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Geospatial Technologies for the Analysis of Runway Macrotexture and its Relationship with Aeronautical Occurrences

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ABSTRACT

This study presents georeferenced data for the characterization of runways at public aerodromes, focusing on the organization of information to support macrotexture maintenance planning. A total of 499 public aerodromes and their respective runways were mapped and categorized according to operational classes. Additionally, 1,174 operational occurrences recorded in 2024 and directly related to runway conditions were extracted. A spatial and statistical analysis was conducted using linear regression between the number of occurrences and the measurement frequency assigned to each aerodrome. The results indicated a statistically significant correlation between the number of occurrences and the suggested analysis frequency. The findings demonstrate the applicability of integrating georeferenced data with operational records in the formulation of monitoring and management strategies aimed at improving the operational safety of airport infrastructure.

Keywords: Aerospace safety; Textures; Runway conditions; Occurrences.

INTRODUCTION

The ability to process and analyze large volumes of data and the availability of open georeferenced data on online platforms have profoundly changed the way the world is understood and represented, enabling the creation of detailed and increasingly interactive maps (Li *et al.* 2024). Modern mapping tools allow the integration of cartographic products with texts, enhancing the understanding of spatial data and enabling the analysis of complex phenomena (Goodfellow *et al.* 2014; Radford *et al.* 2016). Interactive virtual platforms are valuable for highlighting data patterns and illustrating spatial phenomena at various geographic scales (Roth 2013).

In the aviation context, georeferenced data on the texture of airport pavements enable a detailed assessment of runway conditions, helping to identify areas in need of maintenance and improving safety standards. Properly mapped and easily interpretable information on airport runway textures is crucial for identifying maintenance needs, revealing wear trends, and suggesting structural improvements. The overlay of sensor data with satellite imagery feeds maps with details that are difficult to capture without computational assistance, transforming the way airport managers plan and execute maintenance strategies (Jensen and Stensgaard 2023; Zhu *et al.* 2021).

This study aims to explore the use of interactive mapping tools combined with georeferenced data on the conditions of Brazilian aerodromes to optimize runway maintenance planning through the analysis of essential parameters for macrotexture testing. Aerodromes are mapped and runways are quantified and categorized. The minimum frequency required for macrotexture measurements is identified. All relevant occurrences are recorded according to Brazilian Civil Aviation Authority regulations,

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enabling an analysis of the correlations between these conditions and the macrotexture of the runways. A more in-depth statistical analysis of the relationship between macrotexture and operational occurrences was not performed in this study, as it represents an initial exploratory effort focused on mapping, classification, and preliminary data structuring.

LITERATURE REVIEW

The evolution of georeferenced data has been significant in recent decades, with important advancements since the early 21st century. Historically, geographic location accuracy was limited, but digitalization and integration with Geographic Information Systems (GIS) have considerably improved the collection, storage, and analysis of these data (Chang 2018). GIS is used to identify locations on the Earth's surface using a database linked to geographic coordinates, allowing the integration of information layers from various sources on interactive web platforms (Yu *et al.* 2021). These systems use the Universal Transverse Mercator (UTM) Coordinate System to project geographic coordinates into a format that utilizes flat coordinates for each zone of the globe, enhancing data positioning accuracy and enabling high-precision analyses (Li *et al.* 2024). The integration of advanced monitoring technologies with georeferenced data enables a more precise analysis of spatial and environmental parameters, enhancing predictive capabilities in infrastructure assessment (Hashim *et al.* 2024).

The use of remote sensing data has also expanded, with satellites and drones providing valuable information that can be integrated into spatial databases (Zhang and Zhu 2023). These data sources offer a comprehensive and up-to-date view of the studied environments, contributing to more accurate and informed analyses (Wang *et al.* 2022). Ensuring the accuracy and reliability of georeferenced data is essential for optimizing decision-making processes in complex engineering applications, particularly in aerospace and infrastructure management (Copriva *et al.* 2024). These tools are essential for creating visual representations and analyzing geospatial data in various applications, including the assessment of airport runway macrotexture.

