

Probabilistic and sensitivity analysis in airfield pavement design

Análise probabilística e de sensibilidade no dimensionamento de pavimentos aeroportuários

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ABSTRACT

The structural performance of airfield pavements is influenced by variables related to the materials and the thicknesses of the layers, and understanding their effects is essential for safe and optimized projects. This study evaluates the performance of airfield pavements by combining probabilistic and sensitivity analysis. The probabilistic analysis was conducted using Rosenblueth's point estimate method, quantifying the impact of variability in resilient moduli and layer thicknesses on the structural response. The sensitivity analysis identified the most critical parameters by calculating their relative influence on the vertical deformation at the top of the subgrade and on the cumulative damage factor (CDF). The results indicated that the subgrade resilient modulus has the greatest influence on pavement performance, followed by the thicknesses of the subbase, surface, and base layers. Reducing the variability of all input parameters increased the estimated service life from 13.1 to 19.0 years. This hierarchy highlights the importance of quality control, prioritizing subgrade characterization and uniformity, in addition to inspection during layer construction, offering technical support for the development of rational designs.

RESUMO

O desempenho estrutural de pavimentos aeroportuários é influenciado por variáveis relacionadas aos materiais e às espessuras das camadas, e a compreensão de seus efeitos é fundamental para projetos seguros e otimizados. Este trabalho avalia o desempenho de pavimentos aeroportuários combinando análise probabilística e análise de sensibilidade. A análise probabilística foi realizada por meio do método das estimativas pontuais de Rosenblueth, quantificando o impacto da variabilidade dos módulos de resiliência e das espessuras na resposta estrutural. A análise de sensibilidade identificou os parâmetros mais críticos, calculando sua influência relativa sobre a deformação vertical no topo do subleito e sobre o fator de dano acumulado (CDF). Os resultados indicaram que o módulo de resiliência do subleito exerce a maior influência no desempenho do pavimento, seguido pelas espessuras da sub-base, do revestimento e da base. A redução da variabilidade de todos os parâmetros de entrada elevou a vida útil estimada de 13,1 para 19,0 anos. Essa hierarquia evidencia a importância do controle tecnológico, priorizando a caracterização e a uniformização do subleito, além da fiscalização durante a execução das camadas, oferecendo subsídios técnicos para o desenvolvimento de projetos racionais.

1. Introduction

The growth of air transportation has driven the evolution of aircraft, resulting in higher operational weights and increased tire pressures, which impose greater loads on airfield pavements (Garg *et al.*, 2018). This scenario demands more robust pavements and updated design methodologies to ensure safety and durability under new traffic conditions.

Maintaining this infrastructure is complex, as factors such as climate, increased loads, construction deficiencies, and inadequate or absent maintenance accelerate deterioration, potentially compromising operational safety (Oliveira, Almeida & Ramos, 2016). Therefore, it is essential to adopt methodologies that realistically represent the operational demands and local characteristics of the materials.

Considering current approaches, pavement design is carried out using mechanistic-empirical methods implemented in software such as FAARFIELD (United States), Alizé-Aéronautique (France), and APSDS (Australia), based on the Layered Elastic Theory (LET) (Vieira, 2015). In Brazil, the National Civil

Aviation Agency (ANAC) does not define its own design method, recommending only the ACN/PCN (Aircraft Classification Number/Pavement Classification Number) system (ANAC, 2021), developed in the 1980s and currently considered limited (ANAC, 2022). Similarly, in Canada, pavement design has traditionally been performed using design charts, which also impose restrictions in terms of the flexibility and precision of the resulting designs (PWGSC, 1997).

The direct application of foreign models is also questionable, as it does not reflect local conditions such as climate and the materials that compose pavement structures. In response to this limitation, ICAO developed the ACR/PCR (Aircraft Classification Rating/Pavement Classification Rating) method, which represents an improvement but still presents constraints, such as the uniform consideration of the Poisson's ratio and the exclusive use of vertical deformation at the top of the subgrade as a failure criterion (Castro & Oliveira, 2024).

It should be noted that pavement design and pavement strength classification are distinct procedures. Classification systems such as ACN/PCN and ACR/PCR are intended to assess whether an existing pavement can accommodate the operation of a given aircraft, whereas design methods determine the layer thicknesses required for a pavement to withstand defined traffic over its design life. Despite this difference in purpose, both procedures rely on a structural analysis of the pavement, sharing the same mechanical response models.

In this context, the heterogeneity of materials and the variability of the construction process are parameters often considered immutable in traditional design methods. Probabilistic analysis allows for incorporating the uncertainty of input parameters (Brown, 1994), providing insight into the reliability of the design and reducing the risk of under- or over-designing the airfield pavement.

Despite the relevance of these parameters, traditional software tools have limitations regarding the inclusion or adjustment of these variables. This restricts the designer's ability to perform sensitivity analyses or adapt the models to the specific conditions of the project. Consequently, this can lead to over-designed projects, with excessive costs and structural constraints, or under-designed projects, compromising operational safety and pavement service life.

