Model for estimating the percentage of deterioration of installed anti-personnel mines (APMs)

Modelo para estimar el porcentaje de deterioro de las minas antipersonal (MAP) instaladas

Modelo para estimar a porcentagem de deterioração de minas antipessoais (APMs) instaladas

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Received: January 20th, 2025
Accepted: March 25th, 2025
Available: May 5th, 2025

How to cite this article:
J.D. Pedraza-H, C.E Montenegro-Marin, P.A. Gaona García, and J.J. Bocanegra García, "Model for estimating the percentage of deterioration of installed anti-personnel mines (APMs)", *Revista Ingeniería Solidaria,* vol. 21, no. 2, 2025.
doi: https://doi.org/10.16925/2357-6014.2025.02.11

Research article. https://doi.org/10.16925/2357-6014.2025.02.11

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Abstract

Introduction: This article presents research on the estimation of deterioration in deployed anti-personnel mines (APMs), developed in collaboration with the AICMA Group, with Argelia (Antioquia, Colombia) as a priority case study, and the Universidad Distrital in 2024 and 2025 years.

Problem: The widespread presence of APMs from the non-international armed conflict in Colombia poses a critical threat to communities and demining personnel. A key operational risk stems from the lack of accurate information regarding the physical degradation and functional status of buried devices, hindering safe and efficient humanitarian demining.

Objective: The study aims to develop a stochastic predictive model, based on artificial intelligence, to estimate the percentage of physical deterioration of installed APMs by integrating environmental variables, constituent materials, and exposure time.

Methodology: A neural network model was implemented in Python, processing key databases including mine records (AICMA), historical climatological data (IDEAM), material degradation coefficients, and soil erosion rates to capture non-linear degradation dynamics.

Results: The result is a model capable of estimating a quantifiable deterioration percentage for APMs. This output provides demining teams with a safety indicator to prioritize suspected hazardous areas with likely inactive devices and to select safer extraction methods, based on the estimated risk level.

Conclusion: The model represents a strategic technological advance for humanitarian demining in Colombia, offering an objective tool for operational decision-making that can optimize resource allocation, reduce personnel risks, and shorten clearance timelines in contaminated areas.

Keywords: Model, APM, The Halo Trust, Deterioration Factor, Non-International Conflict.

Resumen

Introducción: Este artículo presenta una investigación sobre la estimación del deterioro de las minas antipersonal (MAP) instaladas, desarrollada en colaboración con el Grupo AICMA, con Argelia (Antioquia, Colombia) como caso de estudio prioritario, y la Universidad Distrital en los años 2024 y 2025.

Problema: La presencia generalizada de MAP procedentes del conflicto armado no internacional en Colombia supone una amenaza crítica para las comunidades y el personal de desminado. Un riesgo operativo clave se deriva de la falta de información precisa sobre la degradación física y el estado funcional de los dispositivos enterrados, lo que dificulta un desminado humanitario seguro y eficiente.

Objetivo: El estudio tiene como objetivo desarrollar un modelo predictivo estocástico, basado en la inteligencia artificial, para estimar el porcentaje de deterioro físico de los APM instalados mediante la integración de variables ambientales, materiales constituyentes y tiempo de exposición.

Metodología: Se implementó un modelo de red neuronal en Python, procesando bases de datos clave que incluyen registros de minas (AICMA), datos climatológicos históricos (IDEAM), coeficientes de degradación de materiales y tasas de erosión del suelo para capturar la dinámica de degradación no lineal.

Resultados: El resultado es un modelo capaz de estimar un porcentaje cuantificable de deterioro de los APM. Este resultado proporciona a los equipos de desminado un indicador de seguridad para priorizar las zonas sospechosas de peligro con dispositivos probablemente inactivos y seleccionar métodos de extracción más seguros, basándose en el nivel de riesgo estimado.

Conclusión: El modelo representa un avance tecnológico estratégico para el desminado humanitario en Colombia, ya que ofrece una herramienta objetiva para la toma de decisiones operativas que puede optimizar la asignación de recursos, reducir los riesgos para el personal y acortar los plazos de limpieza en las zonas contaminadas.

Palabras clave: Modelo, APM, The Halo Trust, Factor de deterioro, Conflicto no internacional.

Resumo

Introdução: Este artigo apresenta uma pesquisa sobre a estimativa da deterioração de minas antipessoais (MAPs) implantadas, desenvolvida em colaboração com o Grupo AICMA, tendo Argelia (Antioquia, Colômbia) como estudo de caso prioritário e a Universidade Distrital em 2024 e 2025.

