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Airport pavement evaluation systems for maintenance strategies development: a systematic literature review

Ingrid Rebouças de Moura[a]*, Franco Jefferds dos Santos Silva[b], Luis Henrique Gonçalves Costa[c], Edmon Darwich Neto[a], Herbert Ricardo Garcia Viana[a]

[a] *Department of Industrial Engineering, Universidade Federal do Rio Grande do Norte, Natal, Brazil*
[b] *Department of Mechanical Engineering, Universidade Federal do Sul e Sudeste do Pará, Marabá, Brazil*
[c] *Department of Civil Engineering, Universidade Federal Rural do Semi-Árido, Angicos, Brazil*

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Abstract

Due to the high growth in air transport, combined with the urgency to increase capacity and suitability of the airport infrastructure, the need to adopt more efficient measures in the system arises of pavement management. Aiming to assist researchers in future studies within the theme related to management and initiatives of maintenance on airport pavements, a review of the existing literature was sought regarding the assessment systems and models for pavement conditions. These methodologies are responsible for steering the decision making regarding the actions of treatment and structures rehabilitation. From this, the purpose of this Systematic Review of the literature is to enable the identification of research and relevant contributions, and above all, to serve as a support and database for a greater understanding of the methodologies used in the assessment of airport pavement conditions. Publications were identified on the basis of a structured search strategy, with the selection of 283 papers on the Scopus and Web of Science databases, and after reading the title and abstract, 41 papers were read in full, leading to the implementation of a bibliometric analysis and a qualitative synthesis. It should be noted that among the most important findings and arguments in this article is the use of 15 different methods for prediction of pavement conditions, most of which fall into the category of empirical-mechanistic models. Finally, important considerations are made regarding the limitations and development of future research for decision making in the strategic context of airports pavements maintenance.

Keywords: Airport infrastructure; Pavements; Maintenance strategies; Evaluation systems; Forecasting models

1. Introduction

The airport is the main infrastructure accountable for connecting the land and air systems [1]. Its proper functioning and performance over time are provided through management strategies, mainly by maintaining the physical assets responsible for aggregating value to the aircraft movement operations. The airport's pavement is exposed to several forms of deterioration, which generally damage the reliability throughout its service life, not to mention the financial expenses related to the rehabilitation of this system [2-5].

The flaws present in the aircraft runways and aprons have direct consequences on the activities that ensure the handling of flights, the safety of operations and the image of the administration. According to Faturechi et al. [6], minor damage to parts of the aerodrome runways severely impairs the operations functionality within the airport.

Although it is noted that there is a major infrastructure concern, it is important to adopt and develop measures that maintain operational conditions, especially regarding safety conditions [1,2,6], so as not to contribute to the possibility of accidents or incidents with passengers. Even with the maintenance function gaining ground over the last decades, due to technological growth and the level of equipment complexity [7], in-depth analyses and studies are lacking in the sector, which would take airports to more competitive levels.

In an airport, the failures and unavailability of runways and aprons result in poor view of the airport by the users, due to the need for interruption of operations, stoppages, delays, as well as repairs costs and time spent by the employees responsible for pavement management. Gendreau and Soriano [8] explained this topic by focusing on computerized airport pavement management systems, where the purpose was to synthesize the operation forms and their functions' specifications, from network detailing, condition assessment, performance prediction models implemented and the planning of the maintenance strategies adopted, also considering the systems focused on road networks due to the scarcity, at the time, of scientific work directed to airport pavements.

With the purpose of adding knowledge to future research and update researchers as to the new methodologies being developed, this systematic review, aims to raise studies and relevant contributions on the application of methods for assessing airport pavement conditions, performance prediction models and variables that need to be

* Corresponding author
E-mail address: ingridreboucasdemoura@gmail.com (I. R. de Moura).
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monitored in a pavement system. From the researches carried out no literature reviews related to the proposed theme were found. The selected publications underwent a structured review protocol in the recommendations of the Preferred Reporting Items for Systematic Review and Meta-Analysis (PRISMA), dedicated to capturing and synthesizing scientific research with the theme addressed. The need for this systematic review comes from the large number of academic productions in the pavement area. The purpose is to quantify these works through a bibliometric analysis, and verify which models were worked on, which variables were analyzed, and if the results found can be justified. The motivation of this research is to serve as a support and database for a greater understanding of the methodologies used in airport evaluation.

This article contains an overview of the review results and is structured as follows: Section (*ii*) contains a brief review of the literature exposing the importance of pavement assessment programs and methods for maintenance elaboration; Section (*iii*) shows the methodology used in the formulation of the review protocol, containing the papers inclusion and exclusion criteria; Section (*iv*) presents the bibliometric analysis for the papers selected in the systematic review; Section (*v*) refers to the qualitative analysis of what was read, researches singularity and methodologies used; and Section (*vi*) has the final considerations presentation.

2. Airport pavement maintenance

For the pavement to be able to meet the traffic to which it will be exposed safely and comfortably, it must have adequate quality and thickness to ensure the necessary reliability, avoiding the occurrence of failures during its use [9]. Other characteristics are also considered important, such as having inherent stability to resist loads, without suffering from traffic's abrasive action, bearing diverse climatic conditions and other factors that help increase deterioration. This way, the need for planning, inspections, maintenance and the best combination of high standard materials with qualified workforce [10] is envisioned.

The dimensions of the runways differ from one airport to another, depending on traffic requirements, available area, financial conditions, etc. [11]. Their system is normally comprised of several structures, and from determining their condition, it is ensured that the aerodrome operator performs the best actions in the maintenance program [12]. When starting an assessment, a number of indicators that influence the pavement conditions must be considered, contributing directly to structural and functional deterioration. These factors impair and cause accelerated aging of the infrastructure, which requires the formulation of more reliable assessments [4]. It is always necessary to analyze and verify if the maintenance strategies employed are obtaining the best results regarding the pavement conservation [5].

