Article

Physical and Mathematical Foundations of Airport Operational Safety: Cotopaxi International Airport, Ecuador

Fundamentos Físicos y Matemáticos de la Seguridad Operacional Aeroportuaria: Aeropuerto Internacional Cotopaxi-Ecuador

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Abstract

This article presents a technical and scientific analysis of the application of physical and mathematical principles in the design of a risk management model for Cotopaxi International Airport in Ecuador. The research is based on international standards established by the International Civil Aviation Organization (ICAO). It employed quantitative and qualitative analysis through technical observation of airport infrastructure, probabilistic assessment of operational risks, analysis of atmospheric physical variables, and the application of mathematical matrices— , severity, and probability. From a physical standpoint, it was determined that factors such as

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altitude, atmospheric density, material strength, and coefficients of friction directly affect landing and takeoff operations. Mathematical risk assessment models made it possible to establish critical levels of operational tolerability. It is concluded that the implementation of an Operational Safety Management System (SMS) based on physical and mathematical principles significantly improves the predictive and preventive capabilities regarding airport incidents. The study demonstrates that the integration of quantitative analysis into airport management increases operational efficiency, minimizes risks, and strengthens the sustainability of air transport.

Keywords: operational safety, aeronautical physics, mathematical analysis, risk management, civil aviation.

Resumen

El artículo desarrolla un análisis técnico-científico de aplicación de fundamentos físicos y matemáticos en el diseño de un modelo de gestión de riesgos para el Aeropuerto Internacional Cotopaxi, Ecuador. La investigación se fundamenta en los estándares internacionales establecidos por la Organización de Aviación Civil Internacional (OACI). Empleó análisis cuantitativo y cualitativo mediante observación técnica de infraestructura aeroportuaria, evaluación probabilística de riesgos operacionales, análisis de variables físicas atmosféricas y aplicación de matrices matemáticas de severidad y probabilidad. Desde el punto de vista físico, se identificó que factores como altitud, densidad atmosférica, resistencia de materiales y coeficientes de fricción afectan directamente las operaciones de aterrizaje y despegue. Los modelos matemáticos de evaluación de riesgos permitieron establecer niveles críticos de tolerabilidad operacional. Se concluye que la implementación de un Sistema de Gestión de Seguridad Operacional (SMS) basado en principios físicos y matemáticos mejora significativamente la capacidad predictiva y preventiva de incidentes aeroportuarios. El estudio demuestra que la integración de análisis cuantitativos en la gestión aeroportuaria incrementa la eficiencia operativa, minimiza riesgos y fortalece la sostenibilidad del transporte aéreo.

Palabras clave: seguridad operacional, física aeronáutica, análisis matemático, gestión de riesgos, aviación civil.

Introduction

Civil aviation represents one of the most complex and multifaceted technological infrastructures ever designed by humans, primarily due to the intricate and simultaneous interaction of a myriad of factors encompassing physical elements, mathematical formulations, human behavior, and environmental considerations that collectively influence operational effectiveness. Within this intricate framework, airport operational safety emerges as an essential aspect that depends fundamentally on the precise and accurate application of established scientific principles related to classical mechanics, aerodynamics, strength of materials, fluid dynamics, probabilistic statistical analysis, and the theoretical foundations of risk management (Liu, 2026; Stroeve et al., 2016) .

Cotopaxi International Airport, located in the city of Latacunga in Ecuador’s central highlands, is of strategic importance to national air transport due to its geographic location and operational capacity. However, the gradual increase in military and private air operations has placed new technical demands on the airport infrastructure and operational safety management systems.

From a comprehensive physical perspective, the operational capabilities of airports are significantly influenced and determined by a variety of fundamental variables, including, among others, atmospheric pressure, air density, ambient temperature, wind speed, the coefficient of friction between the runway and aircraft tires, as well as the structural integrity and strength of the pavement surfaces. The elevation of Cotopaxi International Airport, located at an impressive altitude of approximately 2,800 meters above sea level, introduces a unique set of meteorological conditions that ultimately alter the aerodynamic characteristics of various aircraft, affecting crucial operational parameters such as the required takeoff distance, the distance required for effective braking, and the overall performance of aircraft engines in real-world scenarios (Saputra & Soehodho, 2025; Sivakumar, 2022) .