Problema: A presença generalizada de MAPs originárias do conflito armado não internacional na Colômbia representa uma ameaça crítica para as comunidades e para o pessoal de desminagem. Um dos principais riscos operacionais decorre da falta de informações precisas sobre a degradação física e o estado funcional dos dispositivos enterrados, o que dificulta a desminagem humanitária segura e eficiente.

Objetivo: O estudo visa desenvolver um modelo preditivo estocástico, baseado em inteligência artificial, para estimar a porcentagem de deterioração física de MAPs implantadas, integrando variáveis ambientais, materiais constituintes e tempo de exposição.

Metodologia: Um modelo de rede neural foi implementado em Python, processando bancos de dados importantes, incluindo registros de minas (AICMA), dados climatológicos históricos (IDEAM), coeficientes de degradação de materiais e taxas de erosão do solo para capturar a dinâmica não linear da degradação.

Resultados: O modelo é capaz de estimar uma porcentagem quantificável de deterioração de munições não detonadas (MND). Isso fornece às equipes de desminagem um indicador de segurança para priorizar áreas suspeitas de conter dispositivos potencialmente inativos e selecionar métodos de extração mais seguros com base no nível de risco estimado.

Conclusão: O modelo representa um avanço tecnológico estratégico para a desminagem humanitária na Colômbia, pois oferece uma ferramenta objetiva para a tomada de decisões operacionais que pode otimizar a alocação de recursos, reduzir os riscos para o pessoal e encurtar o tempo de limpeza em áreas contaminadas.

Palavras-chave: Modelo, MND, The Halo Trust, Fator de Deterioração, Conflito não internacional.

1. INTRODUCTION

The internal armed conflict in Colombia has left a deep mark on its territories, one of the most dangerous manifestations being the indiscriminate presence of anti-personnel mines (APMs) laid by illegal armed actors. These mines continue to pose a latent threat to non-combatant communities and constitute a significant operational risk for humanitarian demining teams [1] Despite the regulatory and operational advances established by the [2] current removal methods still present high risks due to the lack of accurate information on the physical condition and integrity of explosive devices.

The problem is exacerbated by the fact that APMs have been used as a tool for territorial control, according to [3] affecting approximately 110 million explosives worldwide, with 60 countries affected and more than 26,000 victims annually worldwide. In

Colombia, this situation is particularly critical, with military victims of PFMs ranking first in terms of explosive device casualties [4], with a significant impact documented by [5].

The need to estimate the deterioration of installed mines arises from the urgent demand from humanitarian demining groups, particularly the AICMA Group (Acción Integral Contra Minas Antipersonal), for tools to determine whether an EIM retains its detonation capacity or has lost functionality due to accumulated deterioration. According to the report by the Colombian Ministry of National Defense [6], this information is essential for establishing the most appropriate demining method (manual or mechanized) and for prioritizing areas of intervention, optimizing resources, and reducing operation times in the context of national humanitarian demining.

This article presents the development of a stochastic mathematical model that integrates artificial intelligence, following the principles established by Bishop [7] and Goodfellow et al. [8] to predict the percentage of physical deterioration of installed anti-personnel mines, considering environmental variables, constituent materials, and exposure time. The model represents a significant technological advance for humanitarian demining operations in Colombia, providing an objective tool for operational decision-making and contributing to risk reduction for specialized personnel.

2. THEORETICAL AND REGULATORY FRAMEWORK

2.1 International Standards for Humanitarian Demining

Humanitarian demining operations at the international level are governed by the International Mine Action Standards (IMAS), established by the Geneva International Center for Humanitarian Demining which constitute the mandatory regulatory reference for all actors involved in Comprehensive Action against Antipersonnel Mines. These standards establish technical, operational, and management procedures that ensure the safe, efficient, and standardized development of demining activities, as documented in IMAS 10.30 and 10.50 [9] [10] [11].

In the Colombian context, IMAS have been adopted through the Colombian Technical Standards for Comprehensive Action against Antipersonnel Mines (NTC-AICMA), which are mandatory for all operators accredited by the Office of the High Commissioner for Peace [12], This regulatory adaptation ensures harmonization between international standards and the country's operational reality, as established in national technical documentation. There are also works such as that of [13], in which other areas of the military forces carry out a diagnostic investigation called, sustainable military science and technology (ST) in Colombian Air Force (FAC).