The structural performance capability determination, or ability to maintain structural integrity, is obtained by structural assessment, which consists in analyzing the recoverable vertical displacements on the pavement surface. When the pavement is subjected to a given load, the analyses are mainly linked to high transport loads, sub-bed instability, fatigue in the pavement components and environmental conditions [11]. The functional assessments of the pavement, on the other hand, consist in determining the momentary functional performance capacity, which is related to the experience provided to the transport user, that is, the comfort in terms of rolling quality. Functional performance refers to the pavement's ability to meet its main objective, which is to provide a surface with adequate service in terms of driving quality [2,13].

Functional analyses for maintenance decisions are common, since it is related to user safety and comfort, which can cause the structural condition, which is usually not visible, to be overlooked. However, the structural conditions of a pavement are equally important for the user's safety, especially from the engineering point of view [14]. Airport management needs to have an up-to-date database of pavements in their various functional and structural aspects, relying on automated technologies that lead to the development of more efficient measures regarding maintenance activities [3,8]. Butt et al. [15] report the lack of formal procedures in Airport Pavement Management Systems (APMS), which renders them unable to classify the condition of the pavement, not to mention management models that work with probabilistic performance forecasts or system status assignments based solely on the experience of professionals. Budgets for maintenance have restrictions, so there is a need to adequately define each of the actions of pavement interventions [5,16].

It is important to identify strategies based on decision criteria and a maintenance policy with the ability to employ the best procedures [17]. Pigozzi et al. [18] verse about the development of new tools and methodologies, which should be agile and easy to manipulate for analysis of runways, taxiways and aprons, and how necessary they are for regional and seasonal airports, which are generally confronted with low availability of economic resources. Another issue raised by the same authors concerns the increase in demand and in the size of the new aircraft being used, which justifies the concern with analysis of pavement performance and the development of more accurate and useful prediction models for implementation in APMS [19].

3. Review protocol

This systematic review will work to identify and analyze existing methods, techniques and variables for the development of assessment models that are relevant for the determination of maintenance actions, performance prediction and level of degradation of airport pavements. For this, Scopus and Web of Science research databases will be used, with the use of keywords strings and their synonyms, which have previously been defined, according to Table 1.

The searches were made in papers' titles, abstracts and keywords from scientific journals, conferences and other means that work with peer review. It should be noted that the language of the papers must be in English, due to the universality of the language. With the exclusion of duplicate documents, the title and abstract were read with application of inclusion and exclusion criteria, the paper was selected if its relevance was confirmed. The inclusion and exclusion criteria of the research were:

1. Inclusion criteria:
   a. Papers published and available in full in scientific databases or printed versions shall be included.
   b. Papers which address methods, techniques and describe variables for the elaboration of models for assessing or

Table 1
Search terms.

Search database	Strings
Web of Science	((*Airport Pavement*) OR (*Runway*)) AND ((*Deterioration*) OR (*Condition*) OR (*Degradation*)) AND ((*Prediction*) OR (*Forecasting*))
Web of Science	((*Airport Pavement*) OR (*Runway*)) AND ((*Deterioration*) OR (*Condition*) OR (*Degradation*)) AND (*Evaluation*) AND ((*Management*) OR (*Maintenance*))
Scopus	("*Airport Pavement*" OR *Runway*) AND (*Deterioration* OR *Condition* OR *Degradation*) AND (*Prediction* OR *Forecasting*)
Scopus	(("*Airport Pavement*" OR *Runway*) AND (*Deterioration* OR *Condition* OR *Degradation*) AND (*Evaluation*) AND (*Management* OR *Maintenance*))

predicting the conditions (performance or degradation) of pavements shall be included.
c. The works must be approved by the scientific community.

2. Exclusion criteria:
a. Works that are not fully available in the searched databases will be disregarded.
b. Works published as short articles or posters will be excluded.
c. Works that do not deal with airport pavements will be excluded.

Once the inclusion and exclusion criteria have been defined, the work will be read in full. An overview of the adopted protocol is presented in Fig. 1.

After the selection of the articles, "data extraction forms" will be filled in for each work considered valid for systematic review read in full. Besides basic information (bibliographical data, date of publication, abstract, among others), these forms should contain the synthesis of the work, written by the research authors, which will lead the systematic review and subjective reflections on the content and conclusions of the study. A qualitative analysis will also be developed for the collection of attributes related to: the name of the methods used, the variables considered, the statistical techniques employed and the domain of application of the proposed method. For this last analysis, it was decided to divide the work by purpose: those dealing with the elaboration of performance prediction models and those integrating different approaches in the assessment of the state of pavement systems.

4. Bibliometric analysis

Fig. 2 shows the number of selected works distributed per year of publication. 2008 was the most focused year on pavement evaluation, with researches addressing the use of Geographic Information Systems (GIS), to facilitate the verification of adherence on the runway surface [20] or just for storing information and disseminating graphic images [21], and mainly, in obtaining models for predicting pavement conditions seen in Herrin, Fuselier [22], McNerney [23], Leahy et al. [24], Gopalakrishnan and Ceylan [25].

