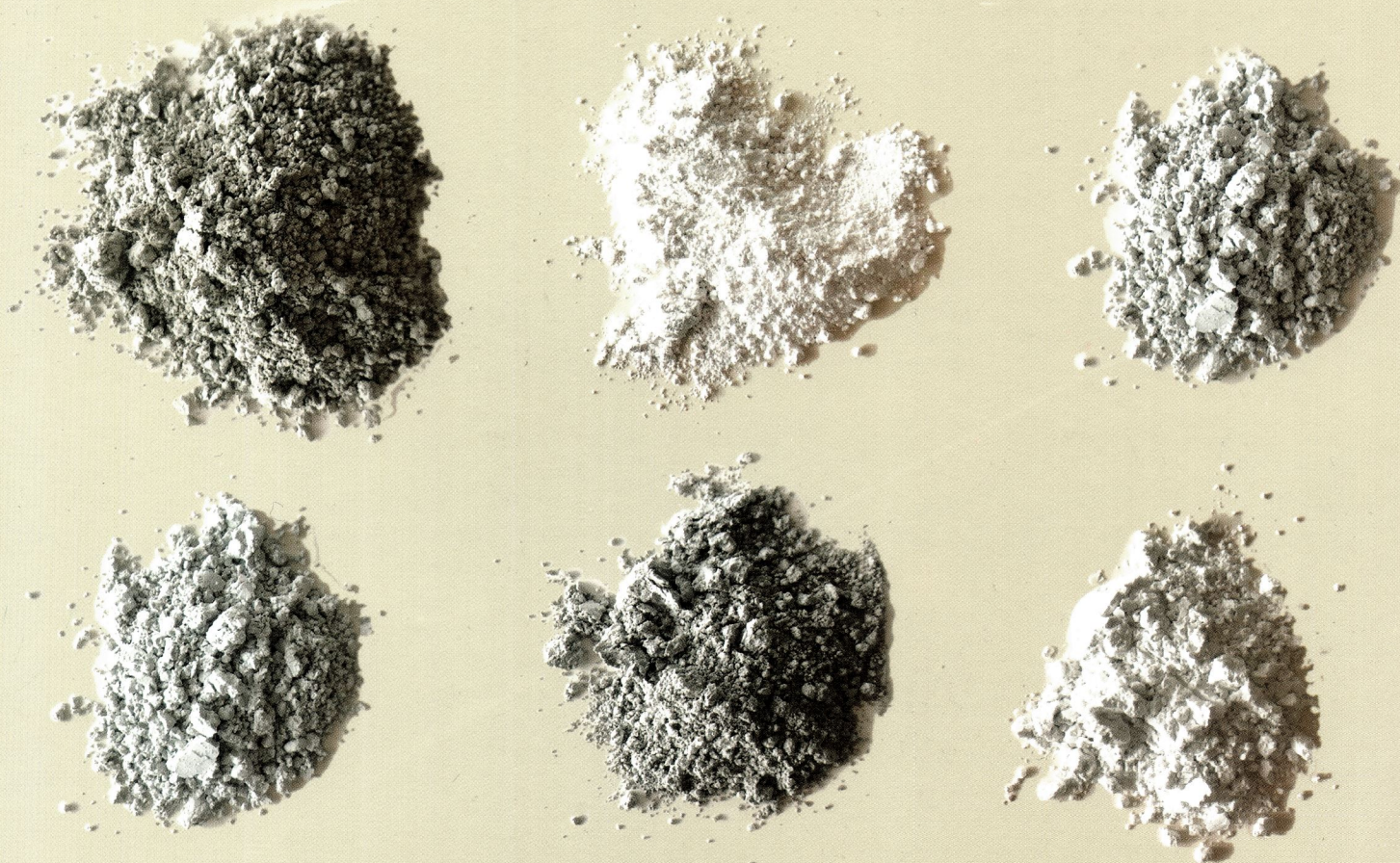


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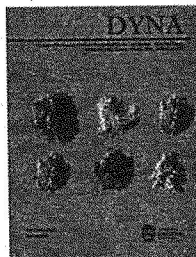
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Our Cover

Predicting the flowability of UHPC and identifying its significant influencing factors using an accurate ANN model

Authors

Joaquín Abellán-García, M. Iqbal Khan, Yassir M. Abbas & Francisco Pellicer Martínez



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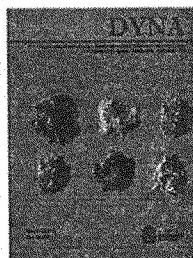
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Nuestra carátula

Predicción de la trabajabilidad del UHPC e identificación de sus factores de influencia significativos utilizando un modelo ANN preciso

Autores

Joaquín Abellán-García, M. Iqbal Khan, Yassir M. Abbas & Francisco Pellicer Martínez



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A view of agile organizations: bibliometric analysis

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Abstract

Agile organizations represent a transformation in the search for convergence in relation to the dynamic challenges of the environment, market transformations and the growing complexity of social systems. The objective of this study was to develop a descriptive bibliometric study to identify research trends on agile organizations. Web of Science and Scopus databases were used to retrieve scientific production. Bibliometric indicators of production, collaboration, visibility, and impact were analyzed. The analysis of 150 documents, with the total participation of 340 authors, showed a growth rate of 4% per year in the time interval from 1995 to the beginning of 2023. Dominant trends were identified with respect to the research topic, the first referring to the human factor, organizational innovation and organization and management, and the second, agile methods, agile transformations, agile software development and agile organizations.

Keywords: agile organizations; agile methods; agile transformations, bibliometrics.

Una mirada a las organizaciones ágiles: análisis bibliométrico

Resumen

Las organizaciones ágiles representan una transformación en la búsqueda de convergencia en relación con los desafíos dinámicos del entorno, las transformaciones del mercado y la complejidad creciente de los sistemas sociales. El objetivo de este estudio fue desarrollar un estudio bibliométrico descriptivo para identificar las tendencias de investigación sobre organizaciones ágiles. Se utilizaron las bases de datos Web of Science y Scopus para la recuperación de la producción científica. Se analizaron indicadores bibliométricos de producción, colaboración, visibilidad e impacto. El análisis a partir de 150 documentos, con la participación total de 340 autores, evidenció un crecimiento a una tasa del 4% anual en el intervalo de tiempo desde 1995 hasta inicios de 2023. Se identificaron tendencias dominantes respecto al tema de investigación, la primera referida al factor humano, innovación organizacional y organización y gestión, y la segunda, reúne métodos ágiles, transformaciones ágiles, desarrollo ágil de software y organizaciones ágiles.

Palabras clave: organizaciones ágiles; métodos ágiles; transformaciones ágiles; bibliometría.

1 Introduction

In the context of digitalization, agility and flexibility, structural changes in the way organizations proceed are taking shape [1]. Securing a robust competitive stance and attaining superior business performance poses a formidable task for companies, particularly amidst the uncertainties of a dynamic business landscape [2]. In that sense, the concept of Agile Organization acquires special relevance with respect to the new requirements when generating competitive advantages, innovation spaces and value co-creation. The changing environment is a source of threats and opportunities; however, agile companies extract maximum performance from emerging opportunities [3]. Consequently, for [4] the idea of an agile

organization is a key element in management principles, intending to adapt production methods to an ever-evolving environment. According to [5], investigating agile transformation encompasses examining the context of a straightforward business model and a compact team, along with considering assumptions related to enhancing quality and reducing costs. For [6] agility is defined as a company's capacity to respond swiftly and adjust rapidly to new environmental conditions, addressing ongoing and unpredictable changes within competitive markets. Likewise, [7] define agility as the capability to sustain profitable operations in a competitive environment marked by continuously and unpredictably changing customer preferences. Thus, agile development teams acquire knowledge about customer priorities, while

representatives from the customer side gain understanding regarding the feasibility and costs associated with implementing their requirements [8]. Consequently, changes in the organizational environment require agility to overcome new challenges amid technological transformations, competitive scenarios, and the increasing complexity of social systems as open systems in dynamic equilibrium. According to [9], the general characteristics of agility with the potential to be applied to all aspects of the company are the following: “flexibility, responsiveness, speed, change culture, integration and low complexity, mobilization of core competencies and high-quality customized products”. However, for [3] organizational agility is in a co-dependent relationship from the knowledge, freely usable information, experience, and creativity of its members. A specific challenge when implementing agile methodologies in larger-scale projects is the effective coordination between teams. Scaling agility to encompass broader initiatives introduces additional considerations and hurdles in coordinating with other organizational units, including Human Resources, Marketing, Sales, and Product Management [10]. In that vein, organizations in line with Agile Transformation require higher levels of innovation in a scalable way to achieve significant and functional changes towards dynamic states of adaptability amidst elements of unpredictability and uncertainty in their customer relationships and changes in the market, customer expectations and the environment. In this order of ideas, agile frameworks are increasingly incorporated for the transformation of organizations at all levels, to navigate through intricacy and unpredictability [11]. Hence, the adoption of agile software development approaches in extensive organizations is becoming more prevalent. Nonetheless, dealing with multiple teams and diverse products concurrently necessitates a heightened level of coordination and communication effort, diverging from the single-team environments for which agile methodologies were initially conceived [12].