The contemporary operational safety paradigm has undergone a significant transformation, shifting away from historically reactive methodologies that primarily address incidents after they occur, toward sophisticated predictive frameworks that are meticulously grounded in mathematical probability theories and comprehensive severity assessments. The Safety Management Systems (SMS) that the International Civil Aviation Organization (ICAO) has meticulously formulated and established serve to effectively integrate advanced quantitative models that are essential for the precise identification, comprehensive assessment, and strategic mitigation of the various aviation risks that may arise in the aviation sector. These sophisticated systems employ a wide range of statistical tools, intricate probabilistic matrices, and multi-criteria decision-making models that work in concert to accurately estimate and determine what constitutes acceptable levels of risk in the context of aviation operations. Therefore, the evolution of these methodologies represents a fundamental advance in the field of operational safety, as it reflects a deep understanding of risk management that is both proactive and based on empirical anddata .

The integration of artificial intelligence and advanced decision-making frameworks into airport management has significantly revolutionized methodologies for forecasting and mitigating operational risks. Contemporary studies indicate that the application of machine learning techniques, multi-criteria evaluation, and intelligent networks facilitates the improvement of aviation systems' resilience in a context of considerable operational unpredictability. AlMarri, Bahroun, and Hassan (2026) highlight that artificial intelligence applied to airport transportation improves predictive capabilities regarding operational, environmental, and security threats through automated models capable of analyzing large volumes of data in real time. Complementing this approach, Yang (2026) demonstrates that multifactorial predictive models based on *machine learning* enable the identification of risk patterns during ongoing airport operations, reducing disruptions and enhancing operational efficiency.

Similarly, Jahangoshai Rezaee and Yousefi (2018) propose intelligent multi-criteria analysis systems that integrate probabilistic, operational, and human variables to prioritize airport threats and optimize strategic decision-making. Meanwhile, Li et al. (2016) incorporate quantitative mathematical models and complex network theory to assess the vulnerability of aviation systems to localized threats, enabling the design of resilience strategies capable of minimizing operational disruptions and ensuring the continuity of air transport. Taken together, these studies demonstrate that the integration of artificial intelligence, mathematical modeling, and multi-criteria analysis constitutes a fundamental tool for the development of smart, resilient, and sustainable airports.

In mathematical terms, airport risk management can be expressed through probabilistic models of adverse event occurrence. The quantitative assessment of operational risk is given by the following relationship:

$$R = P \times S$$

Where:

- R = Risk
- P = Probability
- S = Severity

This model forms the mathematical basis for modern operational safety systems implemented in the aviation industry.

The objective of this study was to conduct a scientific analysis of airport operational safety by integrating physical and mathematical principles applied to Cotopaxi International Airport. The study aimed to demonstrate that the rigorous application of scientific principles allows for the optimization of airport management, the minimization of operational risks, and the strengthening of air transport sustainability.

The scientific significance of this research lies in the interdisciplinary integration of applied physics, aeronautical engineering, mathematical analysis, and operational management. Similarly, the study provides a quantitative perspective that enhances traditional airport evaluation models.

Theoretical Framework

Operational Safety in Civil Aviation

Aviation operational safety is characterized by the condition in which hazards related to air operations are mitigated and controlled to acceptable thresholds through a continuous process of hazard identification and risk assessment (Heidt et al., 2016; Rey et al., 2021; Yu et al., 2025) .

The International Civil Aviation Organization (ICAO), through Annex 19, requires that each airport establish an operational safety management system (SMS) capable of integrating technical, administrative, and operational protocols designed to reduce incidents and accidents.

From a systemic perspective, operational safety encompasses:

- Human factors
- Physical elements.
- Meteorological variables.
- Airport infrastructure.
- Technological frameworks.
- Mathematical management models.

The interaction between these elements determines the operational stability of the airport system.

Physical Fundamentals Applied to Airport Operations

Aerodynamics and Atmospheric Conditions

Takeoff and landing operations depend directly on aerodynamic principles associated with lift and drag (Bueso & Betancourt, 2017; Skorupski, 2016) .

Lift is expressed by:

$$L = \frac{1}{2}\rho V^2 S C_L$$

- *Where:*
- $L = \text{lift.}$
- $\rho = \text{air density.}$
- $V = \text{relative velocity.}$

- $S = \text{wing area.}$
- $C_L = \text{lift coefficient.}$

Atmospheric density decreases significantly with altitude, affecting the ability to generate lift. Because Cotopaxi International Airport is located in a high-altitude Andean region, aircraft require longer takeoff and landing distances.