To overcome these constraints, a computational tool based on layered elastic theory (LET) was developed in this study. This tool allows customization of parameters that directly affect the structural performance of the pavement. In this way, it expands the designer's ability to evaluate different scenarios by incorporating variables that cannot be directly addressed in commercial design software.

The objective of this paper is to evaluate the impacts of heterogeneity in the resilient modulus and layer thicknesses on the structural performance of airfield pavements, using probabilistic analysis based on Rosenblueth's point estimate method and sensitivity analysis through the coefficient of elasticity. Thus, the tool provides support for decision-making in pavement design projects, enabling airfield operators to identify which factors have the greatest influence on structural performance, prioritize interventions, and optimize resources during the design stage.

2. Literature review

Accurately predicting the service life of a pavement and the failure modes to which it will be subjected is a complex task due to the uncertainties associated with the input parameters used in the design process. These uncertainties can be classified into four main categories (Thoft-Christensen & Baker, 2012):

- Physical uncertainties: related to the variability of traffic, material properties, and layer thicknesses;
- Statistical uncertainties: associated with the selection of the most appropriate probability distribution and the estimation of parameters from finite samples;
- Model uncertainties: resulting from simplifications, idealized assumptions, and lack of information about actual boundary conditions and structural interactions;
- Human errors: introduced during the design, construction, and operation stages.

Given these uncertainties, pavement engineering seeks to balance safety and economy by adopting reliability levels that represent the acceptable risk to the structure. Reliability theory emerges as a tool that allows for quantifying risk, ensuring that the pavement fulfills its functions throughout the design

period. Structural reliability can be defined as the probability that a structure will not fail to perform its intended function during its service life (Nowak & Collins, 2012).

In the context of pavements, the main parameters that influence structural performance over time include (Tighe, He & Haas, 2001; Noureldin *et al.*, 1994):

- Subgrade properties, represented by the resilient modulus (RM);
- Thickness and stiffness of the pavement layers;
- Traffic conditions, expressed in terms of equivalent single axle loads;
- Climatic conditions during the design period;
- Construction quality and methods used;
- Maintenance schedule and planned interventions.

Each of these parameters presents natural variability that directly impacts the predicted pavement performance. Therefore, replacing deterministic methods with probabilistic approaches becomes a necessity. While deterministic methods work only with mean values, probabilistic methods incorporate means, variances, and probability distributions, allowing for a more robust risk analysis.

It has been observed that the mechanical properties of the layers and their thicknesses are the most critical factors, followed by traffic variability and the so-called lack-of-fit errors, which are related to model calibration errors Dalla Valle & Thom (2015). In terms of fatigue performance, the factors that had the greatest impact on response variability were the resilient modulus of the asphalt layer and the thickness of the surface layer, both directly related to the occurrence and extent of cracking. The thickness of the granular base, in turn, showed little influence on this type of failure.

On the other hand, for performance related to permanent deformation (rutting), the most critical parameters were the thickness of the granular base, the thickness of the asphalt surface layer, and the resilient modulus of the subgrade. Table 1 presents a summary of the Coefficient of Variation (COV) values reported in the literature for different input parameters.

This variability demonstrates that no design parameter is deterministic (Motta, 1991). Thus, the statistical treatment of variables is essential to ensure more realistic predictions of performance and service life (Mello *et al.*, 2016). In deterministic analyses, the exclusive use of mean values implies a reliability level of 50%, meaning that there is an equal probability of the actual damage being higher or lower than predicted. This level may be acceptable in lower-priority projects, but it is not suitable for airfield pavements, which operate under high loads and strict safety requirements.

For structures of this magnitude, it is recommended to work with higher reliability levels, ensuring

Table 1 • Coefficient of variation (C.V.) values for input parameters

Input Parameter/ Property	Description	Variation Range (%)	Typical C.V. (%) Reference Structure	Distribution Type	Reference
Layer Thickness	Surface	3–12	7	Normal	Timm, Newcomb & Galambos (2000), Noureldin <i>et al.</i> (1994)
		—	10	Normal	Franco (2000)
	Binder / layer with asphalt binder	5–15	10	Normal	Noureldin <i>et al.</i> (1994)
	Granular base	10–15	12	Normal	Noureldin <i>et al.</i> (1994)
		—	10	Normal	Franco (2000)
	Granular subbase	10–20	15	Normal	Franco (2000)
Resilient Modulus (RM)	Surface / layer with asphalt binder	10–20	15	Normal	Noureldin <i>et al.</i> (1994)
	Granular base	10–30	20	Normal	Noureldin <i>et al.</i> (1994),
	Granular subbase	10–30	20	Normal	Franco (2000)
	Subgrade	10–30	20	Normal	

that the structure has sufficient capacity to withstand severe conditions or unexpected variations. In this context, reliability can be understood as the probability that the pavement will fulfill its function throughout its entire design life, maintaining its structural and functional performance.