This paper developed a descriptive bibliometric study of scientific research on agile organizations by analyzing the academic production based on bibliometric indicators. The research question was posed in the following terms: what are the main trends in the scientific production on agile organizations? Regarding the main results of the study, the volume of scientific production corresponds to 131 sources with the participation of 340 authors from various institutions and an annual growth rate of 4%. Regarding citation per article, the highest average of total citations per article is 85.2 with 5 articles in 2001 and the lowest is 0.08 with 12 articles in 2022. Finally, the keyword analysis has been developed in terms of co-occurrence, the most frequent descriptors are "agile organizations", "decision making", "organization and management" and "agile manufacturing systems". In terms of conclusions, agile methods imply a relevant lesson for organizational management, to think about organizational innovation and the proper management of teams or people in organizations.

2 Materials and methods

The present research is based on the Guidelines for Bibliometric Methods in Management and Organization [13]

and the Integrated Methodology for Bibliometric Analysis [14]. In this sense, data obtained from the Scopus and Web of Science databases were integrated to perform the bibliometric analysis, in the search for an overview of the scientific production around agile organizations.

2.1 Data collection

Table 1 presents the search terms applied in Scopus and Web of Science to obtain the final data set for the analysis. The cutoff date for the search and data extraction was February 19, 2023. The R package used to integrate the Scopus and Web of Science data is called "tosr" [15]. Once the integration process has been carried out in R, duplicate documents are eliminated (30) and the final data set is obtained (150).

3 Results

The presentation of the results was performed by means of the R bibliometric research tool called Bibliometrix and the web application Biblioshiny [16]. The general information of the final dataset used for the bibliometric analysis is presented in Table 2. The papers were collected from 131 sources published between 1995 and 2023 (February 2023). The total number of authors is 340 and the annual growth rate 4% according to statistics provided by Biblioshiny. A total of 150 documents were used for the analysis.

Table 1.

Databases consulted, search terms and results.

Database	Search terms	Results
Scopus	TITLE-ABS-KEY ({agile organization})	144
Web of Science	TS= ("agile organization")	36
Total results		180
Duplicate elimination		30
Final data set		150

Source: Own elaboration.

Table 2.

General information on the final data set.

Description	Results
Main data information	
Time interval	1995:2023
Sources	131
Documents	150
Annual growth rate %	4
Average document age	8,85
Average citations per document	12,35
References	5070
Document content	
Keywords Plus (ID)	694
Author's keywords (DE)	362
Authors	
Authors	340
Authors of single-authored documents	43
Authors' collaboration	
Single author documents	47
Co-authors per document	2,43
International co-authorships %	0,6667

Source: Own elaboration.

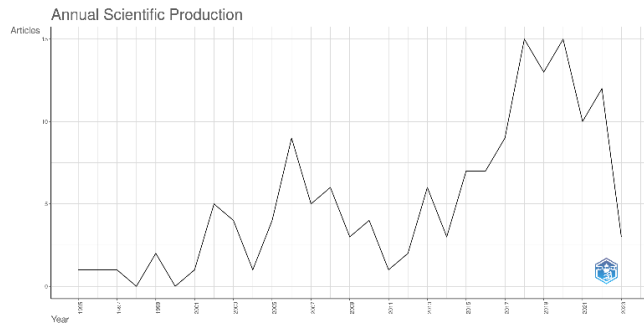


Figure 1. Annual scientific production.
Source: Own elaboration.

3.1 Scientific production

Fig. 1 presents the scientific production of documents by year. The volume of production is recorded in 131 sources with the participation of 340 authors from various institutions (170 affiliations). Regarding author collaboration, of the total of 150 papers, 47 are single-authored papers and international co-authorships are 0.6667%. Research on agile organizations at the general level is on the rise with a backward trend from 2006 to 2011, starting in the year 1995 with one paper and reaching its highest points in 2018 and 2020 with 15 papers each year. It should be noted that the year 2023 (January 2023) constitutes the data collection period and the number of articles is 3.

3.2 Citation

The average total citations per article, average total citations per year and citation years in relation to the annual production of articles are presented in Table 3. In that sense, the highest average of total citations per article is 85.2 with 5 papers in the year 2001 and the lowest is 0.08 with 12 papers in 2022; the highest average of total citations per year is 5.01 for the year 2007 and the lowest 0.02 for the year 2003 (excluding the data collection period).

3.3 Relevant sources

A total of 131 sources published research related to agile organizations from 1995 through February 2023. A source is a journal, conference, proceedings, or book published in one or more sources in the bibliographic collection [14]. Fig. 2 presents the top ten sources based on the number of papers published in each. The sources with the highest number of papers are as follows: Lecture Notes in Business Information Processing (LNBIP); Lecture Notes in Computer Science (LNCS) (including the subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics); Proceedings - Agile Conference, 2008; Conference, Proceedings - Agile Conference, 2006 and Proceedings of the Annual Hawaii International Conference on System Sciences (HICSS) with 3 papers each.

Table 3.

Average total citations per article and year.

Year	Average total citations per article	N	Average total citations per year	Citable years
1995	1	1	0,03	29
1996	2	1	0,07	28
1997	12	1	0,44	27
1999	12,5	2	0,50	25
2001	0	1	0,00	23
2002	44,6	5	2,03	22
2003	0,5	4	0,02	21
2004	20	1	1,00	20
2005	8,75	4	0,46	19
2006	6,33	9	0,35	18
2007	85,2	5	5,01	17
2008	14,17	6	0,89	16
2009	5,67	3	0,38	15
2010	3,5	4	0,25	14
2011	2	1	0,15	13
2012	2,5	2	0,21	12
2013	5,17	6	0,47	11
2014	23	3	2,30	10
2015	16,29	7	1,81	9
2016	5,71	7	0,71	8
2017	2,67	9	0,38	7
2018	6,8	15	1,13	6
2019	14,69	13	2,94	5
2020	19,47	15	4,87	4
2021	6,3	10	2,10	3
2022	0,08	12	0,04	2
2023	0	3	0,00	1

Source: Own elaboration.

3.4 Relevant sources

A total of 131 sources published research related to agile organizations from 1995 through February 2023. A source is a journal, conference, proceedings, or book published in one or more sources in the bibliographic collection [14]. Fig. 2 presents the top ten sources based on the number of papers published in each. The sources with the highest number of papers are as follows: Lecture Notes in Business Information Processing (LNBIP); Lecture Notes in Computer Science (LNCS) (including the subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics); Proceedings - Agile Conference, 2008; Conference, Proceedings - Agile Conference, 2006 and Proceedings of the Annual Hawaii International Conference on System Sciences (HICSS) with 3 papers each.

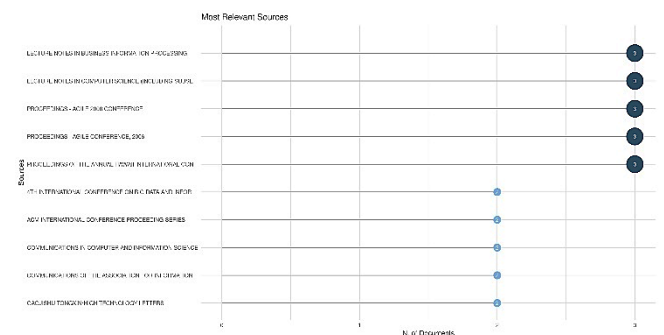


Figure 2. Relevant sources.
Source: Own elaboration.