Through this systematic review 22 articles related to 14 different journals were identified. Transportation Research Record was the journal with the most publications related to this research issue, as can be seen in Table 2. To evaluate the prestige and reputation of the journal, the performance metric based on SCImago Journal Rank (SJR) was sought on Scopus, with the highest grade attributed to the International Journal of Geomechanics (1,444), followed by the International Journal of Pavement Engineering (0,900), both focused

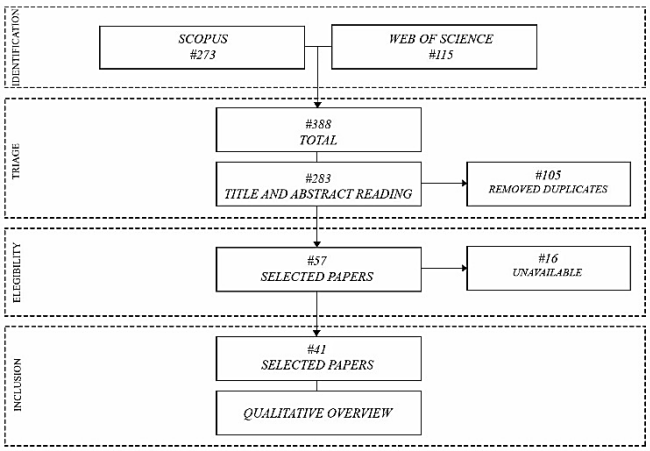

Fig. 1. Systematic review phases.

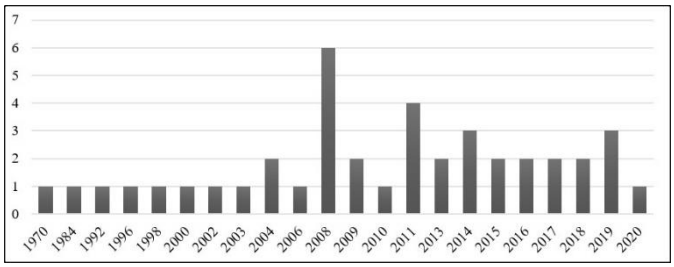

Fig. 2. Distribution of selected works per year.

on paving, and Cold Regions Science and Technology (0,860), which deals with scientific and technical problems in cold weather regions.

Other papers were obtained from various sources (Table 3), with special attention to the Airfield and Highway Pavements Conference, an international conference that brings together researchers in the transportation and airport security areas, with the aim of encouraging the exchange of information in the fields of road pavements, airports and other technologies related to airport security.

Evaluating the works according to the authors and number of citations per article, 110 different researchers were identified, the authors with publications with the highest number of citations indicated by Scopus, are highlighted in Table 4.

The study's methodology guides how the research will be conducted, and, according to Polater [26], the key to the success of a project lies in selecting the type of research that is best suited to what is intended. In this sense, it was observed that approximately 65% of the chosen papers used the case study, followed by experimental research, surveys and others, as shown in Fig. 3.

In this research, the authors' region of institution was not of interest, the focus was aimed, instead, at the place where the research was carried out, an important factor for the development of evaluation systems and models, since weather is one of the main factors for deterioration of pavements. Out of the 41 papers selected, the majority included airports and laboratories located in the United States of America (USA), especially the International Airports of Denver and Atlanta. China follows with 7 papers and Italy with 5 papers, as shown in Fig. 4.

Table 2
Number of publications from journals.

Journals	Quantity	SJR
Transportation Research Record	7	0.537
International Journal of Pavement Research and Technology	1	0.819
SAE Technical Papers	1	0.322
Road and Transport Research	1	0.170
Journal of Transportation Engineering Part B: Pavements	1	0.224
Journal of Computing in Civil Engineering	1	0.825
IES Journal Part A: Civil and Structural Engineering	1	0.241
International Journal of Geomechanics	1	1.444
International Journal of Pavement Engineering	2	0.900
European Journal of Environmental and Civil Engineering	1	0.545
Cold Regions Science and Technology	2	0.860
Canadian Journal of Civil Engineering	1	0.320
Applied Mechanics and Materials	1	0.112
Advanced Materials Research	1	0.121

Table 3
Number of publications from other sources.

Other Sources	Quantitiy
T and DI Congress: Congress of the Transportation and Development Institute of ASCE	2
International Conference on Transportation Infrastructure (ICTI)	1
Lecture Notes in Civil Engineering	1
International Air Transportation Conference	1
Proceedings of the LACCEI international Multi-conference for Engineering, Education and Technology	1
ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences	1
COTA International Conference of Transportation Professionals (CICTP)	1
China-Japan Workshop on Pavement Technologies (CJWPT)	1
Airfield Pavements: Challenges and New Technologies	1
Airfield and Highway Pavements Conference	7
International Conference on Transportation Engineering (ICTE)	1
International Conference on Transportation Information and Safety (ICTIS)	1

Table 4
Number of citations of the most outstanding authors in relation to the selected papers.

Authors	Citations	Papers
Kim, H.	33	1
Buttlar, W. G	33	1
Tutumluer, E.	20	1
Kim, I. T.	20	1
Nuijten, A. D. W.	12	1
Al-Qadi, I. L.	12	1
Coni, M.	12	1
Lahouar, S.	12	1
Portas, S.	12	1
Asadabadi, A.	11	1
Faturechi, R.	11	1
Levenberg, E.	11	1
Miller-Hooks, E.	11	1

5. Qualitative overview

The development of Airport Pavement Management Systems (APMS) and verification of Airside assets requires a lot of time and effort, so that the use of programs and software for support are extremely necessary to control the structural and functional information [5,27]. From the papers studied in this review, the software presented in Table 5 were surveyed and described as to their application to support the creation of models, information control, or even the simulation of scenarios in the airports investigated.

Regarding the papers' study areas, it was observed that most of them offered proposals for treatment and evaluation of functional conditions, that is, parameters that are related to user comfort and rolling conditions. The quantity of papers per area can be seen in Table 6. This result is consistent with the statements made by Tarefder and Rahman [14], who emphasize the current concern in the development of evaluation systems in the functional area, although at the beginning these studies were more focused on structural critical factors [28]. In any case, any effective and useful evaluation procedure should consider both areas [8].