Probabilistic tools have been gradually incorporated into design methods. The point estimate method (Rosenblueth, 1975) is a simplified technique that allows for analyzing the impact of variability in input variables using a reduced number of performance function evaluations.

The application process of Rosenblueth's method consists of replacing each random variable with two extreme values, shifted by one standard deviation ($\pm\sigma$) from its mean. All possible combinations of these values are then analyzed, allowing the calculation of the mean and standard deviation of the structural response. Based on these results, the characteristic value for performance verification is obtained using Equation 1:

$$\varepsilon_c = \bar{\varepsilon} + k\sigma, \quad (1)$$

where: ε_c is the characteristic value of strain, stress, or displacement; $\bar{\varepsilon}$ is the mean value of the response; σ is the standard deviation; k is the reliability factor, which may vary according to the desired reliability level (e.g., $k = 1.645$ for 95%).

In the context of airfield pavements, some software tools already explicitly incorporate probabilistic concepts. Alizé-Aéronautique, for example, allows the designer to define an acceptable risk level, referred to as Design Risk (r), which represents the fraction of the runway length that may require reconstruction at the end of the design period in the absence of reinforcement interventions (STAC, 2016).

This approach is implemented through the calculation of the Risk Coefficient (kr), which adjusts the fatigue law of bituminous materials. More conservative risk values result in lower kr , reducing the allowable fatigue and leading to more robust and safer designs.

It is important to note that, in the French methodology, this probabilistic modeling is limited to the fatigue criterion. The permanent deformation criterion, applied to granular layers and the subgrade, continues to be treated deterministically (STAC, 2016).

In turn, the FAARFIELD software, developed by the FAA, does not directly incorporate a reliability concept. Its iterative calculation process seeks a design in which the CDF (Cumulative Damage Factor) is equal to 1, within a tolerance defined by the designer, which may range from 0.005 to 0.05 (FAA, 2021). This tolerance, however, does not represent a reliability or risk level; it is merely a numerical convergence tool for the iterative process. Thus, unlike Alizé, the FAARFIELD approach remains deterministic in this aspect.

Sensitivity analysis is an important tool for quantitatively verifying the effects that different input parameters exert on the structural performance of the pavement. Small variations in certain parameters may not cause significant impacts on pavement performance, while other variables may have a major influence on its service life (Barker & Brabston (1975); Parker et al. (1979)). To quantify this relationship, the sensitivity of the pavement service life (L) with respect to an input parameter (x) can be defined through a dimensionless equation, expressed in Equation 2:

$$S_{x,L} = \frac{\partial L}{\partial x} \cdot \frac{x}{L}, \quad (2)$$

This formulation allows for the comparison of variables with different physical units, such as resilient moduli and thicknesses. Thus, the magnitude of $S_{x,L}$ expresses the degree of influence of the parameter on pavement behavior, regardless of its nature or unit of measurement.

This method was applied by McQueen et al. (1995) in the calibration of the LEDFAA program, the predecessor of FAARFIELD, and was used by the Federal Aviation Administration (FAA) to identify the parameters with the greatest impact on the design of airfield pavements. The studies indicated that among the evaluated variables, subgrade strength, total pavement thickness, and aircraft-applied load are among the most relevant factors in defining the service life and structural safety of these infrastructures.

The relationship between variables can also be expressed through a logarithmic transformation, known as the log-log model, which allows for the linear analysis of relative variations. This approach

is used in both economic and engineering studies to measure elasticity, defined as the ratio between the percentage change of a response variable and the percentage change of an independent variable (Gujarati & Porter, 2009). In this context, elasticity is given by Equation 3:

$$\eta_x = \frac{\partial \ln Y}{\partial \ln X} \quad (3)$$

Elasticity expresses how a response variable (Y) proportionally reacts to a variation in an input variable (X), such as resilient modulus or layer thickness. Positive values of η_x indicate that an increase in the input parameter results in a proportional increase in the response variable. Conversely, negative, η_x values indicate an inverse relationship, where an increase in the input parameter leads to a decrease in the response variable.

Values close to zero indicate that the analyzed variable has little influence, while higher values indicate that small variations in the parameter can cause significant changes in the structural response. Thus, elasticity allows for prioritizing which factors should be more strictly controlled during the design and construction of airfield pavements, for example.

3. Methodology

The first step consisted of developing a proprietary computational tool based on the Elastic Theory for Multilayer Systems, aiming to determine the structural responses of the airfield pavement under loading. From these responses, it was possible to calculate stresses and strains throughout the layers and at the top of the subgrade, which was used as the main design criterion. The structural modeling adopted was based on the classical theory of [Burmister \(1944\)](#), which is used in the mechanistic design of flexible pavements. The model was implemented following the guidelines proposed by [Khazanovich & Wang \(2007\)](#), using a set of simplifying assumptions that allow for the mathematical formulation of the problem. The main assumptions adopted were:

- All pavement layers are modeled as linear elastic, homogeneous, and isotropic materials;
- Each layer has a constant thickness, except for the subgrade, which was modeled as a semi-infinite space;
- The layers are considered infinite in the horizontal directions, eliminating edge effects;
- There are no initial stresses or strains present before the load application;
- The interfaces between layers are perfectly bonded, with no relative sliding;
- The load applied by each wheel is uniformly distributed over a circular area.