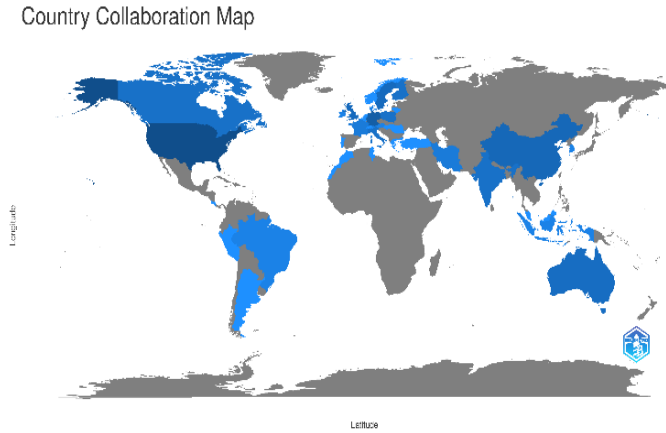


Figure 6. Scientific production by country.
Source: own elaboration.

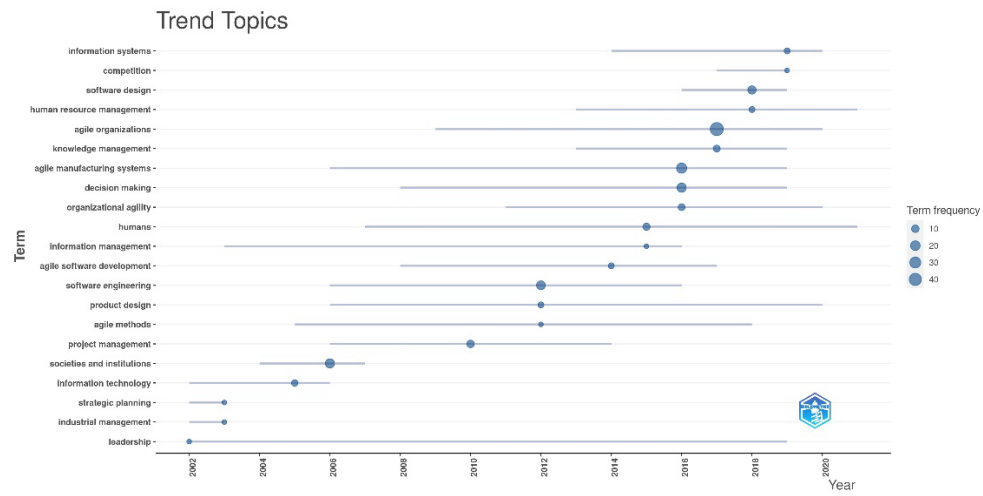


Figure 7. Trend Topics.
Source: own elaboration.

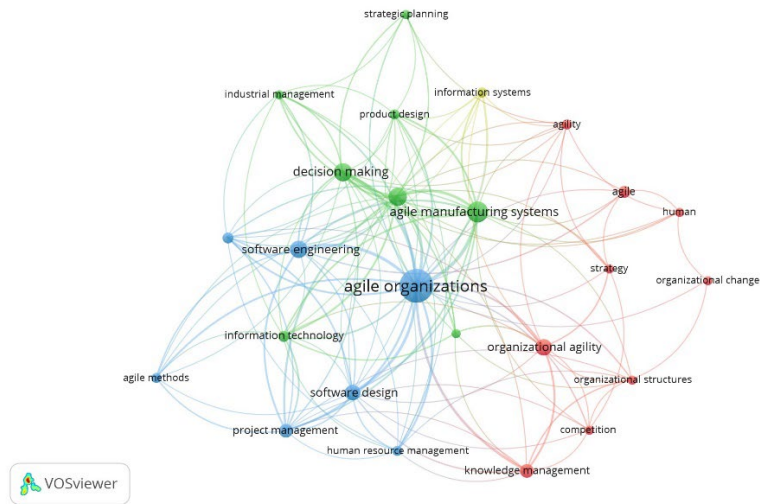


Figure 8. Co-occurrence network.
Source: own elaboration.

3.1 Trend topics

For trending topics, the keyword frequency criterion by year was used. The bibliometric analysis revealed trends of research related to agile organizations in recent studies and are presented in Fig. 7: Agile Manufacturing Systems (24: 2016), Partnerships and Institutions (18: 2006), Decision Making (18: 2016), Software Engineering (16: 2012), Software Design (13: 2018), Project Management (10: 2010), Organizational Agility (8, 2016), and Knowledge Management (8, 2017).

3.2 Co-occurrence network

Finally, the keyword analysis has been developed in terms of co-occurrence using the software tool for building and visualizing bibliometric networks VOSviewer. Fig. 8 presents the visualization of the keyword co-occurrence network. The highest frequency descriptor is "agile organizations" with an intermediate of 602.51 followed by "decision making", "organization and management" and "agile manufacturing systems" with intermediate of 213.75, 156.00 and 128.12, respectively.

Cluster 1 (blue) is focused on agile organizations around topics such as Software Engineering and Design, Project Management, Agile Methods, and Human Resources. Cluster 2 (green) relates the topics of Agile Manufacturing Systems, Decision Making, Product Design, Industrial Management, Strategic Planning, and Industrial Management. Finally, cluster 3 (red) focuses on Organizational Agility exploring topics related to Organizational Structure, Knowledge Management, Strategy, Competence and Organizational Change Management.

4 Discussion and conclusion

Agile organizations arise as a demand from the environment in which structural changes are made [1] to achieve dominant competitive positions [2], this concept somehow replaces that of Market Orientation that was coined in the 90s and that, although in its beginnings it raised an internal and external view of the organization, it has focused on three approaches: product innovation, organization performance and customer orientation. internal market [17].

In this sense, the concept of Agile Organizations leads to Agile Transformation in which relevance is given to quality improvements, cost reduction, operating profitably, as well as the ability to suddenly adapt to a changing environment [6-8]. Consequently, the agility of an organization places value on having managers who allow their teams to develop with flexibility to make the most of their creativity. Likewise, other results show three clusters that combine, first, human resources and project management, second, manufacturing and design with decision making, and third, structure, strategy, change and knowledge management. This allows us to analyze the relevance of organizational management and all its fields of action in the field of thinking about an agile organization.

Finally, the results of this study allowed the identification

of two dominant trends with respect to the research topic. The first involves issues such as the human factor, organizational innovation and organization and management, which represents a trend in terms of organizational structuring from the individual in their relationships in an organizational context in the pursuit of agility. The second groups agile methods, agile transformations, agile software development and agile organizations, among others, which implies the consolidation and results of the application of agile frameworks across different levels of organizations. Consequently, it is evident that the agile methods that started in Software Engineering as a response to achieve projects that respond quickly to the needs of users, left a relevant lesson for Organizational Management, to think about organizational innovation and the proper management of teams or people in organizations.

4.1 Future research challenges and opportunities

Therefore, future research should explore ways to operationalize and measure organizational agility and concepts such as: Agile enterprise, Agile Work Culture, Agile Manufacturing, Agile Methods, Agility Capability, Agility Facilitators, Agility Enablers, Organizational Agility, Human Resource Agility, Co-evolution, Edge of chaos and Self-organization to continue with the study of concepts from the organizational level towards complexity in the midst of open social systems that imply increasing challenges in terms of adaptability.

5 Glossary

Agile enterprise. An agile enterprise is an organization that employs fundamental principles from complex adaptive systems and complexity sciences as a foundation for achieving success [4]. Agile companies respond promptly and efficiently to shifting markets, propelled by tailored products and services [18].

Agile Manifesto. In 2001, a collective of software developers, recognizing the imperative for change, released the Agile Manifesto, giving rise to the "Agile" methodology aimed at adapting to diverse requirements [19]. The manifesto represents the basis for most agile methods and practices today [20].

Agile methods. A distinct set of methodologies, referred to as agile methods, is employed to tackle diverse challenges arising from evolving requirements, unpredictable outcomes stemming from technological intricacies, and the dynamic nature of systems, including uncertainty induced by overall system complexity [4].

Agile organizations. Organizations that swiftly acquire knowledge by integrating their agility capabilities with the functions of the organization, adjust promptly to the environment, anticipate change, cultivate a culture aligned with this approach, and embrace agile methodologies [19].

Agile work culture. An agile work culture involves promptly adapting to environmental changes rather than adhering strictly to a predefined process. The term originated in the context of software development, allowing programmers the flexibility to develop the product

continuously and fluidly [21].