2.2 Regulations Applicable to the Proposed Model

The development of the model is aligned with the following IMAS standards:

- IMAS 05.10 - Information Management: Establishes that all operational decisions must be based on robust, georeferenced information systems. [14]
- IMAS 07.11 - Risk Assessment: Defines procedures for identifying, analyzing, and mitigating risks associated with the presence of mines. [15]
- IMAS 09.10, 09.11, and 09.12 - Demining Techniques: Describes specific methods according to terrain, type of device, and environmental conditions. [16] [17] [18]

2.3 Theoretical Foundations of the Model

The proposed model is based on three main theoretical frameworks:

1. Soil erosion model: Used to assess the influence of terrain type, runoff, and progressive exposure of mines, following the principles established in the soil mechanics literature [19].
2. Aeronautical material wear model: Adapted to simulate the deterioration of materials exposed to extreme conditions of humidity, pressure, and temperature, based on the studies by [20] on the wear of metallic materials in tropical environments.
3. Applied artificial intelligence: Implementation of neural networks to model non-linearities in degradation and classify the operational status of APMs, following the approaches developed by [21].

3. METODOLOGY

3.1 SYSTEM ANALYSIS AND DESIGN

The proposed system is designed as a tool to support the humanitarian demining process in Colombia by estimating the percentage of deterioration of anti-personnel mines (APMs) installed in affected areas. Figure 1 shows the number of devices detected by department, and Figure 2 shows their geographical distribution in Colombia, The data has been taken from [22].

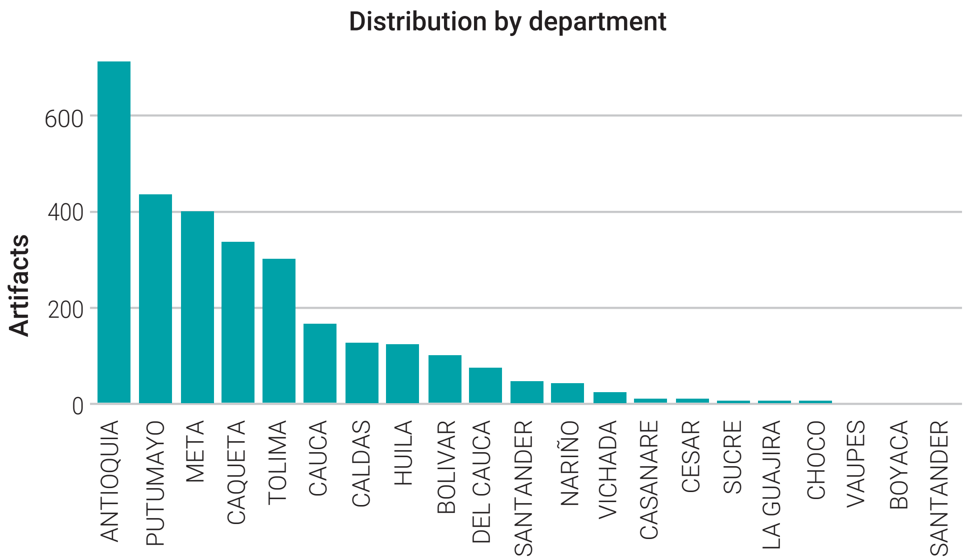

Figure 1. Number of artifacts per department.

The analysis of the problem is based on three main axes: the materials that make up the APM, the time elapsed since its installation, and the climatic conditions of the environment in which it is located. The integration of these factors allows the accumulated deterioration to be modeled using a stochastic approach based on a dynamic logistic model.

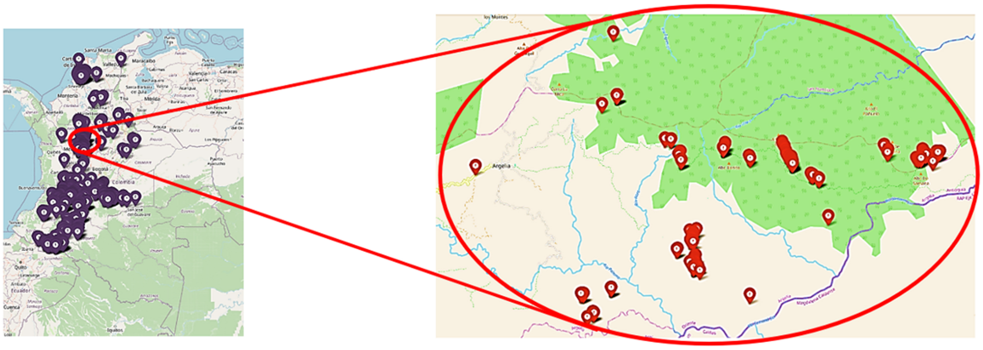

Figure 2. Distribution APM of artifacts in Colombian territory. [23]

A. System Inputs

The system is fed by three main types of data:

Structural characteristics of the APM: The materials used in its construction are considered, as they influence its resistance to deterioration due to environmental factors. This information is provided by the AICMA Group, based on its technical inventory of artifacts.