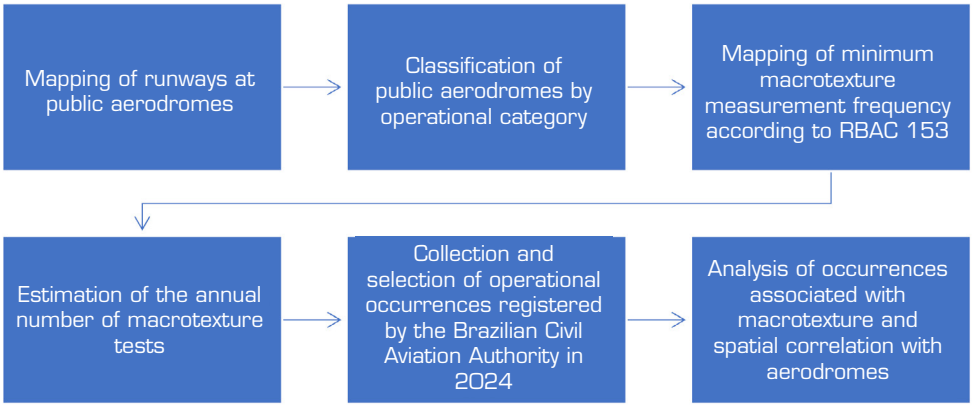
The Sand Patch Method is a widely used technique for measuring the surface texture of pavements. It involves uniformly spreading a known volume of sand over a defined area and calculating the macrotexture depth by dividing the sand volume by the spreading area. This procedure estimates the average distance between the surface's peaks and valleys. The method is standardized in Brazil by the Brazilian Association of Technical Standards (ABNT 2016) and adopted by the National Civil Aviation Agency (ANAC 2023), particularly for runway assessments. Internationally, it is recognized in several technical standards, including the American Society for Testing and Materials E965-15 (ASTM 2015), International Organization for Standardization 13473-1 (ISO 2004), and Federal Aviation Administration AC 150/5320-12C (FAA 1997), which describe procedures for evaluating skid resistance and macrotexture on both highway and airport pavements.

Adequate macrotexture of the pavement surface is crucial to ensure sufficient skid resistance for aircraft, significantly reducing the risk of hydroplaning during landings and takeoffs, especially under wet runway conditions. Several studies indicate that macrotexture directly influences skid resistance and the overall braking performance of aircraft, making it a key factor in accident prevention (FAA 1997; ISO 2004; Yager 1983).

Additionally, implementing regular maintenance practices to ensure macrotexture quality not only enhances safety but also increases runway durability, resulting in long-term cost savings (Rodrigues *et al.* 2023). The combination of accurate measurement methods, such as the Sand Patch Method, with advanced monitoring technologies enables proactive runway management. This approach allows for the early identification of potential issues and the execution of timely interventions, enhancing safety and efficiency in airport operations (ANAC 2024; ASTM 2015; FAA 1997; ISO 2004).

METHODOLOGY

The methodological approach adopted in this study was structured in sequential stages, including the mapping of runways at public aerodromes, the classification of aerodromes by operational category, and the definition of macrotexture measurement frequencies according to RBAC 153. It also involved estimating the total number of required tests, collecting and selecting operational occurrences reported in 2024, and conducting a final analysis to explore the relationship between surface conditions and safety-related events. Figure 1 presents an overview of this workflow.



Source: Elaborated by the authors.

Figure 1. Methodology Flowchart.

The first step of this study consisted of mapping Brazil's public aerodromes, with particular emphasis on identifying the number of runways at each facility. A total of 3,735 aerodromes were considered, including 3,236 private (87%) and 499 public (13%) facilities. This stage focused exclusively on public aerodromes due to data availability, and a georeferenced map was generated to illustrate their spatial distribution and operational structure. The identification of aerodromes with one or more runways enabled the detection of infrastructure concentration, especially in regions with greater air traffic demand, such as the Southeast and South.

In the second stage, public aerodromes were classified into operational categories based on the annual passenger volume they are capable of handling. According to ANAC (2023) criteria, four operational classes were considered: Class I (less than 200,000 passengers), Class II (200,000 to 1 million), Class III (1 to 5 million), and Class IV (more than 5 million passengers per year). This classification provided a clear overview of airport hierarchy and capacity, and it was used to elaborate a thematic map representing the spatial distribution of these categories across the national territory.

The third phase focused on determining the minimum frequency of macrotexture measurements required for each aerodrome, according to the average number of daily landings with jet-engine aircraft at the predominant runway threshold (ANAC 2023). A map was created to visualize the recommended frequency ranges: every 30, 60, 90, 180, or 360 days. The range was color-coded and associated with each aerodrome according to its operational demand, thereby supporting decision-making for runway monitoring and maintenance scheduling.