Since the actual aircraft loading consists of multiple wheels, the model applied the principle of superposition, in which the total pavement response is obtained by the algebraic sum of the individual responses caused by each wheel of the landing gear. The mathematical solution was implemented using the Hankel Transform, which converts the problem from the spatial domain to the transformed domain, simplifying the resolution of the multilayer system. The procedure was divided into three main steps:

1. Transformation of the problem into the Hankel transform domain, converting the partial differential equations into ordinary differential equations;
2. Algebraic solution in the transformed domain, resulting in integration coefficients (A , B , C , and D) for each layer, totaling $4n$ coefficients for a system with n layers;
3. Inverse Hankel transform to return to the spatial domain and obtain stresses and strains at any point within the pavement.

The transform parameter, denoted as m , can be interpreted as a spatial frequency, allowing the problem to be decomposed into independent components that, when recombined, provide the global response of the system. The boundary conditions adopted were:

- Vertical stress at the surface equal to the load-applied pressure;
- Zero shear stresses at the surface;
- Continuity of stresses and displacements between bonded layers;
- Null stresses and displacements at infinite depth within the subgrade.

The analytical solution of the inverse Hankel integral is not closed due to the oscillatory nature of the Bessel functions involved. Therefore, a numerical approach based on Gaussian quadrature was adopted. The process was implemented as follows:

- Definition of a fixed number of Bessel function roots ($N = 300$) for discretizing the domain;
- Application of specific integration points ($n_{ip} = 30$) for the first intervals, ensuring accuracy in the solution;
- Use of an interpolation technique to improve computational efficiency, as described by [Khazanovich & Wang \(2007\)](#).

For each point and wheel, the model numerically computes stress and displacement in cylindrical coordinates, converts them to Cartesian, and derives strains via the generalized Hooke's Law, yielding the full stress and strain tensor at any pavement point. The focus here is the vertical strain at the top of the subgrade, the structural failure criterion for airfield pavements. Figure 1 shows the flowchart of this calculation process.

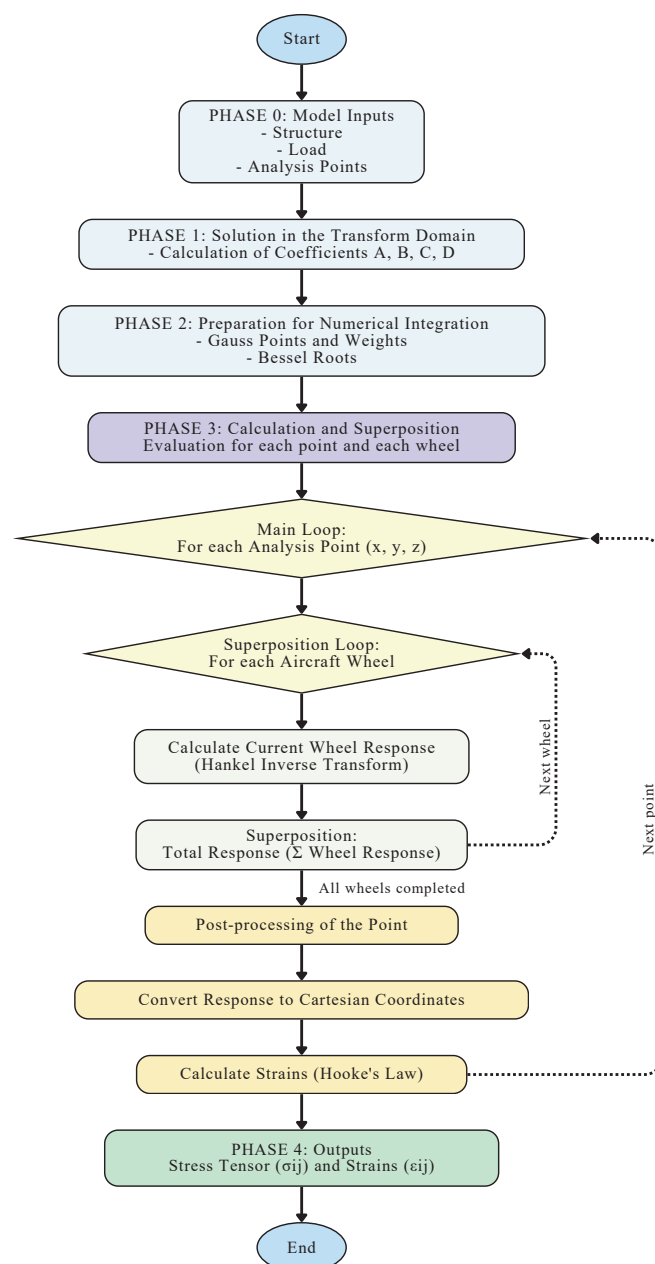


Figure 1 • Flowchart of the structural analysis for determining pavement stresses and strains.