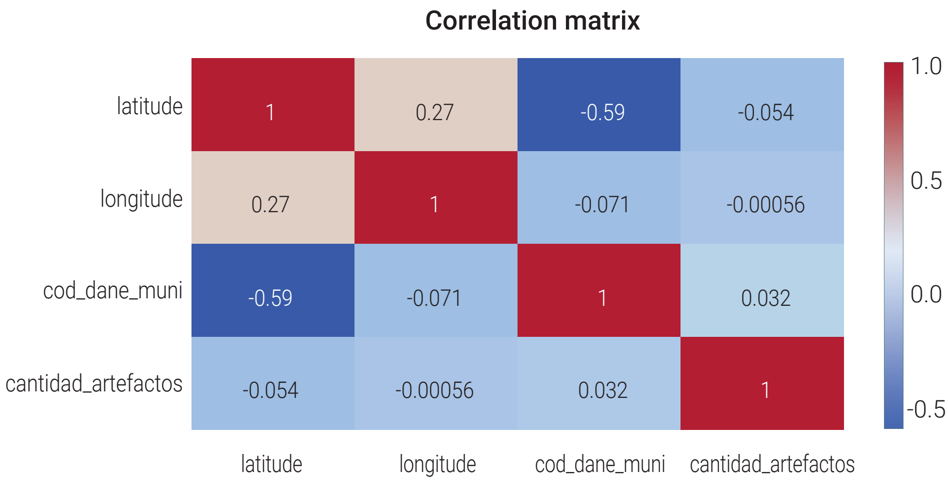

Figure 3. Correlation matrix of variables in the artifacts.

Historical weather conditions: Data on relative humidity, temperature, precipitation, atmospheric pressure, air salinity, and environmental pollution levels are collected. This information is obtained from satellite records and weather stations, such as those of the IDEAM.

Installation time: This refers to the period that the APM has remained in the field since its installation. This variable allows the cumulative behavior of deterioration to be modeled.

The variables are analyzed using a correlation matrix (Figure 3) and their distribution by type of artifact (Figure 4).

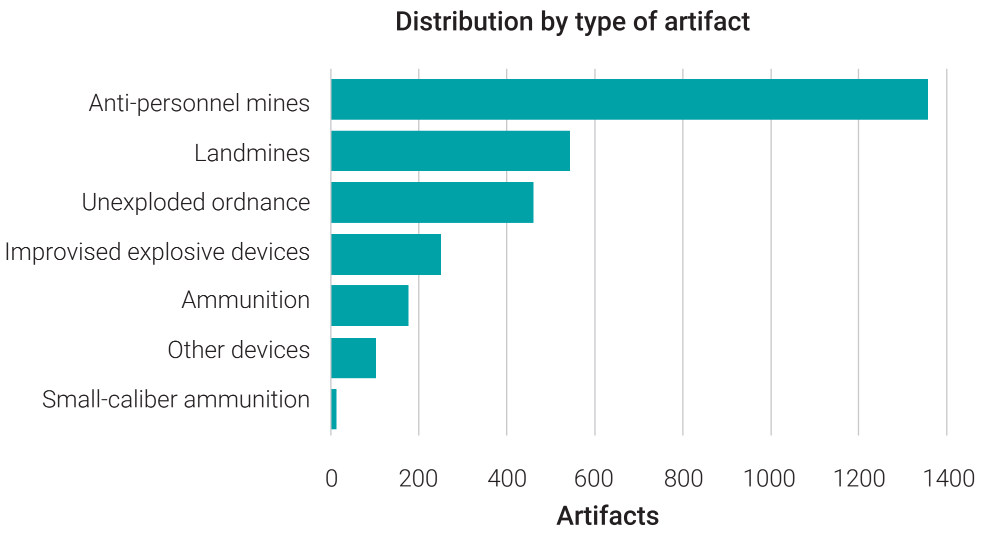

Figure 4. Distribution by type of artifact.

B. Model Processing

The logical design of the system is based on an exponential mathematical model, which represents the cumulative degradation of APM over time. The general formula used is:

$$D(t) = 1 - e^{-\lambda t}$$

Where:

D(t) is the percentage of cumulative deterioration at time

λ is the degradation rate, determined by material, climatic, and installation factors.