Agile. The agile paradigm advocates for conducting the software development activities of a project in an iterative and incremental life cycle, aiming to generate value at the conclusion of each cycle. It emphasizes active involvement of stakeholders and end users in these cycles [19].

Agility. Agility surfaced nearly three decades ago in response to dynamic economic landscapes and increased global competition [19]. Agility is the quality of an organization that empowers adjustments in the execution scope of operations, processes, and business relationships in reaction to evolving external and internal circumstances [4].

Co-evolution. Co-evolution serves as a critical process through which a company assimilates knowledge from experience and adjusts; the agile company consistently transforms in alignment with, and in response to, external factors in the environment [4].

Edge of chaos. The edge of chaos is a transitional zone positioned between anarchy or complete randomness and a state of equilibrium; the agile enterprise ideally functions within this realm, requiring a delicate balance between continual change and constraints that may impede the organization's transformative endeavors [4].

Self-organization. Self-organization refers to the spontaneous, unplanned, and feedback-driven interactions that occur within agile enterprises [4].

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Bibliometric study of distribution system state estimation: advances and challenges

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Abstract

An active distribution network with a large amount of distributed energy resources (DER) requires knowledge of the operational status of the network. In this sense, state estimation is one of the most widely used techniques and a well-developed concept in transmission systems. DERs have some monitoring, protection, and control devices. But due to the large size of the network and the number of users, the massive installation of meters is not yet economically feasible. Therefore, it is necessary to generate artificial measurements to perform all stages of distribution system state estimation (DSSE). DSSE is currently the subject of active research, so this article performs a descriptive bibliometric study, which qualitatively and quantitatively analyzes the topics found in the specialized literature in the period from 2000 to 2022 and part of the 2023. It also identifies the advances, challenges, and proposals for future lines of research in DSSE.

Keywords: distribution system state estimation; bibliometrics study; pseudo-measurements; observability analysis; topology analysis; bad data detection.

Estudio bibliométrico de la estimación del estado de los sistemas de distribución: avances y retos

Resumen

Una red de distribución activa con una gran cantidad de recursos energéticos distribuidos (DER) requiere conocer el estado operativo de la red. En este sentido, la estimación del estado es una de las técnicas más utilizadas y un concepto bien desarrollado en los sistemas de transmisión. Los DER disponen de algunos dispositivos de supervisión, protección y control. Pero debido al gran tamaño de la red y al número de usuarios, la instalación masiva de medidores aún no es económicamente viable. Por lo cual, es necesario generar mediciones artificiales para realizar todas las etapas de la estimación del estado del sistema de distribución (DSSE). DSSE es actualmente objeto de investigación activa, por lo que este artículo realiza un estudio bibliométrico descriptivo, que analiza cualitativa y cuantitativamente los temas encontrados en la literatura especializada en el periodo comprendido entre 2000 al 2022 y parte del 2023. Asimismo, se identifican los avances, retos y propuestas para futuras líneas de investigación en DSSE.

Palabras clave: estimación del estado del sistema de distribución; Estudio bibliométrico; pseudomediciones; análisis de observabilidad; análisis de topología; detección de datos erróneos.

1 Introduction

An active distribution network can be defined as a synergy (join development) of the traditional electric network with modern technologies of information, measurement, protection, control, and communication that allow a more efficient, secure, and reliable operation of the network from the technical and economical point of view. In this new

paradigm, Distribution System Operators (DSO) must carry out actions or take decisions to maintain the levels of reliability and service quality, so it is necessary first, to have a complete knowledge of the network state. Thus, the state estimation (SE) is one of the methods mostly used, since it uses real-time measures of voltages and bus flow injections, flow and current line measurements that can be obtained from the HV/MV, reconnectors, switchers in MV, Distribution

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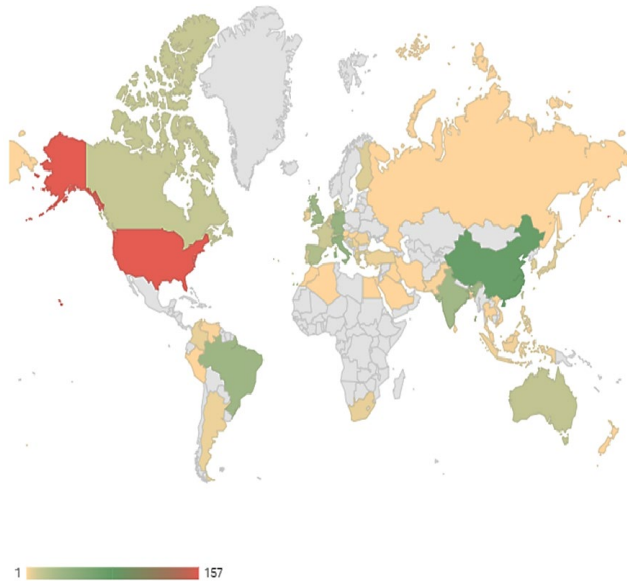


Figure. 1. Density per number of publications in DSSE per country
Source: Own elaboration.

Phasor Measurement Units (D-PMU or μ PMU) [1], smart meters [2] and artificial measurements which allow the observability of the system and thus execute the SE algorithm.

Having into account that the SE is a well-developed concept and widely used in transmission systems (TS), its use at the distribution level still has problems of implementation due to the low amount of measurements available since the massive installment is not economically viable up to now, apart from the unbalance of phases, network size, inaccurate network models due to lack of updating or previous validation, design form, and construction, where the line lengths are shorter and have higher R/X relations. So, countries like the United States, China, Germany, Italy, Brazil, United Kingdom, India, and the rest of the world consider distribution system state estimator (DSSE) an object of active research as it is observed in Fig. 1.

The DSSE is an important tool for distribution network monitoring, as it allows estimating the behavior of the network in a short time. This is useful for distribution system management, as it allows operators to optimize network configuration and detect potential problems before they occur. In addition, DSSE are used to monitor network performance, detect not only the presence of faults on distribution lines but also of unwanted loads, estimate the status of distribution network equipment, find out changes in network behavior, and adjust power supply to meet demand. However, DSSE faces challenges due to errors in the network topology data, the need for a large number of measurements with little error at the time of data acquisition and the subsequent communication with the control center.

Despite the challenges and complexity of the problem, in the state-of-the-art review, it was identified that the most used method for the DSSE is Weighted Least Squares (WLS). The first proposals in this sense were developed in the '90s [2]. After those proposals, there were incorporated

Automated Meter Reading (AMR), intelligent meters with architecture Advanced Metering Infrastructure (AMI), and renewable and non-renewable Distributed Energy Resources (DERs). Later, it was included and analyzed the impact and implementation of synchronized or non-synchronized D-PMU. These advances and developments can be found in several state-of-the-art reviews [2-7]. In [2,4] technologies, obstacles, challenges, and components of a DSSE are presented and analyzed. Related works on SE in transmission and distribution systems and critical issues of DSSE concerning the mathematical formulation and other components for estimating the state of DS are analyzed in Dehghanpour's paper [8]. In [5] highlights the importance of using Machine and Deep Learning to address DSSE. The advantages, disadvantages and applications and a summary of different DSSE methods is presented in [6,7].

The aim of this work, in addition to complementing the aforementioned reviews of the state-of-the-art, is to make a descriptive bibliometric study, in which the topics found in the specialized literature of the last two decades are analyzed not only qualitatively but also quantitatively. The topics found are classified into the three areas that make up a DSSE: input data, functions, and applications, which in turn are divided into sub-areas that have a description of the proposals in the period 2018-2022. This is to identify the advances, challenges, and proposals for future lines of research in DSSE.

The content of this paper is organized as follows: the search procedure and literature review with the classification of topics and subtopics of aspects that make up a DSSE are detailed in Section 2, followed by a description of each. Proposals for future research with the problems that the authors considered relevant to DSSE are included in Section 3. Final conclusions are developed in Section 4.

2 Searching procedure and bibliographic analysis

In the literature review, each paper is analyzed and classified according to the areas described in the Section, so that it can be a quantitative and qualitative distribution to evidence the most investigated areas as well as those relegated ones. All this is done to identify trends and suggest future lines of research. The procedure is established in the following way:

1. Selection of a database: the database covers a complete review of papers or chapters using IEEE Xplore, Google Scholar, ISI Web of Knowledge, and Scopus searching motors.
2. Selection of papers from the database: the compilation covers the main themes of the field of DSSE; each paper is analyzed to verify its relation with the theme and to consider to which classification area or subarea (detailed in Section 3) it belongs.
3. Gathering information: All selected attributions of predefined classifying levels are searched and extracted from each paper.
4. Relational database: a relational database is created and completed since the same paper can provide contributions to different areas of Section 3.
5. Identification of main trends: Based on data stored in

step 4, the papers are grouped obtaining quantitative data and percentages. These are visually grouped to identify trends according to the year of publication.