The surveyed works are distributed in two main functions: i) they select a model for pavement performance prediction; and ii) they adopt tools for evaluating the state of the pavement systems. These surveys are presented in the following topics.

5.1. Pavement performance prediction models

Pavement performance prediction models can be divided into three main categories: empirical models, mechanistic models and empirical-mechanistic models. Out of the 24 papers that developed performance prediction models, it can be seen in Fig. 5 that most opted for empirical-mechanistic models and that few used mechanistic models, which was already expected by the complexity of these models at the mathematical and physical levels.

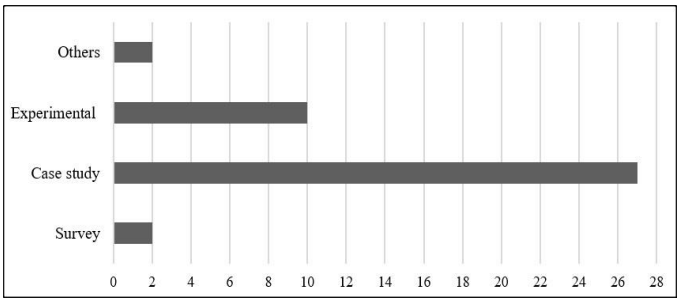

Fig. 3. Types of research.

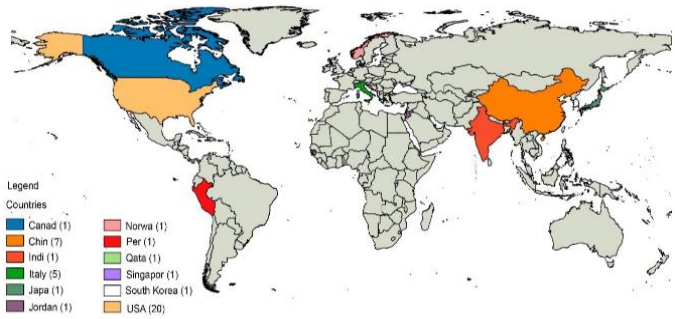

Fig. 4. Countries searched in the selected papers.

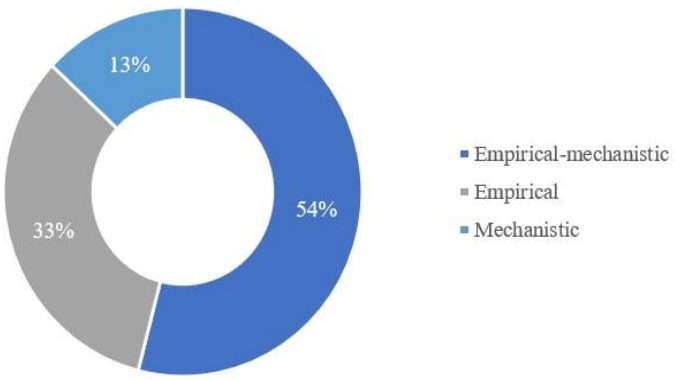

Fig. 5. Studied models categories.

Table 5
Software Used in the Selected Papers.

Software	Paper	Use
MATLAB	Liu et al. [29], Vyas et al. [30], Barbarella et al. [31]	- MATLAB is used in the development of pavement performance prediction models. In this proposal a model in Artificial Neural Networks (ANN) is developed using the software [29]. - MATLAB is used for the calculation of multi-criteria decision making methods: Analytical Hierarchy Process (AHP) and Fuzzy Inference System. The methodology used is to obtain the sections that have the highest priority in maintenance [30]. - The program is also used for code setting, in order to optimize calculations of runway inclination for checking roughness important parameters [31].
Excel Solver	Campos and Gonzales [32]	- Solver, a built-in Excel add-in tool, is used to build logistic regression algorithms to predict the functional conditions of pavements within the scope of the airport database under study [32].
BAKFAA; LEDFAA	Huang et al. [33]	- The program (BAKFAA) developed by FAA, it is used in the characterization of pavement layers as a function of analysis of deflection data, for the first stage of the research by Huang et al. [33]. - LEDFAA is used by Huang et al. [33] in the second stage of their study to predict the pavement service life with the traffic changes at the airport assessed, which means a structural assessment.
MicroPAVER	Villarreal and Hossain [34], Rada et al. [35]	- Villarreal and Hossain [34] used MicroPAVER to establish pavement deterioration models based on the PCI (Pavement Condition Index) from 137 runways and general aviation airports in the State of Kansas. - Rada et al. [35] also use the software to obtain PCI forecast curves from John F. Kennedy International Airport.
ILLI-PAVE; GT-PAVE	Kim and Tutumluer [36]	- Kim and Tutumluer [36] used the ILLI-PAVE and GT-PAVE programs to evaluate the history of pavement defects for analysis on the pavement sections in terms of sub-bed strength. And to accurately calculate the granular layers stress conditions in the field.
SPSS	Suh et al. [37], Shahin and Becker [38]	- Suh et al. [37] use statistical software in the regression models for the pavement deterioration functional prediction (PCI) elaboration. - SPSS was also used for the same purpose by Shahin and Becker [38], along with other programs that did the pavement response analysis.
Backprop; ILLI-SLAB	Ceylan et al. [39]	- Back-propagation is an ANN training algorithm, used by Ceylan et al. [39] through the Backprop 3.5 program to build a model for predicting maximum pavement stresses and bending. - The ILLI-SLAB it was used for finite element analysis on the floor slabs to validate the results obtained by the model developed in ANN [39].
Abaqus	Hammons [40]	- The commercial software ABAQUS was used in finite element analysis, both in the comparison and in the construction of the models for forecasting structural responses [40].
H51; BISAR	Shahin and Becker [38]	- Shahin and Becker [38] used several programs to obtain pavement performance prediction models. The H51 program was used to calculate the structural response as a function of PCC pavement slab thickness, and sub-bed properties. BISAR was applied in the flexible pavements analysis, using the elastic layers linear theory.
Softwares GIS (ArcGIS, ArcMAP, Super Map, ArcPad ou outros)	Tu et al. [41], McNerney and Keegan [43]	- Tu et al. [41] introduce the concept of 3D modeling in a GIS tool for the information improvement in the pavement management system. GIS software such as ArcGIS, Super Map and others offer assistance in storing important airport plans and data. - GIS tools can also be used to classify pavement sections. In the case of McNerney and Keegan [43] research, ArcMAP has been connected via Bluetooth to GPS receivers and cameras for capturing pavement high-resolution digital images.
CityEngine	Tu et al. [41]	- CityEngine is used in the airport pavement modeling, which would be exported to the Qgis software. The tool was chosen for providing 3D interactive environments supported by traditional modeling techniques [41].
Expert choice; ELMOD	Vyas et al. [30]	- Expert choice is a decision making software and was used to classify pavement sections using the AHP (Analytic Hierarchy Process) method. The tool allowed the decision matrices analysis, obtained by the expert judgement. ELMOD is another software cited in the paper to quantify one of the criteria used, in this case for ACN/PCN (Aircraft Classification Number /Pavement Classification Number) data analysis [30].
ADINA	Pasindu et al. [42]	- It is used to develop a finite element model that assesses the degree of aquaplaning occurrence due to deformations present in the pavement. The main application is in obtaining the interaction tire-fluid-pavement [42].
HIPERPAV II	McNerney and Keegan [43]	- McNerney and Keegan [43], before developing the system in GIS tool, used the HIPERPAV II software in the analysis of the data obtained from the pavement construction, observing the plastic contraction cracks and thermal cracks appearance probability.
MHIS-Airport	Wang et al. [44]	- Used to reproduce the virtual images collected by the Digital Highway Data Vehicle (DHDV). The software allowed the implementation of the images for evaluation of surface defects through PCI [44].
FAARFIELD	Watkins et al. [21]	- FAA's FAARFIELD software is used for the purpose of evaluating new aircraft entering airport traffic in terms of pavement response to different axle and load configurations [21].