2.2.2 Strength of Materials and Airport Pavements

Airport runways are subjected to dynamic loads generated by heavy aircraft. The structural strength of the pavement depends on physical properties such as the modulus of elasticity, compressive strength, and fatigue resistance of materials (Claros et al., 2017; Wang et al., 2026) .

The mechanical stress applied to the pavement can be expressed as:

$$\sigma = \frac{F}{A}$$

Where:

- σ = mechanical stress.
- F = applied force.
- A = contact area.

Cracks identified on the airport's operational apron represent stress concentrators that increase the probability of structural failure.

2.2.3 Friction and Braking Distance

Safety during landing depends on the coefficient of friction between the tires and the runway.

The minimum braking distance is given by:

$$d = \frac{V^2}{2\mu g}$$

Where:

- d = braking distance.
- V = landing speed.
- μ = coefficient of friction.
- g = gravitational acceleration.

The presence of moisture, cracks, or surface deterioration reduces the coefficient of friction and increases the risk of runway excursions.

Mathematical Models for Risk Management

Aviation risk management uses probabilistic models to estimate occurrence and scenarios .

The cumulative probability of failure can be modeled using Poisson distributions:

$$P(X = k) = \frac{\lambda^k e^{-\lambda}}{k!}$$

Where:

- P(X=k) = Probability that k events will occur
- λ = Expected average number of occurrences
- e = Euler’s constant
- k! = Factorial of k

In turn, multi-criteria assessment uses severity and probability matrices to classify operational risks (Sivakumar, 2022; Yu et al., 2025) .

Risk Matrix

Airport risks can be classified according to:

PROBABILITY	LOW SEVERITY	MEDIUM SEVERITY	HIGH SEVERITY
Low	Acceptable risk	Moderate risk	Significant risk
Average	Moderate risk	High risk	Critical risk
High	High risk	Critical risk	Unacceptable risk

This approach allows for the prioritization of technical interventions and the optimization of operational resources.

Applicable International Regulations

ICAO Annex 14 establishes specifications related to:

- Runway geometric design.
- Airport signage.
- Lighting systems.
- Safety strips.
- RESA areas.
- Taxiways.
- Airport obstacles.

For its part, Annex 19 regulates Operational Safety Management Systems (SMS), promoting preventive and predictive models.

Materials and methods

The research was conducted using a mixed-methods approach with a quantitative focus, integrating physical-mathematical analyses and a qualitative assessment of operational conditions.

The study adopted a non-experimental design of a descriptive, correlational, and applied nature. The methodology was structured into four fundamental phases:

- Technical diagnosis of infrastructure.
- Physical and operational assessment.
- Mathematical risk modeling.
- Design of mitigation strategies.

The data were collected from a group of 52 employees from various operational and administrative departments at Cotopaxi International Airport.

A census sampling method was used due to the small size of the population.

- Data Collection Techniques and Instruments
- The techniques used were:
- Direct technical observation.
- Structured surveys.
- Semi-structured interviews.
- Airport inspection forms.
- Document analysis.

The instruments used included:

- Likert-type questionnaires.
- Observation guides.
- Risk assessment matrices.
- Operational frequency statistical models.
- Mathematical Modeling
- The quantitative analysis included:
- Descriptive statistics.
- Probabilistic analysis.
- Multi-criteria matrices.

- Severity assessment.
- Calculation of risk indices.

The overall operational index was estimated using the following formula:

$$IOR = \sum_{i=1}^{n} P_i S_i$$

Where:

IOR = Operational Risk Index.

P_i = associated probability.

S_i = event severity.

n = total number of events evaluated

Physical-Operational Analysis

The physical-operational study considered:

Effective runway length.

Pavement conditions.

Coefficient of friction.

Atmospheric density.

Ambient temperature.

Slope gradients.

Operational lighting.

Structural strength.

Critical meteorological factors such as crosswind, relative humidity, and horizontal visibility were also evaluated.

Scientific Validation

Based on the criteria of Rios Insua et al. (2018) , methodological reliability was validated through:

- Triangulation of information.
- ICAO regulatory comparison.
- Statistical consistency analysis.
- Technical verification of observations.

Results

The technical analysis revealed significant deterioration in various operational areas of the airport.

Runway Condition

The following were identified:

- Longitudinal cracks.
- Surface wear.
- Reduced coefficient of friction.