6. Deep analysis of each trend: based on the main trends identified in step (5) and the knowledge of the authors, the research lines are proposed.

2.1 Analysis and bibliographic classification per research areas

In order, to obtain a solution with the DSSE algorithm it is necessary to count with minimum information of the system which depends on the number of state variables to be calculated and the number of existent measurements. These data are for the electrical modeling of the network as well as other additional information which are used to obtain a solution. Data related to the local characteristics of the electric network must be previously analyzed and if it is necessary these must be completed artificially, only then the algorithm of DSSE can be run. The result of the algorithm must overcome a stage of detection and identification of bad data to be ready to be used in a Distribution Management System (DMS). All this process described before is classified into data, functions, and applications together with the number of papers per area (Fig. 2).

From the classification of Fig. 2. 795 papers published between 2000 and 2023 were analyzed, where 48,19%, 37,73%, and 14,08% consider the analysis of data, functions, and applications respectively (Fig. 3).

It must be noted that 42,96% of the total amount of publications are from the period 2018-2022, where it maintained the trend of the areas of study (see Fig. 4a). Nevertheless, it is evident that 60,05% of the contributions are centered in four areas (see Fig. 4b). First, the static DSSE algorithms with 25%, second the solution and temporal synchronization with 11,78%, third the location and distribution of different types of measurements with 12,64% and at last, the analysis and algorithms of data generation for pseudo measurements with the 10,63%.

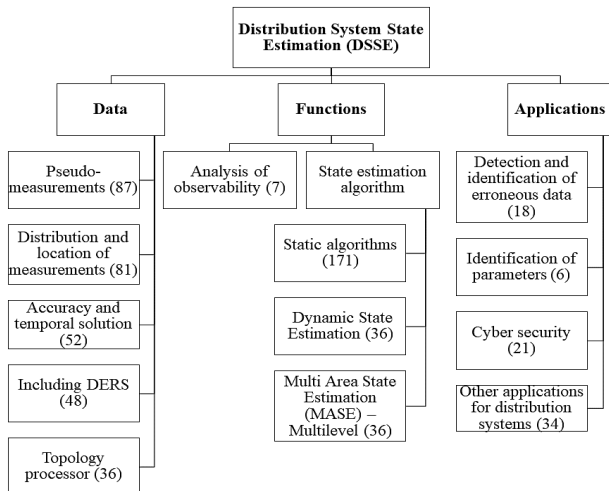


Figure 2. Classification per areas of research in DSSE
Source: Own elaboration.

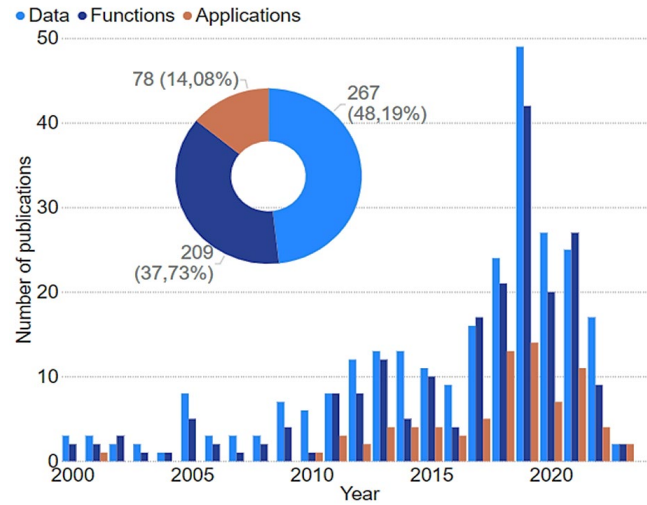


Figure 3. Percentage and distribution of papers according to data, functions, and applications
Source: Own elaboration.

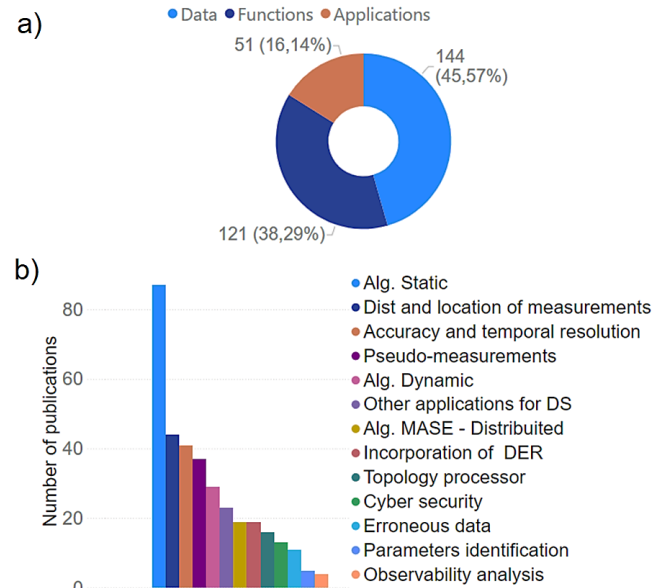


Figure 4. a) Distribution per component b) Number of papers per area of research in the period 2018 – 2023.
Source: Own elaboration.

In addition, the data analysis concluded that 1 out of 6 articles studied the DSSE problem in balanced or single-phase networks the rest corresponds to multiphase and unbalanced systems. In the following sections, the description of each area and the different methodologies proposed in the literature are presented in detail, together with the percentages per number of papers per area in the period 2000-2023. Due to space reasons, only those papers which the authors considered more relevant from 2018-2022 are referenced; several from 2023 are included.

2.2 Input Data

DSSE inputs include every knowledge of the system which could affect the result, as well as the physical characteristics of the network. These data include the information technology and the physical attributes gathered at the control center and visualized through a Supervisory Control and Data Acquisition (SCADA) system and which provide measurements such as:

SCADA Measurements: They generally provide data at the substation level, including the active and reactive power, the current magnitude at each distribution feeder, and the voltage magnitude in the bus of the substation. Besides, metering installed along the feeder, which is also included.

1. Smart meters: These meters are installed at the customer's side, connected through bidirectional networks of communication with the system of data management located at the electric company. These devices can provide measurements of active and reactive power, voltage and current and medium power.
2. PMU o D-PMU: The main output is the phasor measurement of voltage waveforms and sampled currents, magnitude, and angle, with which other measurements can be derived and calculated.
3. Pseudo-measurements: To compensate for the lack of data, the set of input data must be increased artificially and/or corrected to compensate for erroneous data. This can be done using "pseudo-measurements", which are generated artificially, for example, active/reactive power, voltage, current, etc.
4. Virtual measurements: these are voltage falls to a zero in closed commutation devices, zero power flows in open commutation devices, and zero bus injections passive in nodes, as a commutation station.

Other important aspects to be considered are data or network parameters, i.e., all permanent features of the electric system which do not change in the daily operation. In particular, those network parameters include network connectivity, line parameters (line and mutual impedance, phase configuration, etc.) bus parameters (connected customers, network equipment, derivation elements, etc.), and equipment parameters (transformers, switchers, protection elements, etc.).

2.2.1 Pseudo-measurements

The existent measurements are stored to be used later on to generate the missing data required for the DSSE, which are used as pseudo-measurements. This represents the 13,88% where it can be found the analysis of uncertainties and correlations detailed in [9]. As well as load forecasting proposals with methods of load estimation [10] and allocating profiles [11], Markov model [9]. Finally, it must be mentioned criteria based on learning such as Artificial Neural Networks [12–14], Relevance Vector Machine (RVM) [15], and clustering techniques [16].

2.2.2 Distribution and location of measurements

This area deals with the 12,92% of the papers which have

the aim of determining the location of PMUs, smart meters, pseudo-measurements, and line flow meters among others, through optimization functions with constraints that consider costs, yield indexes, number of measurements, measurement redundancy and the error in the DSSE. An analysis of the state-of-the-art in this field is presented in [17].