Table 6
Study Areas.

Study Area	Quantity
Structural	13
Functional	20
Structural and Functional	8

It is observed that the works, in general, resort to the use of regression techniques; computational modeling: using mainly Artificial Neural Networks (ANN) [25,29,39]; and complex numerical models: that work with the physical representation of the process, excluding any empirical analysis [45-47]. The probabilistic models of performance prediction, identified in Gendreau and Soriano's review [8], continue to be worked on and developed through Markovian models, seen in researches related to pavements surface wear, as in Shah et al. [48], who develop prediction models based on the critical states of the Foreign Object Damage (FOD) index, which occurs when failures present on the pavement release fragments of material capable of causing damage to aircraft and jeopardizing flight operations. For this model, the authors investigated the causes of failure, relying mainly on the knowledge of experts to build the stochastic matrix, assigning a probability associated to each expected FOD state. Campos and Gonzales [32], with the database from an Airport in Peru, also used the Markov Chains to formulate probabilities, but in this case the method was used to establish the changes in the Pavement Condition Index (PCI) values, and this methodology, integrated with the logistic regression, made it possible to obtain the index estimates. Gendreau and Soriano [8] emphasize the importance of forecasting models in maintenance management systems, but make it evident that stochastic processes work with uncertainties and often interfere with obtaining accurate forecasts.

Other authors have also developed studies focused on the functional area, such as Herrin and Fuselier [22], Suh et al. [37], Shahin and Becker [38] with linear, polynomial and power models, Al-Suleiman et al. [49] with logarithmic and power models, and Yuan and Mooney [50] using the least squares method. These authors worked mainly with factors related to: interventions, PCI, pavement age, cracks in the slab, traffic, climate, pavement dimensions and mechanical properties, type of surface, construction and maintenance history, and basic drainage conditions.

In the structural field, the use of finite elements is highlighted, which is present in the studies of Liu et al. [51] to obtain pavement responses and for the forecasts development with the use of Poisson distribution techniques and linear models. The variables in this study were restricted to the materials properties and the traffic volume, also addressed by Yanti et al. [11] as structural failure-causing factors. Kim and Tutumluer [36] also investigated the pavement structure with power regression and logarithmic models, with experimental application of static and dynamic stress analysis. Huang et al. [33] went further, exploring functional and structural aspects, comparing different approaches: The LEDFAA software procedure for FAA projects, the Airport Pavement Design Method of China (APDMC) and the PCI regression model. With this study, the authors identified that the type of failure analysis present in the methodologies affect the forecasts results. These conclusions show the importance of understanding how the models are evaluating each pathology, and especially, knowing which type of method best meets the characteristics of each pavement [8,15,33].

When working with empirical-mechanistic models, Liu et al. [29] build a model using Artificial Intelligence, through a range of randomly collected data for ANN training on 33 landing and take-off runways. For pavement life prediction proposal validation, the authors also performed practical applications, counting on variables such as pavement thickness, air traffic, temperature, maximum deflection at the edge and center of the runway in the Heavy Weight Deflectometer (HWD) test and life cycle performance. Gopalakrishnan and Ceylan [25] and Ceylan et al. [39] used the same approach, although with a much smaller sample and only with the main variables that interfere with the structural condition. Hossain et al. [19] also uses a reduced amount of variables in the construction of an RNA model to predict pavement irregularity, obtaining results very consistent with reality, and even providing the reduction of data collection activities in the field by the maintenance team.