Based on this classification, the fourth step consisted of estimating the total number of macrotexture measurements required annually across public aerodromes. According to data from 2024, a total of 599 tests were projected, considering different testing frequencies depending on aerodrome characteristics. Table 1 summarizes the number of aerodromes assigned to each frequency category and the corresponding total number of tests per year. These figures provide a quantitative baseline for understanding the scale of inspections required to comply with regulatory standards and ensure safe runway conditions.

Table 1. Estimated frequency of macrotexture testing by aerodrome (2024).

Testing frequency	Number of aerodromes	Tests per aerodrome per year	Total tests per year
Every 30 days	4	12	48
Every 60 days	3	6	18
Every 90 days	11	4	44
Every 180 days	8	2	16
Every 360 days	473	1	473
Total	499	-	599

Source: Elaborated by the authors.

The fifth stage involved collecting data on operational occurrences reported in 2024, obtained from the Brazilian Civil Aviation Authority's database. A total of 3,493 occurrences were analyzed, of which 1,174 were selected for being directly associated with runway conditions. These included categories such as runway excursion, loss of control on the ground, abnormal runway contact, ground collision, runway incursion, ice formation on the runway surface, and loss of takeoff capability. Events unrelated to runway surface, such as bird strikes or engine failures, were excluded from the analysis. This study did not include the direct measurement of runway macrotexture depth values. The available database contained information on the required testing frequency and reported operational occurrences, but it did not provide the results of the macrotexture tests themselves. For this reason, the analysis was limited to estimating testing frequencies and correlating them with operational data, characterizing an exploratory approach to the use of geospatial technologies in aerodrome safety assessment. In this study, distribution maps were used to illustrate the spatial relationship between operational occurrences and macrotexture testing frequencies. These maps are exploratory visualizations and do not apply kernel density estimation or bandwidth parameters, serving only to highlight patterns of concentration in the dataset.

The final step consisted of correlating the selected occurrences with macrotexture monitoring data. A geospatial analysis was conducted using a 1-km radius around each aerodrome, and statistical techniques, including linear regression, were applied to explore potential relationships between measurement frequency and the number of reported occurrences.

The classification of these aerodromes by operational category, the definition of macrotexture measurement frequencies (ANAC 2023), and the estimation of the annual number of required tests were included in this study. It also encompasses the collection and selection of relevant operational occurrences registered in 2024 and the subsequent analysis of their correlation with macrotexture conditions. This systematic approach supports the understanding of how surface conditions influence safety outcomes and reinforces the importance of continuous monitoring and preventive maintenance of airport pavements.