In addition, there are proposals related with noise of non-Gaussian measurements [18], chaos simulation and/or Monte Carlo [10,19], Genetics Algorithm [20], Heuristic Methods, Combined or Hybrid [9,21] Integer Linear Programming (ILP) [22], Mixed Integer Semi-Definite Programming (MISDP) [23], Information Entropy Evaluation and multi-objective optimization [24].

2.2.3 Accuracy and temporal solution

Another field is the analysis of the accuracy and temporal solution, which includes 8,29% of the works, where it is considered that the distribution system is commonly comprised of a wide variety of measurement equipment, located at different voltage levels and with different time resolutions and measurement errors, Table 1.

Thus, these data considered have a wide range of temporal resolution and different measurement errors. In this sense, two fields of study are identified. The first one is related to the analysis of measurements, i.e., correlations, accuracy, and uncertainties that can appear considering measurements with or without synchronism. The second one is related to the effects that the different types of measurements have on the result of the DSSE, here, the different types of measurements and communication techniques, times of acquisition, non-synchronic and lacking measurements are included. The different areas of research identified are detailed in Table 2.

Table 1.
Type of measurement, location, and temporal resolution

Type	Error	Location		Temporal resolution			
		MV	LV	msec	sec	min	hours
D-PMU	1%	X		X	X		
SCADA	3% to 5%	X			X	X	
AMI	10%		X			X	X

Source: Own elaboration

Table 2.
Areas of research referred to measurements and their effect on the DSSE.

Area	Analysis	Ref.
Analysis of measurements	Correlations	[25]
	Accuracy and uncertainties	[26,27]
	Optimal management of the information	[28]
	Synchronic	[29,30]
	Non-synchronic	[31,32]
Effects in the DSSE	Including measurements	[33]
	System of communication	[34,35]
	Times of acquisition	[36,37]
	Non-synchronic measurements	[29,38]
	Lacking measurements	[39]

Source: Own elaboration

2.2.4 Including DERS in the DSSE

Publications related to the inclusion of the renewable and non-renewable DERs in the DSSE correspond to 7,66%. They include the analysis of the correlation between the DERs and the result of the DSSE in [11] and how it affects the result is developed in [40]. To deal with this theme the injection curves and DERs measurements are used as well as the result of the DSSE in [41], then mathematic models according to the type of generator [42] or models which consider environmental variables [43], and others with probabilistic points of view [44] and learning ones [45].

2.2.5 Topology processor

Its function is to verify that the parameters and network model are the correct ones before running the algorithm of the DSSE. This represents 4,78% of the works and they include proposals where the basic topology will suffer changes over time due to local events such as faults, line disconnections, commutation events, etc. Therefore, various proposals have been done which include the analysis of uncertainties in the network topologies [46], in which variables related to the commutation devices and/or measurements are used [47,48]. As well as methods based on decision trees [49], or learning [50,51], verifying signs of temporal series [52], and an approach based on tracking data [53,54].

2.3 Functions

2.3.1 Analysis of observability

The aim is to determine if the number of available measurements as well as their geographical distribution allows estimating all the states of the system. It must be taken into account that, if the measurements are wrongly distributed, this can be over-determined in one zone and even though be unobservable. Proposals in this area correspond to 1,12%, these are focused on knowing if the system is or not observable. Thus, redundant and critical measurements were identified, detecting observable isles. Therefore, various methodologies have been introduced based on: numerical approaches [55,56], learning, heuristic, topological, algebraic, null space, probabilistic, and graphs theory [57] just to mention the most important ones.

2.3.2 State estimation algorithm

As it was mentioned the most widely used method in the DSSE is WLS. Greater details of the mathematical formulation of this method can be found in [4,58].

Nevertheless, depending on the state variables calculated, these can be Node Voltage (NV) or Branch Current (BC). In the literature, these two formulations are compared as regards their implementation, inclusion of PMU, computing time, numerical stability, convergence, sensitivity, and other aspects in [4]. The BC offers better advantages than the NV in the DSSE. A similar comparison was done in [59] with PMU synchronized and non-synchronized measurements from the SCADA.

Table 3.

Proposals for static algorithms of DSSE

Methodology		Ref.
Weighted Least Squares (WLS)	Linear approach	[22,60]
	Modifications to WLS	[61,62]
	Load flow	[63]
Alternative ones	Alternative WLS	[64,65]
	Admittance Matrix Based (AMB)	[66]
	Accelerated Probabilistic State Estimator (APSE)	[67]
Robust	Hybrids	[49,68]
	Interval Arithmetic (IA)	[27,69]
	Block tensor completion	[70]
Heuristic and computational intelligence techniques	Neural networks	[71,72]
	Semi-definite programming (SDP)	[73]
	Particle Swarm Optimization (PSO)	[68]
	Another heuristic algorithm	[74]

Source: Own elaboration

Table 4.

Proposals for dynamic algorithms and MASE – Multilevel

Methodologies		Ref.
<i>Kalman filter</i> (KF)	KF	[75]
	<i>Ensemble KF</i> (EnKF)	[76]
	IEKF	[42,77]
	<i>Unscented KF</i> (UKF)	[78]
	<i>Augmented Complex KF</i> (ACKF)	[79]
Alternative to KF	<i>First-Order Prediction-Correction</i> (FOPC)	[80]
	<i>Alternating Direction Method of Multipliers</i> (ADMM)	[81]
	FASE - Recursive	[82,83]
	Hybrids	[84]
	Hybrid AC/DC	[85]
MASE – Multilevel – Distributed		[19,86]

Source: Own elaboration

Nevertheless, no matter the type of state variable calculated, they are classified in statics with 27,27%, dynamics known as Dynamic State Estimation (DSE) or Forecasting-Aided State Estimation (FASE) with 5,74% and Multi Area State Estimation (MASE) – Multilevel approach with 5,74%. Static algorithms are divided into methodologies based on WLS, alternatives to WLS, robust approaches, and those based on computational intelligence and heuristic methods. Dynamic algorithms are based on the Kalman filter and other alternative methods. Proposals of static, dynamic, and MASE-Multilevel algorithms are detailed in Tables 3 and 4, respectively.

2.4 Applications of the estimated state

2.4.1 Detection and identification of bad data

Erroneous measurements are processed, identified, and eliminated here, those which are erroneous due to faults in the communication or to the package of false metrics/data [64] from the calculated state. This area belongs to the 2,87% of the works, where the methodologies are based on statistical analysis, such as the chi-square test, normalized residual test [45,87], and orthogonal formulation [88]. Besides, techniques with approaches to neural networks and geometrics are also included.

2.4.2 Identification of parameters

Only in 0,96% of them are analyzed how the line impedances and network equipment affect the quality result of the state estimation. Proposals are related to the connectivity of the network/mapping of incidence [89] and line parameters [90].

2.4.3 Cyber security

This topic represents the 3,35%, where it is analyzed how the malicious alteration of data from certain measurement devices [91], the injection of false data [92], and topological data affect the knowledge of the real state of the system and the risk in the privacy and confidentiality of users. A review of the state-of-the-art in this area can be seen in [93].

2.4.4 Other applications for distribution systems

The aim of using the DSSE in real time operation is to provide a higher level of confidence of the network state to support decision making or to find an optimal solution. These proposals correspond to 5,42%, as the ones included in [94], where the results indicate that the identification of non-technical losses from the erroneous data detection approach is promising. While a sensitivity analysis of the DSSE with respect to phase mislabeling of single-phase service transformers is presented in Trevizan et al [95]. In Bindu et al. [96] a methodology for using DSSE in DG interconnected distribution network is proposed which, in turn, depends on the minimization of system losses. In [97], a centralized self-healing scheme employing a three-phase state estimator with a short-term load forecasting method and a fault location algorithm for service restoration is designed and simulated. Another use for running DSSE with topology detection is to locate faults and isolated components [60,98] [66,104]. In demand response schemes, DSSE improves the basis for sending load disturbance signals to dynamic consumers [99]. Finally, in transmission and distribution operator coordination, DSSE improves load forecasting techniques and current state accuracy integrating into the transmission model [100]. In addition, it can be included in applications or algorithms that contribute to data cleansing, network optimization and topology, system reliability, dynamic energy pricing, monitoring, and operation control.