More complex numerical models are presented in the article by Cai and Pan [45], in problems related to the deformations prediction. The authors applied, in their research, variables related to the material isotropic properties, thickness and loading, proposing the use of 3 methodologies: Propagator Matrix Method (PMM), Stiffness Matrix Method (SMM) and Precise Integration Method (PIM) employed in a case study in FAA testing pavements. Nuijten [46] also uses mechanistic methodologies, aimed at investigating surface temperature conditions, a factor of great interest for maintenance planning, especially in airports located in cold weather regions, where harsh weather conditions may jeopardize safety during aircraft landing and take-off. In order to build a temperature prediction model, Nuijten [46] uses meteorological data, pavement dimensions and thermophysical properties, air traffic data, amount of chemicals used in the pavement and below-surface temperatures and runway cover. These models, which do not make use of subjective methods, are encouraged by Butt et al. [15], who report their concern with the use of entirely subjective and probabilistic systems, which do not reflect the real condition of the pavements for maintenance management.

The methodologies are defined according to the extent of the database, tests or laboratory experiments performed. Researches such as Liu et al. [29], Villarreal and Hossain [34], Suh et al. [37], Al-Suleiman et al. [49], Shahin and Becker [38], Yuan and Mooney [50] and Horne and Sparks [52] count on a larger number of samples, which contributed to obtaining more reliable forecast results. Another fact observed is the decrease in the use of empirical models during the years, visualized in Table 7, which contains a summary from the specific characteristics of the works that use forecasting methodologies, regarding the method, area, variables used, purpose of the model, type of pavement and each survey's category.

5.2. Tools for Evaluating the Condition of Pavement Systems

As previously mentioned, Geographic Information Systems (GIS) have been increasingly employed in airport management, and, in this review, four studies were identified using this tool to assist in pavement maintenance programs. Tu et al. [41] used 3D GIS illustrations for the maintenance program decision making, the research purpose was to demonstrate the application of this tool and how it is possible to develop this type of proposal in an airport. McNerney and Keegan [43] describe the benefits of this type of implementation and then use the tool for integration, data collection and geospatial inspections, enabling the pavements surface assessments improvement, in addition to the use of GIS for maintenance actions prioritization. Other applications can also be identified in Ho and Romero [20], who have inserted the technology in the context of checking skid areas through the pavement's scanned images. The authors also point out that the use of these new methods can help in the competitiveness between airports, increasing operations efficiency and improving the service level to aircraft and passengers [20].

Although some countries do not yet have this type of information storage, the FAA controls and collects data from airports through this type of tool, which is addressed in different AC's (Advisory Circulars). On AC 150 / 5300-17C, for example, the FAA [53] provides guidance on the use of remote sensing technologies in data collection that describe an airport's physical infrastructure. This advisory circular

Table 7
Summarization of Papers Dealing with Forecasting Methodologies.

Author	Method	Area	Variables	Purpose	Type of Pavement	Model Category
Liu et al. [29]	Computer Model (ANN)	Structural	Thickness, service life, air traffic, temperature, maximum deflection at runway edge and centre in HWD test and life cycle performance.	Service life	Rigid	Empirical-mechanistic
Cai and Pan [45]	Numerical Modeling (PMM, SMM, PIM)	Structural	Material properties (isotropic and transverse isotropic modules), pavement geometry and surface load	Structural Deformation	Flexible	Mechanistic
Campos and Gonzales [32]	Markov Chains and Logistic Regression	Functional	Interventions, age and PCI	PCI	Flexible	Empirical
Celauro et al. [54]	Fractional Model	Functional	Temperature and physical properties	Viscoelastic behaviour	Flexible	Empirical-mechanistic
Nuijten [46]	Physical Model	Functional	Weather data, pavement dimensions, pavement thermal and physical properties, air traffic, amount of chemicals used on runway, runway surface temperature, sub-surface temperatures and runway cover.	Surface temperature	Flexible	Mechanistic
Huang et al. [33]	LEDFAA, APDMC and Linear Regression	Structural, Functional	Material properties, pavement dimensions, air traffic and aircraft design parameters	Service life	Mixed	Empirical-mechanistic
Villarreal and Hossain [34]	Family Method	Functional	PCI and surface type	PCI	Rigid, Flexible	Empirical
Liu et al. [51]	Finite Elements, Poisson Distribution and Linear Regression	Structural	Material properties and air traffic	Freezing and defrosting cycles	Rigid	Empirical-mechanistic
Al-Qadi et al. [47]	Instrumentation	Structural	Material properties, load response, effect of different loads, FWD data	Pressure on the layers	Flexible	Mechanistic
Kim and Buttlar [55]	Finite Elements	Structural	Viscoelastic and fracture properties, weather data and load application	Pavement cracks	Rigid	Empirical-mechanistic
Herrin and Fuselier [22]	Regression and Approximation Curves	Functional	PCI, floor cracks and air traffic	PCI and Pavement Cracks	Rigid	Empirical
McNerney [23]	FACS Method	Functional	Surface defects (alkaline silica reaction; fatigue; cracks, fissures and flaking; and chips)	Remaining service life	Rigid	Empirical
Leahy et al. [24]	Laboratory Tests and Elastic Layer Model	Structural	Material properties, environment, pavement geometry and air traffic.	Rutting	Flexible	Empirical-mechanistic
Gopalakrishnan and Ceylan [25]	Computer model (ANN)	Structural	FWD data and geomaterial characterization	Flexible pavement layer modules	Flexible	Empirical-mechanistic
Kim and Tutumluer [36]	Regression (power and logarithmic functions)	Structural	Load application and static and dynamic tension states	Rutting	Flexible	Empirical-mechanistic
Yuan and Mooney [50]	Regression by the Least Squares Method	Functional	Surface type, pavement function, construction and maintenance history, defect nature, climate zone, basic drainage condition and pavement thickness	PCI	Rigid, Flexible	Empirical
Shah et al. [48]	Markov Chains	Functional	FOD index, ravelling, longitudinal and transverse cracks, drainage, routine maintenance, age and annual departures	FOD	Rigid, Flexible	Empirical
Suh et al. [37]	Regression (linear, polynomial and power functions)	Functional	PCI and Age	PCI	Rigid	Empirical
Ceylan et al. [39]	Computer model (ANN)	Structural	Air traffic, temperature and material properties	Bending and Deflection Tensions	Rigid	Empirical-mechanistic
Hammons [40]	Finite Elements	Structural	Material properties, dimensions and applied load	Load transfer efficiency	Rigid	Empirical-mechanistic
Al-Suleiman et al. [49]	Regression (Power and logarithmic functions)	Functional	PCI, age and air traffic	PCI	Rigid	Empirical
Rada et al. [35]	PAVER and Derived Predictive Equations	Structural, Functional	Structural Condition Module (CBR; Westergaard slab), traffic mix, pavement type and PCI	Load Capacity, Remaining Life, Failure Time and PCI	Rigid, Flexible, Mixed	Empirical-mechanistic
Shahin and Becker [38]	Linear Regression	Functional	Climate, pavement dimensions, air traffic, age, mechanical properties of the layers, PCI and number of restorations	PCI	Rigid, Flexible	Empirical-mechanistic
Horne and Sparks [52]	Road Condition Reading (RCR) with Diagonal Brake Car Method	Functional	Climate and braking action	Aircraft Stopping Distance	Rigid, Flexible	Empirical-mechanistic