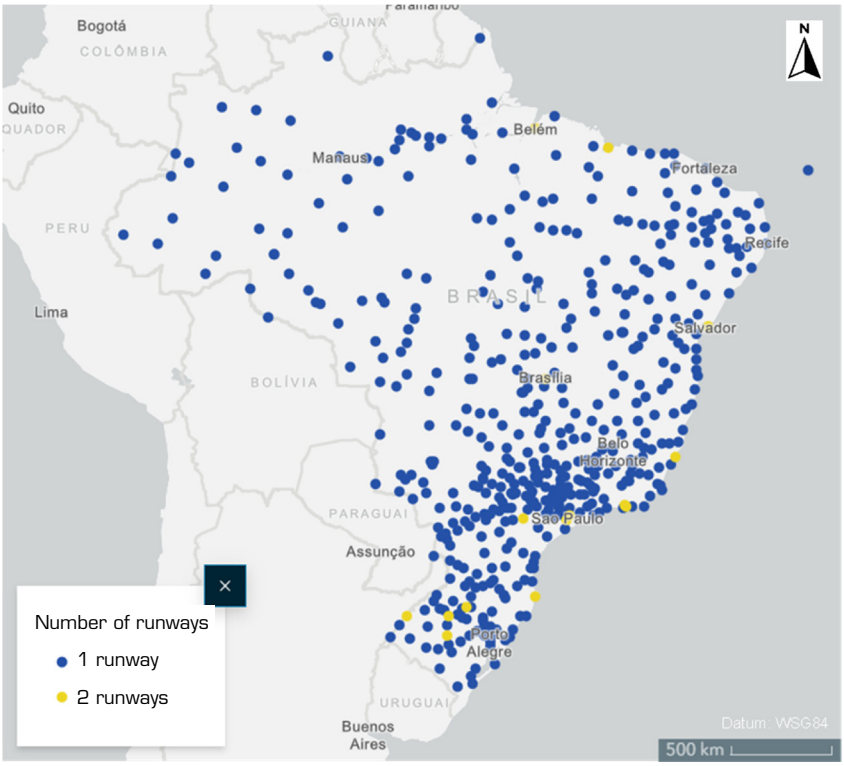
RESULTS AND DISCUSSION

Considering that the Brazilian Civil Aviation Authority provides the number of flights for public aerodromes, the focus was placed on these establishments to provide a more detailed analysis of the number of runways and classes. Figure 2 shows the 14 public aerodromes that play a crucial role in the country's air transport network by having two runways. Aerodromes with a lower number of runways may face limitations, especially in areas with high traffic demand, suggesting the need for expansion or optimization strategies, particularly in the North and Northeast regions, which have only 3 public aerodromes with two runways.

In addition to the number of runways, airports are divided into four classes based on the volume of traffic that each class can support, starting with airports with a capacity of less than 200,000 passengers (Class I) and extending to those with a capacity greater than 5,000,000 (Class IV). Figure 3 reveals that the majority, 450 installations, are Class I, with another 24 being Class II and 16 Class III. The 9 Class IV installations with the highest operational capacity are located in São Paulo (3), Rio de Janeiro (1), Porto Alegre (1), Brasília (1), Salvador (1), Recife (1), and Fortaleza (1). This classification facilitates the analysis of airport operational capacities and enables a more accurate understanding of their roles within the national aviation infrastructure.

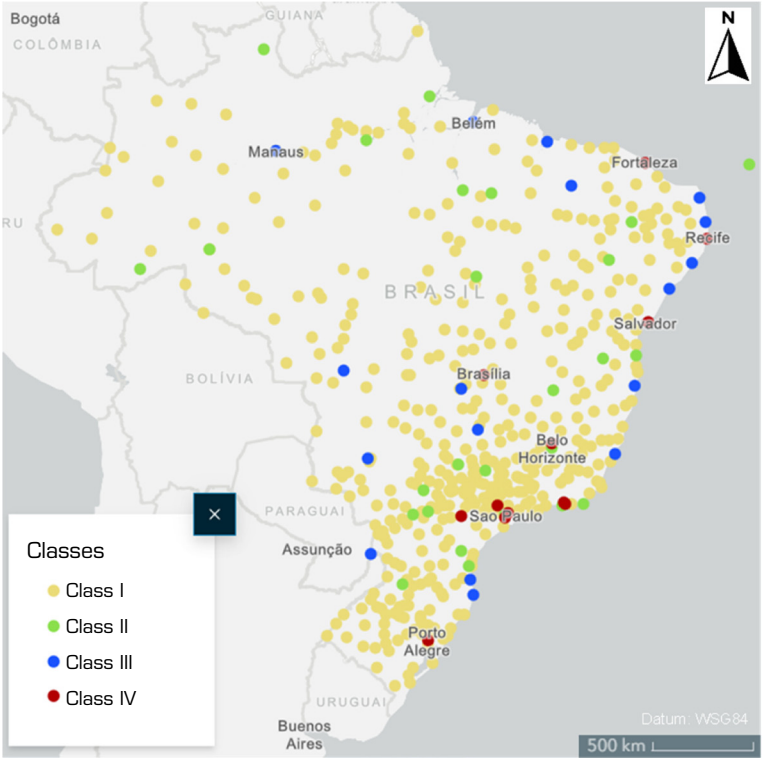
The graphic representations of airports in Brazil help to understand how each airport contributes to the air transport network, supporting strategic decision-making. Maps that promote transparency in service distribution form the foundation for resource allocation and the implementation of policies that promote future actions based on well-founded decisions aligned with identified needs to address regional inequalities.

Operational safety on runways is a key priority in civil aviation. A well-maintained runway not only improves the efficiency of operations but also plays a crucial role in preventing accidents. One of the most critical aspects of runways is the macrotexture, which refers to the pattern of roughness perceptible on a larger scale, directly influencing the tire's grip on the runway. The analysis of macrotexture is recommended by the Brazilian Civil Aviation Authority, due to the annual frequency of landings, specific operational conditions, operational safety risks, or the need to ensure such safety.