The rate λ is defined as a function composed of environmental and structural variables, including soil erosion (E), relative humidity (H), temperature (T), precipitation (R), material resistance index (M), soil stability (S), and installation quality (I):

$$\lambda = f(E, H, T, R, M^{-1}, S^{-1}, I^{-1})$$

C. System Output

The system delivers a single value as output: the estimated percentage of deterioration of a APM at a specific place and time. This value is essential for establishing the level of risk and defining the safest and most efficient removal method.

D. Model Validation

The model will be validated by comparing its predictions with results obtained in controlled laboratory tests. These tests simulate the actual environmental conditions to which mines are exposed, allowing the model coefficients to be adjusted and calibrated.

4. RESULTS

4.1 DESIGN ARCHITECTURE OF THE PROPOSED SYSTEM

The architecture of the proposed system is structured around a model for estimating the percentage of deterioration of anti-personnel mines (APMs), designed to integrate data from satellite sources and specialized technical databases. Its objective is to provide an accurate prediction of the state of preservation of these explosive devices, considering their location, constituent materials, and environmental conditions. Figure 5 shows the conceptual model for calculating the deterioration of an APM.

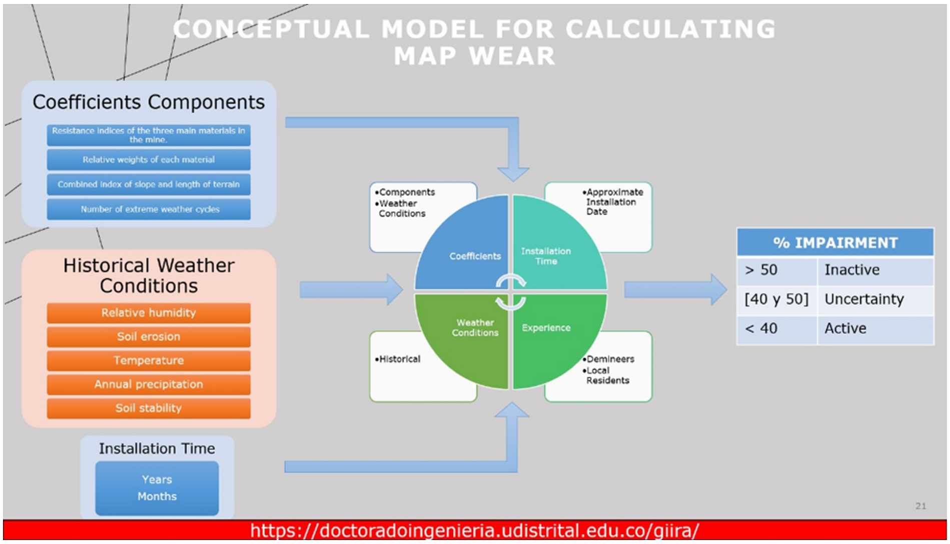

Figure 5. Conceptual model for calculating wear in a APM mine.

A. System Components

The architecture is organized into four main functional blocks:

Satellite Data Source: Provides historical climate information for the target area: relative humidity, average temperature, precipitation, atmospheric pressure, among others. These variables are critical for assessing the cumulative environmental impact on mine materials.

AICMA Group Technical Data: Includes mine type, manufacturing materials, activation mechanisms, installation depth, and estimated date of placement. This information feeds into the model's resistance coefficients [24].

Artificial Intelligence (AI) Processor: Core of the system that implements the stochastic mathematical model, based on a dynamic logistic function. By processing normalized inputs, it estimates the level of accumulated deterioration $D(t)$ of each mine.

User Interface/API: Allows interaction with technical operators or external applications, displaying the estimated percentage of deterioration and offering demining recommendations. It also allows system feedback for future model adjustments.

5. DISCUSSION

The scope of this project is the design, initial implementation, and validation of a mathematical and computational model aimed at estimating the percentage of deterioration of anti-personnel mines (APMs) installed in Colombian territory, based on environmental, material, and temporal variables.

This model is designed to operate at the municipal level, with an initial testing phase focused on areas prioritized by the AICMA Group, such as the municipality of Argelia (Antioquia), where critical environmental conditions and a high concentration of explosive devices have been identified. The variables included in this pilot phase are obtained from IDEAM meteorological records, as well as historical databases of explosive devices from the Office of the High Commissioner for Peace (OACP) [25].