Table 8
Description of the Studies Methods, Objectives, Areas and Variables.

Author	Method	Purpose	Area	Variables
Tu et al. [41]	GIS 3D	Establish the structure of a 3D GIS-based APMS. Introducing a new 3D modeling method.	Structural, Functional	PCI, SCI (Structural Condition Index), ACN/PCN, load transfer capacity, pavement structure service life, slip resistance, smoothness and drainage performance, traffic, environment, foreign object debris (FOD), location, area, age and passenger flow.
McNerney and Keegan [43]	GIS, Geospatial Airfield Pavement Assessment and Management Systems (GAPEMS))	Describe the benefits of implementing APMS that integrate the GIS tool for data collection and evaluation.	Structural, Functional	PCI, remaining service life analysis.
Ho and Romero [20]	GIS, GPS (Geographic Positioning Systems), personal digital assistance	Inspect facilities and mechanisms for maintenance and assessment of slip resistance of runway surfaces.	Functional	Friction.
Barbarella et al. [31]	LIDAR (Light Detection and Ranging)	Validate the use of TLS (Terrestrial Laser Scanning) in time of flight (TOF), to survey the geometric characteristics of taxiways. Develop a software to evaluate the slope and analyze the statistical data.	Functional	Longitudinal and transverse runway uniformity.
Wang et al. [44]	Digital image, DHDV (Digital Highway Data Vehicle)	Apply high resolution digital imaging technology to survey pavement conditions.	Functional	PCI.
Oliveira et al. [56]	BIM	Guide the use of the BIM tool in the maintenance program.	Structural, Functional	Construction process. Asset management activities.
Lee et al. [57]	RDD (Rolling Dynamic Deflectometer), FWD (Falling Weight Deflectometer)	Assess the continuous pavement structure. Present the advantages of using RDD.	Structural	Deflection profile (expansion joints; contraction joints; sliding beams).
Vyas et al. [30]	Analytical Hierarchy Process (AHP), Fuzzy Inference System (FIS)	Justify the need for maintenance and restoration treatment using an objective process. Decide which sections of the pavement should have maintenance priority	Structural, Functional	Deflection, PCI, sub-bed strength and structural index.
Yan et al. [58]	Fuzzy Complex Matter Element, combined weights	Assess the pavements performance.	Structural, Functional	PCI, friction coefficient, IRI, ACN/PCN.
Hachiya et al. [59]	Pavement Rehabilitation Index	Describe the evaluation of the pavements by the Japanese Pavement Rehabilitation Index. Analyze the annual changes of the Osaka Itami airport pavement conditions	Functional	Surface defects (cracking; rutting; irregularity; joint failure)
Pasindu et al. [42]	Finite Elements	Assess the potential for aircraft aquaplaning due to flooded runway floor deformations. Analyze the operational risk.	Functional	Rutting.
Huang et al. [60]	Pavement flatness	Compare methods of evaluating the pavements irregularity. Offer a method for evaluating runway irregularity in asphalt pavements.	Functional	Longitudinal irregularity.
Schibani et al. [61]	Stochastic Modeling	Characterize the kinematic conditions in landing and take-off operations. Investigate the longitudinal and transverse position of the landing point for different aircraft.	Structural	Kinematic data from landings and take-offs.
Hawkins and Covalt [62]	Pavement preservation program	Present the impact that a pavement preservation program offers. Explore the program's funding. Illustrate with real data the importance of preserving the pavement.	Structural, Functional	PCI.
Levenberg et al. [63]	Stochastic modeling	Assess the pavements resilience.	Functional	Weather conditions, types and probabilities of interruption, damage and dispersion, ease of maintenance and probability of failure.
Watkins et al. [21]	FAARFIELD (FAA Rigid and Flexible Iterative Elastic Layer Design), GIS	Assess the structural impact on existing pavements from new aircraft added to the fleet.	Structural	Drop deflection tests, dimensions, material properties, load transfer mechanism, substrate support characteristics, external physical loads, external environmental loads.
Ling et al. [64]	Monte Carlo simulation-based genetic algorithm	Develop maintenance and rehabilitation policies for airport pavement considering scenarios of uncertainty	Functional	PCI.

features the use of Light Detection and Ranging (LIDAR) technologies, capable of providing high precision spatial coordinates. In Barbarella et al. [31] a practical application of this system is presented for the pavement longitudinal and transversal uniformity analysis. From obtaining geometric characteristics it is possible to program maintenance operations more safely, since this data facilitates the verification of failures related to water accumulation or surface roughness, which directly affect the safety of the transport users [2,12,31].