Thus, a probabilistic analysis was carried out with the objective of considering the natural variability of the model's input parameters. In this context, the design variables were treated as random variables, and the Rosenblueth method was used to estimate the mean and standard deviation of the structural responses.

The Rosenblueth point estimate method was adopted for its computational efficiency, as it requires a limited number of deterministic evaluations to estimate the moments of the response (Almeida *et al.*, 2025). This efficiency, however, entails limitations. The method provides only the first moments of the response distribution and does not yield the full probability distribution. Monte Carlo simulation overcomes this limitation at the cost of a larger number of evaluations (Cava, Ribeiro & Pereira, 2026).

The variables analyzed were layer thicknesses and resilient moduli. For each variable, a mean value was assigned (Table 2) along with a Coefficient of Variation (COV) (Table 1). The thicknesses and resilient moduli were modeled as normally distributed variables. The vertical strain at the top of the subgrade was adopted as the response variable, from which the CDF (Cumulative Damage Factor) was derived as the structural failure criterion.

Table 2 • Pavement and aircraft data used in the simulations

Probabilistic Analysis				
Structure	Resilient modulus (MPa) (Poisson)	Thickness (mm)	Aircraft	Operations and Annual Growth
Surface	1,721.00 (0.35)	304.00	B777-300ER ¹	3,056 (1.13%)
Base	485.21 (0.35)	300.00		
Subbase	138.61 (0.35)	900.00		
Subgrade	51.71 (0.35)	—		
Elasticity Coefficient				
Structure	RM (MPa) –	RM (MPa) +	Thickness (mm) –	Thickness (mm) +
Surface	1,548.90	1,893.10	273.60	334.40
Base	436.69	533.73	270.00	330.00
Subbase	124.75	152.47	810.00	990.00
Subgrade	46.54	56.88	-	-

¹maximum take-off weight of 352,441 kg, tire pressure of 1,523 kPa, and pass-to-coverage ratio of 1.04.

Seven random variables were considered: the resilient moduli of the four layers and the thicknesses of the surface, base and subbase layers, the subgrade being modeled as a semi-infinite medium. Each variable was replaced by two values shifted by one standard deviation from its mean, resulting in $2^7 = 128$ combinations. The structural response was evaluated for each combination, and the mean and standard deviation of the vertical strain at the top of the subgrade were obtained from the resulting set of 128 values, assuming the variables to be statistically independent.

From the Rosenblueth combinations, the mean ($\bar{\epsilon}$) and the standard deviation (σ) of the vertical strain at the top of the subgrade were obtained. The characteristic strain value was calculated using Equation 1 with $k = 1$, and it is this value, not the mean, that was applied to the failure criterion to obtain the CDF and service life. Accordingly, the no-variation scenario ($\sigma = 0$) reduces to the deterministic case, in which $\epsilon_c = \bar{\epsilon}$.

The CDF calculation incorporated the lateral distribution of aircraft traffic, adopting a wander of 773 mm, the value used by FAARFIELD. The pass-to-coverage ratio was determined from the landing gear geometry and this lateral distribution, and the CDF was evaluated along the transverse profile. The value reported for each scenario corresponds to the maximum CDF along this profile. The pavement structure and the aircraft data adopted in the simulations are presented in Table 2. The B777-300ER was adopted as the design aircraft because it is one of the most structurally demanding aircraft in operation.

While the Rosenblueth method evaluates the overall effect of uncertainties, the elasticity analysis aims to identify which variables have the greatest individual influence on pavement behavior. The

equation used is expressed in logarithmic form (Equation 4):

$$\eta_x = \frac{\ln(Y^+) - \ln(Y^-)}{\ln(1 + \delta) - \ln(1 - \delta)} \quad (4)$$

where: η_x is the elasticity of variable X ; $\ln(Y^+)$ is the pavement response when Variable X is increased by δ ; $\ln(Y^-)$ is the pavement response when Variable X is decreased by δ ; δ is the percentage variation applied to variable X . A value of $\delta = 10\%$ was adopted.

For the probabilistic analysis, the objective was to evaluate the impact of the variability of pavement layer properties on damage accumulation, represented by the CDF (Cumulative Damage Factor), and on the projected service life. Different scenarios were tested using the Rosenblueth method, by modifying the Coefficient of Variation (COV) of the resilient moduli and layer thicknesses to identify which parameters have the greatest influence on structural performance. The COV values adopted in the technological control scenarios were defined within the ranges reported in the literature (Table 1). For the surface layer thickness, whose reported range is 3% to 12%, a COV of 5% was adopted, a value below the typical one (7%) and representative of construction under strict thickness control, which is common in airfield pavements.