3 Proposals of Future Research

After analyzing the literature, proposals have focused on improving the quality of the information and completing the observability of the distribution system before running the DSSE algorithm. However, unlike TS, there are various factors that make distribution system (DS) very diverse in terms of construction, load, topology, investments in technologies or network reinforcements, insufficient metering, adoption of DERs, communication systems, etc. Therefore, DSSE still faces the challenges of estimating non-measurable variables in non-linear DS. Thus, the authors propose the following lines of future research to help achieving the effective adoption of DSSE in the face of ADNs challenges.

3.1 Pseudo-measurements

Accuracy of pseudo-measurements can be improved through the use of a scheme of the close circuit in which the output of DSSE feedback the load models [101], or in turn using data mining techniques [102].

In fact, in case of smart meters, they can have two metering schemes Net Billing or Net Metering. In the case of Net Billing, the pseudo-algorithms could use data from users and injection power to model the load behavior in the DSSE. But in the case of Net Metering, more parameters, models, environmental, social variables, uncertainties, etc. must be selected which allows the recognition of the difference between consumption and generation.

3.2 System operation

At an active distribution network (ADN), being operated dynamically, with constant changes in generation, load, and network topology, among others, the static algorithms of DSSE are not able to capture these changes easily, since they consider that the state of the system does not change much between two consecutive updates of the state estimator. While the DSE or FASE techniques, consider the state temporal evolution over time and they can track the system changes during normal performance [4], requiring only the reduction of the computational load and times of convergence of the DSSE [103]. These are the proposals that take advantage of the MASE executing various estimators in sequence or parallel.

3.3 DERs progressive insertion

The impact of the presence of DERs analyzed from the point of view of the DSSE will depend on the percentage of insertion and the type of installed technology, a low percentage of power injection to the system does not affect the calculus of state variables, but as this percentage increases, the DSO must differentiate between load and generation. In addition, it becomes necessary to consider the uncertainties related to the type of generation due to the dependence on intermittent natural resource and their storage. Thus, approaches, techniques, and the most advanced challenges regarding the modeling of uncertainties of DERs in the electric system are briefly presented in [104].

3.4 Microgrids and storage systems

In the system operation, there must be coordination between the network and the existent microgrid or microgrids, so that the result of the SE be used as input data for the functions of self-reestablishment of a microgrid, and depending on the result of such functions, they will be used as input in the new calculation of DSSE.

In the case of those storage systems that do not belong to a Microgrid, their state will depend on the control system of the inverter or the present regulation, so the DSO needs to quantify the load level about the maximum nominal load of the battery to be used as measurement or in case to obtain observability as pseudo-measurement. These load and

discharge models must be considered within the DSSE, to be able to control temporal variations of state variables [105].

3.5 Efficient metering and data acquisition architectures

It is necessary to develop low-cost smart metering devices that comply with international standards [106] and architectures for data collection from thousands of smart meters in a relatively short period (on the order of minutes) it is not feasible nowadays [107], having into account the diversity of metering technologies installed, the acquisition time and uncertainties associated to each of them [108]. The DSSE must model these uncertainties locally and find ways to take advantage of information from different time scales and combine them with artificial measurements if necessary.

3.6 Relegated research areas

According to Fig. 4b, the contributions to the state-of-the-art during the year 2018-2022 are focused on four areas: static DSSE algorithms, analysis and effects in the DSSE, the resolution and temporal synchronization, location and distribution of different types of measurements, and generation of data to be used as pseudo-measurements.

Nevertheless, according to the proposed classification, the new contributions could focus on areas such as Topological processor which considers the presence of DERs with fast algorithms with a low computational load to detect the constant changes expected in ADN; the detection and identification of bad data using methods based on artificial intelligence; cyber security seen from a point of view of the DSSE. The identification of parameters that use phasor meters at strategic points of the network allows for determining parameters through the measures provided by them. Finally, in the observability analysis and considering the enormous size of distribution networks with few measurements, it was identified that it is still necessary to propose solutions related to the detection of critical measurements that guarantee the observability of the network.

4 Conclusions

From the analysis of the state-of-the-art and the development of ADN, it is understood that in order to improve the real-time operation it is necessary to have an efficient estimation of DSSE. For this reason, this work identified the advances, challenges and proposals for future lines of research in DSSE, after analyzing 795 papers. Thus, a descriptive bibliometric study was carried out, in which the topics that make up a DSSE are qualitative and quantitatively analyzed

Countries such as the United States, China, Germany, Italy, Brazil, the United Kingdom and India have generated around 60% of contributions on the subject and it continues to be an active area of research with new articles being published every year.

Distribution systems are quite diverse in their form of construction, loading, topology, DER adoption, technologies,

etc. Consequently, DSSE faces challenges due to errors in the network topology data and the need of a large number of measurements. However, DSSE is necessary for DSO since it helps them to have higher reliability in the short term through the estimated state because it allows the detection of potential problems before they occur. In addition, DSSE can be included in applications or algorithms that contribute to data cleansing, network and topology optimization, system reliability, dynamic energy pricing, operations monitoring, and control.

The contributions of the period 2018-2022 are focused on four areas: static DSSE algorithms, analysis and algorithms of data generation for pseudo-measurements, location and distribution of different types of measurements, and the resolution and temporal synchronization.

Due to the dynamics and uncertainties expected in the ADN, state estimation conventional techniques proposed for transmission systems cannot be applied to distribution systems. Therefore, future research should focus on DSSE algorithms or FASE and MASE ones with less convergence time and low computational load thinking on a real-time operation.

Barriers to the development of DSSE are mostly related to the availability of communications and the effective use of the information generated by the AMI, as well as the low PMU installed and SCADA distributed measurements.

There are still some pending challenges as regards the DSSE in such areas as pseudo-measurements, system operation, DERs progressive insertion, microgrids and storage systems, efficient metering and data acquisition architectures, and research areas detailed in Section 3. So, it is expected that this paper contributes to developing the research on those themes that may achieve the effective adoption of DSSE by electric service companies.

This work allows an evaluation of the different advances in the areas of knowledge concerning DSSE and can be a guide to propose new lines of research or as a decision-making process for the allocation of resources for research and development in the case that an electric company plans to implement a DSSE in the short term.

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Predicting the flowability of UHPC and identifying its significant influencing factors using an accurate ANN model

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Abstract

In this research, a one-hidden layer artificial neural network paradigm (ANN) was created to forecast the slump flow of ultra-high-performance concrete (UHPC). To achieve this goal, 3,200 ANNs were evaluated to estimate the fresh UHPC's slump flow utilizing 793 observations. The performance metrics measured on training and test data subsets were in the same order of magnitude, thereby pointing out the proper work of the *k-fold* validation procedure. The results of the connection weight approach analysis (CWA) indicated that water dosage had the highest positive importance in slump flow, preceding the superplasticizer volume ratio. Other factors that positively influenced slump flow were the water-to-powder ratio, the dosage of high-alkali glass powder, the water-to-binder ratio, and limestone concentration. The most negative influences on rheology were the high-alumina FC3R and metakaolin. The ANN accurately predicted the slump flow of UHPC, while the results of the CWA analysis were well-correlated with previous research.

Keywords: ANN; slump flow; k-fold validation; connection weight approach; supplementary cementitious materials.

Predicción de la trabajabilidad del UHPC e identificación de sus factores de influencia significativos utilizando un modelo ANN preciso

Resumen

En esta investigación, se desarrolló un modelo de red neuronal artificial de una capa oculta para pronosticar el flujo estático del concreto de ultra alto rendimiento (UHPC). Se evaluaron 3200 redes neuronales artificiales para estimar el flujo estático del UHPC fresco utilizando 793 observaciones. Las métricas de rendimiento medidas en los subconjuntos de datos de entrenamiento y de testeo estuvieron en el mismo orden de magnitud, lo que indica el trabajo adecuado del procedimiento de validación cruzada *k-fold*. Los resultados del análisis de enfoque de peso de conexión (CWA) indicaron que el contenido de agua tuvo la mayor importancia positiva en el flujo estático, precediendo a la relación de volumen del superplastificante. Otros factores que influyeron positivamente en el flujo estático fueron la relación agua-polvos-totales, la dosificación de polvo de vidrio con alto contenido de álcali, la relación agua-aglutinante y la dosificación del carbonato cálcico. La influencia más negativa en la reología fueron el FC3R alto en alúmina y el metacaolín. La ANN predijo con precisión el flujo de asentamiento de UHPC, mientras que los resultados del análisis CWA se correlacionaron bien con investigaciones previas.