Presence of structural deformations.

From a physical standpoint, surface irregularities disrupt the uniform distribution of loads and increase the risk of hydroplaning.

The observed operational coefficient of friction was below the values recommended by ICAO under wet conditions.

Atmospheric and Aerodynamic Assessment

The airport’s altitude results in reduced atmospheric density, affecting:

- Engine performance.
- Aerodynamic lift.
- Takeoff run distance.
- Braking capacity.

Atmospheric density can be approximated using:

$$\rho = \frac{P}{RT}$$

Where:

ρ = air density

P = atmospheric pressure.

R = specific constant of air.

T = absolute temperature.

A decrease in density reduces the aerodynamic efficiency of aircraft.

Operational Risk Assessment

Statistical analysis identified the following major risks:

Risk	Probability	Severity	Level
Runway Excursion	High	High	Critical
Unauthorized entry	Medium	High	High
Lighting failure	Medium	Medium	Moderate
Ground collision	Low	High	Moderate
Structural pavement failure	High	Medium	High

The results show a predominance of risks related to infrastructure and perimeter control.

Survey and Interview Results

The results indicated:

- 78% of staff consider current operational security measures to be insufficient.
- 82% recognize the need for ongoing technical training.
- 69% identify critical deterioration in infrastructure.
- 91% believe it is necessary to implement a comprehensive SMS.

Physical Assessment of Lighting and Signage

Inconsistencies were detected in:

- Light intensity.
- Sign reflectivity.
- Lighting uniformity.
- Markings on traffic lanes.

From a physical perspective, reduced light intensity affects nighttime visual perception and slows drivers' reaction times.

Predictive Risk Modeling

The probabilistic simulation showed that implementing corrective measures can reduce potentially hazardous events by up to 63%.

The predictive model revealed a positive correlation between:

- Structural condition of pavements.
- Coefficient of friction.
- Probability of lane departure.

Discussion

The results obtained demonstrate that airport operational safety cannot be limited solely to administrative procedures but must be based on quantifiable scientific principles.

From a physical standpoint, the altitude of Cotopaxi International Airport represents a critical variable that significantly affects aircraft performance. Reduced atmospheric density decreases lift and necessitates higher operating speeds, thereby increasing the structural demands on the runway. The deterioration observed in the pavement increases localized stresses and reduces the capacity to dissipate dynamic loads. This phenomenon is consistent with international research on structural fatigue at high-altitude airfields.

Mathematically, the probabilistic models used demonstrated a high predictive capacity for identifying critical operational scenarios. The use of risk matrices made it possible to prioritize vulnerabilities and optimize mitigation strategies.

The research shows that modern airport systems must incorporate quantitative analysis tools capable of integrating physical, human, and operational variables. The findings are consistent with previous research conducted at airports in Ecuador, Honduras, and Colombia, where the implementation of SMS systems based on technical analysis significantly reduced the occurrence of incidents.

Furthermore, the research confirms that airport infrastructure constitutes a dynamic system continuously subjected to variable physical loads. Therefore, operational safety management must include continuous monitoring using mathematical models of structural behavior.

The study also highlights the importance of the human factor. The lack of specialized technical training increases the likelihood of operational errors. Based on human reliability theory, human errors can be modeled probabilistically and reduced through continuous training.

Finally, the research demonstrates that interdisciplinary integration among physics, mathematics, and aeronautical engineering significantly strengthens airport management models.

Implementation of an Integrated SMS System

We propose implementing an Operational Safety Management System consisting of:

- Continuous structural monitoring.
- Probabilistic risk assessment.
- Digital tracking systems.
- Specialized technical training.
- Periodic physical inspection.

Physical Rehabilitation of Pavements

Priority actions include:

- Repair of structural cracks.
- Improvement of drainage systems.
- Increasing the coefficient of friction.
- Reinforcing road surfaces.
- Optimizing lighting systems

Recommended:

- Replacement of damaged light fixtures.
- Implementation of LED lighting.
- Photometric calibration.
- Increase reflectivity.

Strengthening Perimeter Security

Proposed:

- Renovation of perimeter fences.
- Smart sensors.
- Video surveillance.
- Automated access control.

Integration of predictive mathematical models

- Operational management must incorporate:
- Predictive algorithms.
- Continuous statistical analysis.
- Operational simulation.
- Dynamic risk assessment.

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