4. Analysis and discussion of results

Before applying the probabilistic and sensitivity analyses, the Demoiselle software, developed in this study, was verified against FAARFIELD, the reference software for airfield pavement design. Two airfields with real pavement structures and traffic mixes were adopted as case studies. In both cases, a Poisson's ratio of 0.35 was adopted for all layers and no annual traffic growth was considered. For each aircraft, the maximum CDF obtained with FAARFIELD was compared with the value calculated by Demoiselle under identical structural and traffic conditions. The results of this comparison are presented in Table 3. The results showed agreement between the two software packages. For airfield A, the differences in CDF were below 2%, and for airfield B, the CDF values coincided for all aircraft. This agreement confirms the consistency of the layered elastic implementation adopted in Demoiselle.

Table 3 • Comparison between FAARFIELD and Demoiselle CDF values

Aircraft	Annual operations	CDF FAARFIELD	CDF Demoiselle	Difference (%)
Airfield A (surface 150 mm / 2,055 MPa; base 340 mm / 438 MPa; subgrade 77 MPa)				
A319-100 std	32	0.03	0.03	0.0
A320-200 std	927	5.43	5.44	0.2
A321neo	70	3.73	3.74	0.3
B737-700	406	1.79	1.79	0.0
B737-800	2048	26.48	27.02	2.0
Airfield B (surface 300 mm / 1,500 MPa; base 250 mm / 250 MPa; subgrade 134.45 MPa)				
A321neo	1087	0.10	0.10	0.0
A330-200	312	0.22	0.22	0.0
B777-300ER	234	0.29	0.29	0.0
B747-400	234	0.01	0.01	0.0
B747-400ER	234	0.01	0.01	0.0
A350-900	234	0.88	0.88	0.0

Table 4 shows the scenarios that were evaluated for a confidence level of 84% ($k = 1$) and the respective adopted COV (%) values. The COV values and the corresponding service life were also reported.

The results indicated that reducing the variability of the surface and base layer properties had a limited impact on the CDF, resulting in service lives of approximately 13 years, like the standard scenario. This finding suggests that efforts focused exclusively on these layers provide limited benefits, as they do not lead to significant changes in the CDF.

Table 4 • Simulated scenarios and suggested COV (%) values

Scenario	COV Thk (%)			COV RM (%)				Service			Observations
	S	B	SB	S	B	SB	SG	CDF	life (years)		
Standard	7	12	15	15	20	20	20	1.52	13.1	Reference	
Surface – Thickness	5	12	15	15	20	20	20	1.52	13.1	Reduce variation in surface thickness	
Surface – RM	7	12	15	10	20	20	20	1.51	13.1	Reduce variation in surface RM	
Surface – Integrated	5	12	15	10	20	20	20	1.51	13.1	Complete control of surface	
Base – Thickness	7	8	15	15	20	20	20	1.52	13.1	Reduce variation in base thickness	
Base – RM	7	12	15	15	15	20	20	1.51	13.1	Reduce variation in base RM	
Base – Integrated	7	8	15	15	15	20	20	1.50	13.3	Complete control of base	
Subbase – Thickness	7	12	10	15	20	20	20	1.49	13.4	Reduce variation in subbase thickness	
Subbase – RM	7	12	15	15	20	15	20	1.50	13.3	Reduce variation in subbase RM	
Subbase – Integrated	7	12	10	15	20	15	20	1.47	13.6	Complete control of subbase	
Subgrade – RM	7	12	15	15	20	20	10	1.11	18.0	Reduce variation in subgrade RM	
Surface and Granular Layers	5	8	10	10	15	15	20	1.44	13.8	Control of surface and granular layers	
Granular Layers and Subgrade	7	8	10	15	15	15	10	1.06	18.8	Control of granular layers and subgrade	
Surface and Subgrade	5	12	15	10	20	20	10	1.10	18.2	Control of surface and subgrade	
Total - Integrated Control	5	8	10	10	15	15	10	1.05	19.0	Complete technological control	
No Variation	0	0	0	0	0	0	0	0.89	22.4	No variation	

S = Surface; B = Base; SB = Subbase; SG = Subgrade; Thk. = Thickness; RM = Resilient modulus

In turn, the subbase showed a more significant effect. When its COV was reduced, the CDF decreased from 1.52 to 1.47, increasing the service life to 13.6 years. This reduction demonstrates that technological control in this layer can contribute more effectively when compared to the surface or base layers. However, the subgrade proved to be the most sensitive variable. When the COV of the subgrade resilient modulus was reduced from 20% to 10%, the CDF dropped to 1.11, and the service life increased to 18 years. This result reinforces the importance of technological control and homogenization of the subgrade, since this structure represents the foundation of the pavement and is the main criterion to be considered in the design of airfield pavements.