Source: Elaborated by the authors.

Figure 2. Number of runways in public aerodromes.



Source: Elaborated by the authors. Note. Class I: < 200,000 passengers; Class II: 200,000–1 million; Class III: 1–5 million; Class IV: > 5 million passengers.

Figure 3. Classification of public airports by operational class.

Adequate skid resistance is crucial to ensure the braking capacity of aircraft, especially in wet runway conditions, where the risk of aquaplaning increases significantly. The Brazilian Civil Aviation Authority may also request additional friction measurements or establish a frequency. Table 1 shows part of these regulations, which are sets of rules and guidelines that govern different aspects of civil aviation in the country.

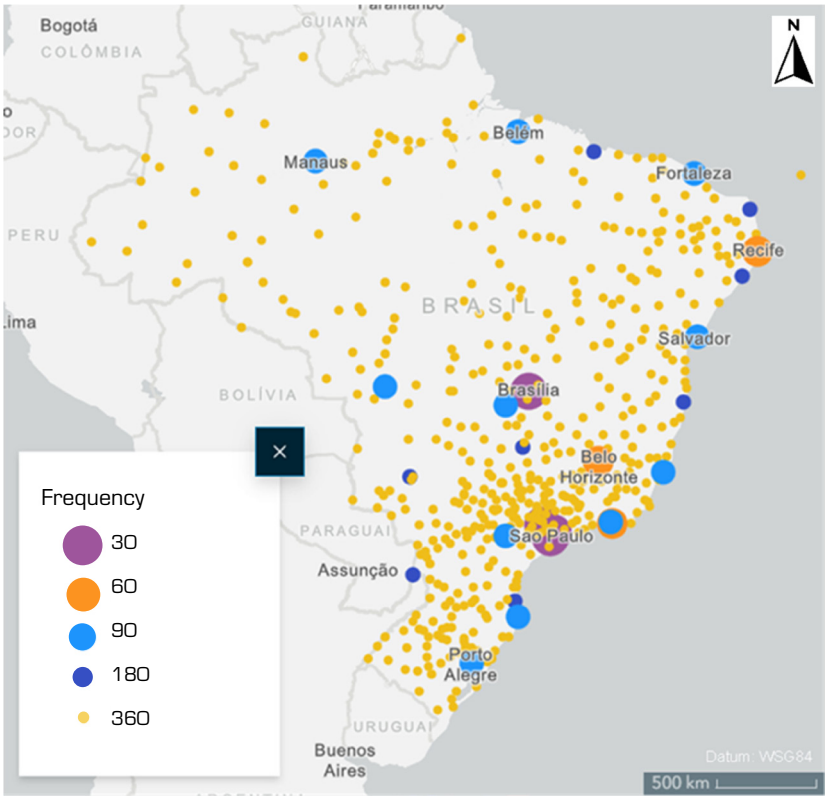
The ANAC (2023) regulations, which are organized into numbered tables and sections to facilitate consultation, cover aspects of certification, operation, maintenance, and other specific areas of civil aviation (Table 2).

Table 2. Minimum frequency of macrotexture measurements.

Range	Average daily landings of fixed-wing aircraft with jet engines at the predominant runway threshold in the last year	Frequency of macrotexture measurements
1	Less than 16	Every 360 days
2	Greater than or equal to 16 and less than 31	Every 180 days
3	Greater than or equal to 31 and less than 91	Every 90 days
4	Greater than or equal to 91 and less than 151	Every 60 days
5	Greater than or equal to 151 and less than or equal to 210	Every 30 days
6	Greater than 210	Every 30 days

Source: Adapted from ANAC (2024).

The map in Fig. 4 was created to highlight the minimum frequency of macrotexture measurements recommended for the runways of public airports based on daily landing data, classified according to ANAC (2024). It shows the number of days with available data for different locations across the country.



Source: Elaborated by the authors.

Figure 4. Minimum frequency of macrotexture recommended by the Brazilian Civil Aviation Authority.

