SICRO table, which were employed to execute the M&R strategies. This approach was informed by the relationship between Table 1 (M&R proposal) and Table 5 (classification of the IRI values of the RWY analyzed). The area under consideration for the analysis is 200 meters in length (the size of the segment under review) and 12 meters in width (6 meters on each side of the axis, as specified for the IRI survey). Table 7 presents the calculated annual costs, categorized by section and in total.

Table 7. Total annual cost per segment of RWY with M&R strategies.

Section/year	2020	2021	2023	Total
[0-200]	R$ 204,367.34	R$ 165,865.01	R$ 211,017.07	R$ 581,249.42
[200-400]	R$ 137,654.26	R$ 16,302.50	R$ 134,317.92	R$ 288,274.68
[400-600]	R$ 137,654.26	R$ 16,302.50	R$ 20,038.50	R$ 173,995.26
[600-800]	R$ 204,367.34	R$ 16,302.50	R$ 134,317.92	R$ 354,987.76
[800-1,000]	R$ 204,367.34	R$ 16,302.50	R$ 211,017.07	R$ 431,686.92
[1,000-1,200]	R$ 137,654.26	R$ 16,302.50	R$ 20,038.50	R$ 173,995.26
[1,200-1,400]	R$ 137,654.26	-	R$ 20,038.50	R$ 157,692.76
[1,400-1,600]	R$ 204,367.34	-	R$ 20,038.50	R$ 224,405.84
[1,600-1,800]	R$ 204,367.34	R$ 16,302.50	R$ 20,038.50	R$ 240,708.34
[1,800-2,000]	R$ 137,654.26	-	R$ 20,038.50	R$ 157,692.76
[2,000-2,200]	R$ 137,654.26	-	R$ 20,038.50	R$ 157,692.76
[2,200-2,400]	R$ 137,654.26	-	R$ 20,038.50	R$ 157,692.76
[2,400-2,600]	R$ 204,367.34	R$ 16,302.50	R$ 20,038.50	R$ 240,708.34
Total	R$ 2,189,783.86	R$ 279,982.51	R$ 871,016.48	R$ 3,340,782.85

Source: Elaborated by the authors.

In 2020, the RWY was classified as very poor (46%) or poor (54%) in all sections, which necessitated the implementation of reinforcement (RF) and RC. This was also the year with the highest costs for M&R strategies in the period analyzed, totaling around R$2.2 million, which represents more than 65.5% of total costs. This observation indicates that in 2020, there was a greater implementation of costly M&R services, attributable to the significant value of the IRI.

Conversely, the 2020 replacement of the coating restored the pavement's functionality, leading to a decrease in IRI values. Consequently, in 2021, there was an 87% reduction in M&R costs compared to the previous year. In the same year, recommendations were made for either preventive maintenance (PM) or do nothing (DN) strategies, which represented the period with the lowest costs.

In 2023, the IRI values increased in comparison to 2021, indicating a progression. This progression is particularly evident in the two sections that require reinforcement, namely the first and last of the initial third. It is recommended that the remaining sections this year receive PM or corrective maintenance (CM). It is noteworthy that the sections requiring CM, RF, and RC incur expenses that exceed those of the sections that only necessitated PM.

The year 2020 concentrates the costs of the very poor category, and there are no RC records for subsequent years. With regard to RF (poor category), most of the costs occurred in 2020; in 2021 these costs decreased, but in 2023 there was an increase due to pavement degradation. There were no costs for the fair category, which requires RC, in 2020 and 2021. With regard to the good category, which requires PM, there was a gradual increase over the period analyzed. As expected, RC and RF costs are higher than CM and PM expenses. Therefore, it is essential to prevent pavement degradation and keep IRI values low in order to minimize M&R costs and impacts on airport operations, since RC and RF activities tend to require breaks in operations more often than PM or CM. The costs were also divided up for analysis by third of RWY, as shown in Table 8.

Table 8. Cost of M&R strategies per third of RWY.

Third/year	2020	2021	2023	Total
1°	R$ 888,410.54	R$ 231,075.01	R$ 710,708.48	R$ 1,830,194.04
2°	R$ 684,043.20	R$ 32,605.00	R$ 80,154.00	R$ 796,802.20
3°	R$ 617,330.11	R$ 16,302.50	R$ 80,154.00	R$ 713,786.61
Total	R$ 2,189,783.86	R$ 279,982.51	R$ 871,016.48	R$ 3,340,782.85

Source: Elaborated by the authors.

The initial third of the study was responsible for the majority of the M&R expenditures, accounting for 55% of the total costs. This is associated with the most deficient pavement conditions, which are characterized by poor ratings in key areas such as surface integrity, surface texture, and overall condition. This phenomenon can be attributed to the location of the aircraft touchdown zone on this particular stretch, where impacts during landing and acceleration for take-off contribute to more pronounced degradation of these sections. Conversely, the third exhibits the most economical costs, attributable to superior IRI ratings in both 2021 and 2023. These findings signify a more gradual deterioration of pavement conditions in comparison to the first third.

CONCLUSION

A thorough examination of the IRI over the 3-year period examined in this article indicates that the data show variation in its values, reflecting changes in the functional condition of the sidewalk over time. The data indicate a trend of improvement in IRI values following the rehabilitation in 2020, with a reduction in its value in 2021. However, in 2023, an uptick in IRI values was observed, suggesting an onset of sidewalk degradation. This variation underscores the necessity for fair M&R interventions to ensure the integrity and quality of the RWY remain within the acceptable limits stipulated by the Brazilian aviation authority, ANAC.

The M&R strategies applied in 2020 improved the IRI scores, as evidenced by the 2021 data, with the sidewalk condition moving from very poor/poor to good/very good. However, the deterioration observed in 2023 indicates the continued need for M&R to ensure the useful life of the pavement. M&R costs have varied over the years, high in 2020 due to costly interventions, reduced in 2021 with preventive maintenance, and high again in 2023 to stem further deterioration. This financial analysis underscores the importance of strategic M&R planning to optimize resources and keep the RWY in proper operating condition.

In summary, the study demonstrates that when M&R interventions are meticulously planned and executed in a strategic and rational manner, they can enhance the functional condition of the RWY. Consequently, continuous maintenance and fair monitoring become imperative for ensuring the effective performance of the sidewalk, thereby reducing future M&R expenditures and enhancing the safety of airport operations.

CONFLICT OF INTEREST

Nothing to declare.

AUTHORS' CONTRIBUTION

Conceptualization: Sousa JLC; **Formal Analysis:** Buitrago SFC, Sousa JLC, and Carneiro RS; **Methodology:** Sousa JLC and Oliveira FHL; **Software:** Buitrago SFC; **Writing – Original Draft Preparation:** Sousa JLC, Carneiro RS, and Chaves JWR; **Writing – Review & Editing:** Sousa JLC and Oliveira FHL; **Visualization:** Sousa JLC, Carneiro RS, and Chaves JWR; **Supervision:** Oliveira FHL; **Final approval:** Sousa JLC.

DATA AVAILABILITY STATEMENT

All data sets were generated or analyzed in the current study.

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