In addition to the isolated analyses, combined scenarios were simulated, which confirmed the observed trend. The simultaneous control of the granular layers (base and subbase) and the subgrade resulted in a CDF of 1.06, with a service life of 18.8 years. In the integrated scenario, where variability was reduced in all variables, the CDF reached 1.05, with a service life of 19 years. Although technological control with no variability represents the ideal situation to ensure pavement quality, the results indicated that the additional gains compared to the isolated control of the subgrade are limited. Thus, prioritizing resources for the characterization and homogenization of the subgrade can be a rational and efficient strategy.

The hypothetical case without variability, used as a reference by the FAARFIELD software, presented a CDF equal to 0.89 and a service life of 22.4 years. This scenario highlighted the difference between deterministic and probabilistic modeling, in which material variability is inevitable (from an executive and technological standpoint). Figure 2 presents the CDF values for each analyzed scenario, as well as the corresponding service lives indicated in the labels above the bars.

The analysis of the elasticity values indicated the degree of sensitivity of the pavement to variations in the structural parameters, both in relation to the vertical strain at the top of the subgrade and the CDF. In all cases, the elasticity values were negative, indicating that an increase in a variable, whether RM or thickness, results in a reduction of the analyzed response. In practical terms, this means that reinforcing or improving a pavement layer by increasing its thickness or RM tends to reduce deformation and accumulated damage, thereby improving its structural performance. The greater the magnitude of the negative value, the greater the influence of that variable on the response being analyzed.

The results showed that the subgrade exerts the greatest influence on pavement performance. For the subgrade RM, the elasticity was -0.69 for strain and -15.39 for the CDF, demonstrating that this structure has a direct impact on the durability of the pavement system. Thus, even small variations in the subgrade RM can cause changes in the pavement service life, reinforcing the importance of strict

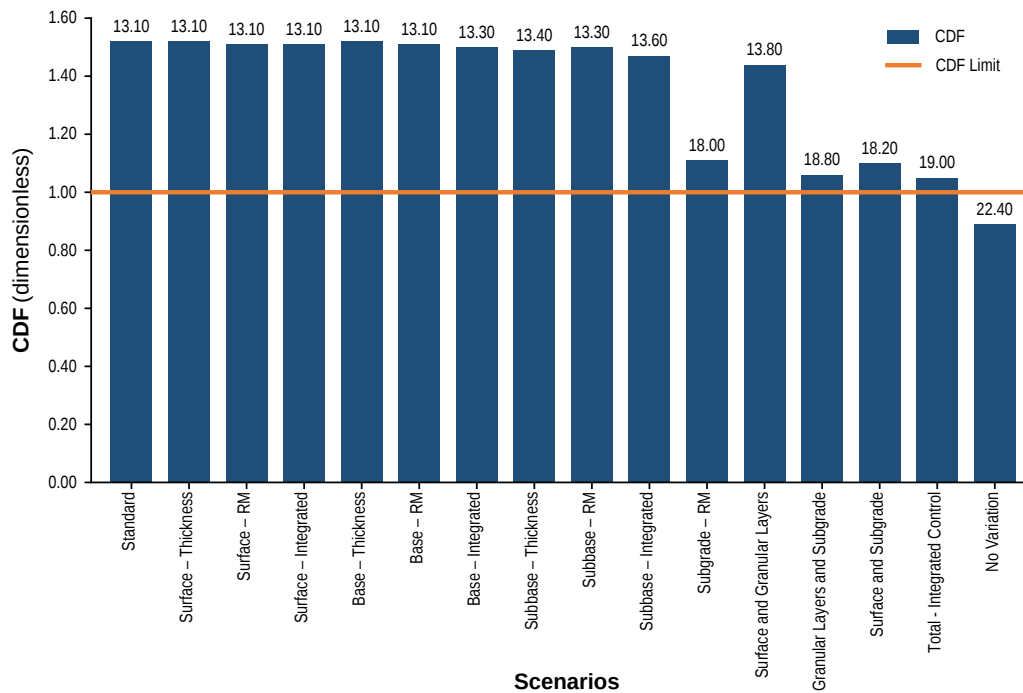


Figure 2 • Effect of parameter variability on CDF and pavement service life.

control in geotechnical characterization and, when necessary, subgrade stabilization. The subbase thickness showed an intermediate effect, with elasticity values of -0.40 for strain and -8.88 for the CDF, higher than those obtained for the RM of this same layer (-0.19 and -4.14 , respectively). This indicates that, for the subbase, ensuring the correct execution of the thickness is more relevant than using stiffer materials.

In the base layer, behavior like that of the subbase was observed, but with lower intensity. The thickness showed elasticity values of -0.22 for strain and -4.91 for the CDF, while the RM had lower values (-0.06 and -1.22). This demonstrates that pavement performance depends more on construction precision and geometric control of this layer than on improvements in material quality.

In turn, for the surface layer, thickness was also more relevant (-0.25 for strain and -5.54 for the CDF) compared to RM (-0.07 and -1.50 , respectively). Although the impact is smaller than that observed in the lower layers, increasing thickness still contributes to reducing accumulated damage.