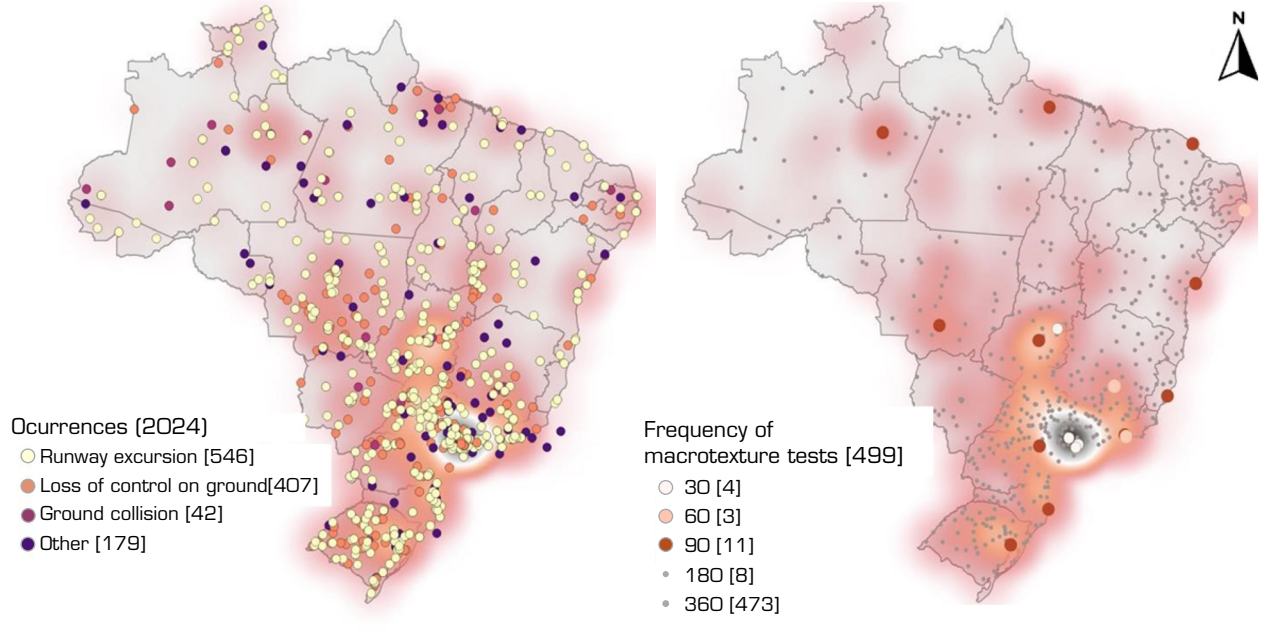
Table 3 presents an estimate of the total number of macrotexture measurements conducted annually at public airports, according to different evaluation frequencies. For each frequency (30, 60, 90, 180, and 360 days), the table shows the number of measurements conducted annually per airport and the total number of airports assigned to that frequency.

Table 3. Estimate of the number of macrotexture measurements per year at public airports.

Frequency	Quantity per year	Number of airports	Total tests per year
30 days	12	4	48
60 days	6	3	18
90 days	4	11	44
180 days	2	8	16
360 days	1	473	473
Total tests per year			599

Source: Elaborated by the authors.

According to ANAC (2024), most accidents on airport runways are caused by human factors, such as communication failures and inappropriate decisions, as well as adverse weather conditions. However, technical problems and inadequate runway infrastructure also contribute to these incidents. Based on an analysis of 3,493 occurrences recorded by ANAC (2024), classified into 34 types, it is interesting to explore categories of occurrences that may be more closely correlated with macrotexture. From the analysis of these occurrence types, a selection of 1,174 occurrences was made in 7 categories: loss of control on the ground (407), ground collision (42), abnormal contact with the runway (156), runway excursion (546), runway incursion (20), ice formation (1), and loss of takeoff conditions on the runway (2) (Fig. 5). Occurrences such as bird strikes, fuel issues, or engine malfunctions were excluded as they are not related to runway conditions.

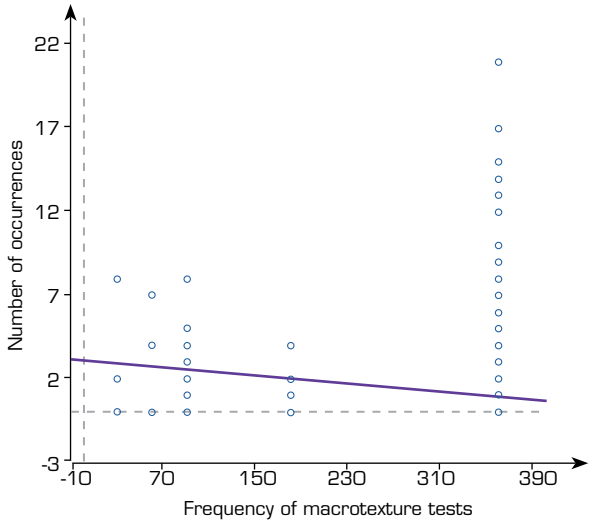


Source: Elaborated by the authors.