The system considers the following inputs:

- Type and manufacturing materials of APMs.
- Installation information (date and technique).
- Historical climatological parameters: humidity, temperature, precipitation, pressure, salinity, and environmental pollution.
- Soil conditions (erosion, stability, composition).

And as output:

A single estimated deterioration value for each APM, expressed as a cumulative percentage, useful for prioritizing removal actions or confirming functional obsolescence, as shown in Table 1.

Table 1. Percentage of deterioration of a APM mine.

% IMPAIRMENT	
> 50	Inactive
[40 y 50]	Uncertainty
< 40	Active

Limitations of Scope

The model is not designed for direct mine detection and does not replace traditional methods of physical exploration or removal.

The accuracy of the model depends on the quality and spatial/temporal resolution of the available climatological and technical data.

Empirical validation in the field is limited, at this stage, to laboratory tests with materials subjected to controlled environmental simulations.

Expected Scope in Later Phases

It is expected that, in future phases, the model can be scaled up to the national level, integrated into geographic information systems (GIS), and linked to the operational platforms of state entities or international humanitarian demining actors.

6. RESEARCH NEEDS

The consolidation of an operational predictive model for estimating the deterioration of anti-personnel mines (APMs) requires a set of technical, human, and logistical resources that allow for the experimental validation of theoretical assumptions and the proper calibration of the parameters of the proposed stochastic model.

A. Infrastructure for Experimental Validation

One of the main requirements is the construction of a controlled test bench that simulates real environmental conditions using accelerated deterioration chambers. The manufacture and implementation of at least nine (9) climate chambers is proposed, capable of reproducing critical variables such as:

- Adjustable ambient temperature.
- UV radiation (simulation of sun exposure).
- Controlled relative humidity.
- Thermal cycles and simulated precipitation.

These chambers will be used to test prototypes (dummies) of mines manufactured with the typical materials used in the field. The purpose is to accurately and controllably measure degradation due to erosion, corrosion, fatigue, and other cumulative effects on these materials over cycles equivalent to months or years of actual exposure.

B. Computing and Monitoring Resources

A physical workspace with the following minimum conditions is required:

- Continuous electrical power (24/7) to maintain stable operation of the chambers and sensors.
- High-availability internet connectivity, necessary for remote monitoring and daily download of sensor logs.
- Local workstation or server with sufficient storage capacity for the data generated (sensors, temperature and humidity records, etc.) and statistical/AI processing.

C. Participation of Demining Experts

Direct collaboration with experts from the AICMA Group and deminers with operational experience in the field is crucial. Their knowledge will be essential for:

- Properly categorizing the types of mines and representative materials in the design of the dummies.
- Labeling events and patterns useful for training the artificial intelligence model.
- Validate the results estimated by the system against real field scenarios.

D. Analytical Tools and Software

Data processing will require the use of statistical analysis, predictive modeling, and machine learning tools. The use of environments such as the following is contemplated:

- Python, with libraries such as pandas, scikit-learn, and tensorflow for data analysis and model training.
- Relational or NoSQL databases to store measurements.
- Visualization with tools such as Power BI or web platforms for the visual delivery of results.

7. CONCLUSIONS

This work presents an innovative approach with high social impact through the development of a stochastic model based on artificial intelligence to estimate the deterioration of anti-personnel mines (APMs) in Colombia. By integrating variables such as installation time, historical weather conditions, and mine manufacturing materials, a system capable of calculating the cumulative percentage of deterioration of these devices is proposed.

The system's architecture is designed to incorporate data from multiple sources—including satellite records and technical databases from the AICMA Group—and process them using a dynamic logistic mathematical model, whose output allows inferring whether an APM is potentially active or obsolete. This information is crucial for demining teams, as it provides an objective tool for prioritizing areas, choosing extraction methods, and optimizing human and technical resources.

However, validation of the model is an essential component that is still under development. To this end, the need to build an experimental test bed with accelerated deterioration chambers has been identified, as well as the design of dummies representative of real mines. In addition, the active participation of expert deminers is essential to ensure the empirical validity of the model and its practical usefulness in the field.

Finally, this project represents a strategic contribution to humanitarian demining operations in Colombia by incorporating predictive modeling and machine learning tools that improve both operational effectiveness and decision-making efficiency. Its implementation will optimize the prioritization of suspected areas, reduce risks for personnel deployed in the field, and shorten cleanup times in contaminated areas. In this way, institutional capacities are strengthened and progress is made in a safer and more cost-effective manner, reducing risks.

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