By comparing the elasticity values for the CDF, which represents the pavement's main failure criterion, it was possible to observe a hierarchy (Table 5).

The elasticity values obtained for the CDF are approximately one order of magnitude higher than those obtained for the vertical strain. This amplification results from the exponential form of the performance equation adopted by the FAA, in which the number of coverages varies exponentially with the vertical strain at the top of the subgrade. Consequently, a small relative variation in strain

Table 5 • Elasticity coefficient values

Rank	Variable	Strain ($\mu\epsilon$)		CDF		Elasticity coefficient	
		Y–	Y+	Y–	Y+	Strain	CDF
1	Subgrade – RM	1376.00	1198.83	3.51	0.16	-0.69	-15.39
2	Subbase – Thickness	1334.00	1230.00	2.02	0.34	-0.40	-8.88
3	Surface Layer – Thickness	1313.19	1248.52	1.49	0.49	-0.25	-5.54
4	Base – Thickness	1309.89	1252.58	1.42	0.53	-0.22	-4.91
5	Subbase – RM	1305.67	1257.25	1.33	0.58	-0.19	-4.14
6	Surface Layer – RM	1290.03	1272.90	1.04	0.77	-0.07	-1.50
7	Base – RM	1288.57	1274.11	1.01	0.79	-0.06	-1.22

produces a larger relative variation in accumulated damage, regardless of which input parameter caused it. Within this framework, the subgrade resilient modulus stands out because it is the parameter with the greatest influence on the strain itself (-0.69 , against -0.40 for the second-ranked variable), and this larger effect is then amplified by the exponent. This predominance of the subgrade is consistent with the findings of Almeida *et al.* (2025), who identified the subgrade resilient modulus as the most relevant variable in modeling the vertical strain at the top of the subgrade in airfield pavements. This hierarchy demonstrates that investing in subgrade improvement, combined with strict control of layer thicknesses during construction, constitutes the most efficient strategy for extending the service life of the structure and optimizing available resources.

Proper characterization and homogenization of the subgrade soil, together with continuous monitoring during construction, are essential steps to ensure satisfactory structural performance. In addition, improvements in the RMs of the upper layers, such as the base and surface, are also important and should be considered in the design, although they have a limited impact when compared to the gains achieved through geometric control of the layers and the uniformity of the subgrade.

Finally, the application of probabilistic approaches in pavement design allowed the quantification of the effect of input parameter variability, providing a rational understanding of pavement behavior. This analysis offers technical support for decision-making in design and construction, enabling the prioritization of interventions that yield greater technical and economic benefits. In summary, implementing technological control for the subgrade and, secondarily, for the granular layers represents a strategic path to ensure durability, operational safety, and the efficiency of airfield pavements.

5. Conclusion

This study presented a computational tool for the design of airfield pavements based on the LET allowing the customization of parameters that cannot be directly adjusted in commercial software. The proposed tool enabled the application of probabilistic and sensitivity analyses, providing a broader evaluation of the structural performance of pavement systems.

The probabilistic analysis, performed using the Rosenblueth method, demonstrated that parameter variability significantly influences pavement service life. Among the evaluated variables, the resilient modulus of the subgrade was identified as the most critical parameter, followed by the thickness of the subbase, the surface layer, and the base. These findings highlight the importance of rigorous technological control during construction, particularly in the characterization and homogenization of the subgrade soil and, subsequently, the granular layers.

The sensitivity analysis complemented the probabilistic approach by quantifying the relative influence of each parameter on the structural response. The elasticity coefficients confirmed the predominance of the subgrade resilient modulus, while the moduli of the granular and surface layers showed comparatively lower influence on the responses analyzed.

Overall, the results provide technical support for a more rational allocation of design and construction resources, prioritizing parameters that most affect pavement durability and structural safety. However, the analyses were conducted, assuming linear elastic behavior of pavement materials and using the Rosenblueth point estimate method to represent parameter variability. In addition, the study focused on structural parameters and did not explicitly incorporate operational and environmental factors, such as aircraft lateral wander and temperature variations, which may also influence pavement performance. Future studies may expand this approach by incorporating these additional variables, enabling a more comprehensive evaluation of airfield pavement behavior.

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CRedit authorship contribution statement

Lucas Cavalcante de Almeida: Conceptualization, Methodology, Software, Investigation, Formal analysis, Data curation, Writing – original draft; *Mariana de Araújo Leite*: Validation, Data curation, Writing – review & editing; *Francisco Heber Lacerda de Oliveira*: Supervision, Writing – review & editing.

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The authors used generative artificial intelligence tools to assist in the writing and translation of parts of the manuscript. All content generated with the support of these tools was critically reviewed, verified, and edited by the authors, who assume full responsibility for the published material.

Competing interests statement

The authors declare that there is no conflict of interest.

Data availability statement

The data that support the findings of this study are available from the corresponding author (Lucas Cavalcante de Almeida) upon request.

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