Figure 5. Spatial distribution of occurrences recorded at public aerodromes in 2024 (left) and recommended frequency of macrotexture tests (right).

Loss of control on the ground refers to the inability to maintain proper control of the aircraft during takeoff or landing roll, resulting in unintended deviations from the expected trajectory. A runway excursion occurs when the aircraft leaves the designated runway limits during takeoff or landing, either by veering laterally or overrunning the runway end. This can be caused by excessive speed when landing occurs at an inappropriate speed or takeoff is performed at an excessive velocity.

To develop a geostatistical analysis of the results, the number of recorded occurrences within a 1-km radius of each aerodrome was summed. The linear regression results reveal a statistically significant correlation between the number of occurrences and the suggested analysis frequency ($p = 0.00086$; $R^2 = 0.03$) (Fig. 6). Although the correlation was significant, the very low R^2 value indicates weak explanatory power. This suggests that testing frequency alone is not sufficient to explain the variation in occurrences, and that other operational, environmental, and human factors also play an important role. Therefore, the regression results should be interpreted with caution.



Source: Elaborated by the authors.

Figure 6. Graph with linear regression results between the number of occurrences (y-axis) and the frequency of macrotexture tests (x-axis).

The graph illustrates a decreasing trend, where a greater number of days between macrotexture tests correlates with a lower number of recorded occurrences near aerodromes. These results emphasize the importance of regular and well-defined monitoring intervals for runway macrotexture, reinforcing the need for rigorous maintenance and the adoption of standardized operational procedures to mitigate risks. Continuous analysis of runway macrotexture, combined with the use of georeferenced data and interactive mapping tools, can assist in identifying areas requiring intervention, contributing to the safety and efficiency of airport operations. Although not the central focus of this study, a concentration of higher occurrence rates was observed in aerodromes located in urban regions with greater air traffic, suggesting a possible relationship between demand intensity and exposure to operational events.

CONCLUSION

The application of geospatial technologies and georeferenced data enabled the spatial analysis and classification of Brazilian public aerodromes, focusing on runway inventory, operational categorization, and the estimation of macrotexture measurement frequencies based on regulatory criteria. The structured mapping approach allowed for the identification of monitoring demands associated with traffic intensity and operational class.

The study incorporated occurrence data provided by the Brazilian Civil Aviation Authority, isolating categories directly linked to runway conditions. A statistical correlation was identified between the frequency of macrotexture tests and the number of recorded occurrences within a defined spatial radius, suggesting a relationship between monitoring periodicity and exposure to operational events. These results reinforce the importance of systematic monitoring of runway macrotexture as a fundamental strategy for enhancing operational safety. However, the statistical analysis revealed a very low R^2 value, which indicates weak explanatory power. This limitation demonstrates that monitoring frequency alone cannot fully explain the variation in operational occurrences.

One limitation of this study is the absence of direct macrotexture measurements, which restricted the analysis to test frequency and occurrence data. The integration of spatial data and structured records proves to be an effective tool not only for optimizing maintenance planning and management policies, but also for preventing accidents and ensuring safer airport operations.

CONFLICT OF INTEREST

Nothing to declare.

AUTHORS' CONTRIBUTION

Conceptualization: Leite MO, Furtado LS, Oliveira FHL; **Methodology:** Leite MO, Furtado LS, Oliveira FHL; **Analysis:** Leite MO, Furtado LS, Oliveira FHL; **Writing – Original Draft:** Leite MO, Furtado LS, Oliveira FHL; **Writing – Review and Editing:** Leite MO, Oliveira FHL; **Supervision:** Oliveira FHL; **Final approval:** Leite MO.

DATA AVAILABILITY STATEMENT

Data sharing is not applicable.

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DECLARATION OF USE OF ARTIFICIAL INTELLIGENCE TOOLS

Artificial Intelligence software ChatGPT (OpenAI) was used in the preparation of this manuscript for grammatical correction, reference formatting, and abstract writing.

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