More specific studies, as in Pasindu et al. [42], focused on evaluating the effects of failures in flight operations. Based on Finite Element analysis, the authors modeled what happens to the aircraft when it passes over a permanent deformation during landing or take-off. The safety and comfort in operations is defined mainly by the evaluation of irregularity on pavement flatness. Huang et al. [60] address the various techniques used in China for control and measurement of this index.

Kinematic data was also the target of some research and contributed mainly in structural analysis, since the understanding of landing and take-off characteristics in different aircraft helps understand the transmission of loads to the ground, which serves both for design criteria and maintenance actions. For this evaluation Schibani et al. [61] used stochastic modeling and statistical analysis, among them the linear regression, Kruskal-Wallis test, Anderson-Darling, Shapiro-Wilk, Maximum Likelihood Estimates, Goodness of fit tests, Kolmogorov-Smirnov and Chi-Square.

Other tools, such as the use of BIM (Building Information Modeling) technologies [56], DHDV (Digital Highway Data Vehicle) for the surface defects survey and identification [44], MCDA (Multiple-Criteria Decision Analysis) methodologies [30,58] and others identified from this systematic review, can be visualized as to their objectives within the pavement management system, performance areas and study variables in Table 8.

It is noticeable that the large number of variables analyzed in the decision making of maintenance strategies may affect the objectives proposed in the work. With this, Di Mascio and Moretti [3] emphasize the importance of functional and structural information management. Some works have shown tools mainly focused on this theme [41,43,44,56] with the adoption of automated technologies, which are already in common use in some countries at large airports.

As the possibly most influential limitation, verified in more than one study, there is the fact of subjectivity involved in the analyses, found in some methodologies that use the MCDA approach [30,58] or stochastic modeling [61,63], characterizing uncertainties in pavement management as discussed in Butt et al. [15]. In addition, other limitations are perceived in the studied areas, focusing on pavement functionality and the restriction of variables, such as the use of PCI as the only important factor in the state attribution of the systems [44,62].

In general, the studies' conclusions suggest the need for research to include new data, efficiency in the manipulation of information and the use of tools to collect the pavements condition assignments. They also indicate that there are problems in the maintenance strategies decision-making process, mainly due to the specific characteristics of the system and the low number of samples worked on. Additionally, the papers also suggest the implementation of initiatives to optimize decisions and activities in the sector in order to ensure the reduction of maintenance and restoration expenditures.

6. Conclusions

The analyses contained in this paper are intended to guide researchers in the area of airport pavement maintenance as to the methods, tools and variables that have already been idealized and applied worldwide. It is noted that some countries are still adapting the various methodologies that can be used in pavement management, a fact proven by the concentration of research in some regions.

As a result of the systematic review we can list the following points present in the bibliometric analysis: (*i*) distribution of publications per year, identifying its beginning in 1970 and the oscillations since then; (*ii*) number of publications per journal, capable of directing the journals that have published papers within this theme and the exposure of their performance metrics by the SJR, in addition to the description of other sources considered as conferences and book chapters; (*iii*) number of outstanding authors and citations in selected papers; (*iv*) definition of the most used type of research, with emphasis on case study; (*v*) distribution of studies by region, to verify which countries have invested the most in pavement research, and making it possible to identify differences between those that were surveyed and the conditions present in other countries. And finally, the results present in the qualitative synthesis it explored: (*vi*) software that was used in the researches and its application; (*vii*) areas that have been studied the most; and (*viii*) methodologies, variables and description of the studies.

It is noticeable that the works raised show concern with the maintenance activities optimization and, mainly, the exclusion of subjective decisions regarding the execution of interventions. Within this context, it is suggested for future studies, considering the development of pavement research, studies with the pavement management processes optimization, taking into consideration limiting factors present in the country's administrative culture and ensuring assertive decisions in maintenance.

Appendix

Review protocol	
Topic	Description
Objective	Identify and analyze the existing methods, techniques and variables for the elaboration of models for the evaluation and/or forecasting of airport pavement conditions.
Review Question	What are the existing methods, techniques and variables for preparing models for assessing and/or forecasting the conditions of airport pavements?
Research databases	Web of Science and Scopus.
Keywords	Airport Pavement, Runway, Deterioration, Condition, Degradation, Prediction, Forecasting, Evaluation, Management and Maintenance.
Document language	English.
Inclusion criteria	1. Papers published and available in full in scientific databases or printed versions shall be included. 2. Papers which address methods, techniques and describe variables for the elaboration of models for assessing or predicting the conditions (performance or degradation) of pavements shall be included. 3. The works must be approved by the scientific community.
Exclusion criteria	1. Works that are not fully available in the searched databases will be disregarded. 2. Works published as short articles or posters will be excluded. 3. Works that do not deal with airport pavements will be excluded.
Synthesis of results	After defining the works definitely included, they will be read in full. The reviewer will summarize each of them, highlighting the year, source of publication, location, name of the database, type of research, type of data and the method used.

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