Palabras clave: ANN, flujo estático; validación cruzada tipo *k-fold*; moldeo de conexión de pesos; materiales cementantes suplementarios.

1 Introduction

1.1 UHPC definition, application, and main challenges

The affordability, resilience, and durability of concrete position it as a widely used construction material. While

conventional concrete (CC) has limitations in meeting contemporary needs, collaborative efforts from 1997 to 2002 resulted in ultra-high-performance concrete (UHPC) [1-2]. UHPC, with superior properties, is reinforced with microsteel fibers and defined by ACI 239R-18 as concrete with a minimum compressive strength of 150 MPa. Its microscopic

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structure and fiber reinforcement contribute to exceptional performance, with a focus on minimizing heterogeneity [3-5]. UHPC employs various reactive powders and maintains a low water content for improved performance [6,7]. Furthermore, UHPC is characterized by its low water content, which lessens the thickness of interfacial transition zones within the cement particles by confining cement particles in small spaces. The disadvantage of this technique is that it reduces the workability of the paste, which requires including superplasticizers in the paste [8]. This concrete is, therefore, objectively designed to exhibit improved ductility in addition to high compressive strength [9].

The popularity of UHPC is growing, evident in its increased applications in bridge construction for both highway and pedestrian use. It finds use in onshore and offshore infrastructures, with notable benefits in earthquake- or impact-prone regions. Recent studies highlight its application in post-stressed railway sleepers, aiming for cost-efficiency and durability. Field tests on prestressed precast UHPC pilings have also been conducted across various structures [10-25].

Nevertheless, while UHPC boasts excellent mechanical performance, its high cost, attributed to expensive constituents and the excessive use of natural resources, hinders widespread adoption [26-29]. To address environmental concerns, waste by-products have been incorporated as supplementary cementitious materials (SCMs) [30-34]. Moreover, the lack of codified guidelines for material and structural designs poses challenges to the utilization of UHPC mixtures with these SCMs [35].

1.2 Importance of workability

Concrete's flowability, crucial for efficient construction, is defined as its ability to work without significant homogeneity loss [36,37]. Assessing this property, often done through a slump cone test, determines how easily fresh concrete can be compacted, finished, and placed on-site without immediate segregation. Customized concrete mixes cater to specific construction types, and flowability is classified as high, medium, low, extremely low, or very low [38]. In concrete technology, flowability is paramount, and advanced mix design procedures alone are insufficient for longevity if proper pouring and compaction are compromised. Hence, understanding factors influencing flowability is imperative.

In the context of UHPC, substituting typical reactive powders with alternative SCMs necessitates rigorous experimental validation to ensure effectiveness [6]. New mixture designs with fewer environmental impacts can alleviate barriers to UHPC popularity. However, mandatory lab experimentation is complex due to cost, duration, and labor intensity. Statistical modeling techniques offer a simplified approach to concrete mix design but face challenges with the large number of variables and complex relationships in UHPC, making traditional regression techniques less effective [38-40].

1.3 Artificial Neural Networks

Artificial Neural Networks (ANNs) have become prominent computational tools for modeling real-life

problem-solving, offering insight into complex relationships between input and output data pairs [41]. Widely applied in civil engineering, ANNs demonstrate competence in solving intricate engineering problems related to traffic management, water resources engineering, structural health monitoring, structural classification, materials simulation, and concrete mix design [6,42-47]. The scientific literature reflects a growing trend in using ANNs to forecast the mechanical properties of various cement-based materials [44-47].

ANNs have also been utilized to predict the performance of UHPC through data-driven approaches but limited studies conducted mostly focused on strength forecasting [48,49]. Despite the effectiveness of ANNs in ensuring prediction accuracy, their application to predict the flowability properties of UHPC, especially when incorporating multiple SCMs, remains a subject of inquiry and requires further exploration.

1.4 Research objectives, significance, and organization

This research aims to create a model utilizing an ANN approach to simulate the UHPC flowability. Given the intricate composition and rheological behavior of UHPC, particularly in terms of fresh mix flowability, developing an efficient mix design is challenging. The study incorporates a Connection Weight Approach (CWA) into the ANN model, conducting a sensitivity analysis to elucidate the impact of mixture features on flowability. The significance of this work lies in its potential to streamline the UHPC mix design process by offering a reliable tool for predicting flowability properties. The developed ANN model could assist engineers and researchers in optimizing UHPC mixture composition, reducing waste, and improving production efficiency. The research methodology involved data collection on the flowability properties of UHPC mixtures, data preprocessing, construction of an ANN model using collected data and relevant mix design parameters, and rigorous assessment of model accuracy and reliability through statistical analyses and comparisons with a testing data subset.

2 Data collection

This study has meticulously compiled a comprehensive database incorporating results from 927 slump tests performed on UHPC mixes with various SCMs. Among these, 210 observations stem from in-house experiments conducted in different studies [47,48], while 717 observations were sourced from international proceedings on UHPC, including events like Kassel 2004, 2008, 2012, and 2016, PhD dissertations, and research published in civil engineering journals. Notably, only UHPC mixture proportions providing virtual packing density or sufficient information to estimate it were included. Approximately 80% of the data relates to the static test as per ASTM C1437, with variations in cones' shapes and dimensions in different published research. To ensure consistency, slump flow values were standardized to the ASTM cone using transformation factors [48]. The experimental campaign initially focused on ASTM III cement, with no quartz powder (QP) in the mixtures but various mineral admixtures (see Fig. 1). The



Figure 1. Mineral admixtures used in this research. From left to right: silica fume, fly ash, GGBFS, glass powder (GP), rice husk ash (RHA), fluid catalytic residue (FC3R), metakaolin (MK), and limestone powder (LP)

Source: The authors.

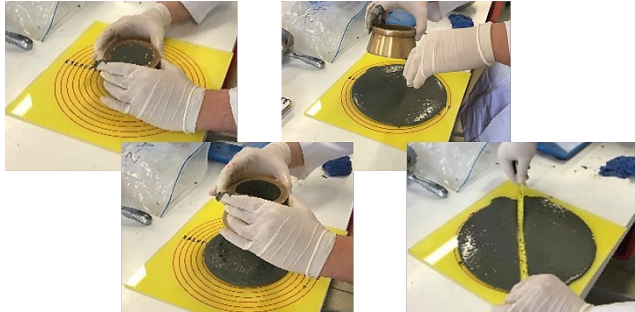


Figure 2. Measurement of the slump flow of UHPC using the cone of the ASTM C1437

Source: The authors.

database expanded to include different cement types, aggregate possibilities ranging from no-aggregate to coarse-aggregate-UHPC, and the use of QP, incorporating findings from relevant research. The slump flow test involved measuring the diameter of the static slump immediately after the UHPC mixing process, following ASTM C1437 specifications, utilizing a truncated cone-shaped mold and flat plate, with the spread mortar diameter measured in four directions to calculate the slump flow (see Fig. 2).

3 Methodology

3.1 Data preprocessing

Data preprocessing involves outliers' detection and normalization. Outliers, defined as significant deviations from a dataset's general behavior, were identified using bivariate boxplots and Cook's distance [49-51]. Further information on these procedures can be found in [48,52-53]. At the end of this process, the database without outliers contained 793 observations.

For its part, data normalization is essential for training ANN regression models. It overcomes issues related to scale and distribution of input variables by bringing them to a common scale (0 to 1 in our case). Normalization ensures equal contribution of each feature to the learning process, prevents dominant features from overshadowing others, and enhances convergence, allowing the model to learn efficiently [48].

Finally, the cleaned and normalized database was split into 80% for training and 20% for testing. Additionally, the training base was divided into four for *k-fold validation*. This rigorous approach enhances the reliability and robustness of the trained network, improving its generalization capability for more accurate regression predictions [47,48].

3.2 Training procedure

The resilient backpropagation algorithm (RProp) was adopted to train the ANN [55]. The RProp is similar to the conventional backpropagation algorithm, but it is considerably faster and does not require any free parameters (like learning rate). Additionally, it uses feed-forward neural networks to perform supervised batch learning, which has been widely adopted in deep learning applications. The principle of RProp is that the derivative size and step size should not negatively affect the weighting step. Therefore, the direction of the weight update is determined solely by the sign of the derivative. Fig. 3 illustrates the application of the RProp algorithm in the current research.

The nonlinearity nature of the ANN is provided by the activation function known as log sigmoid. The method of this activation function has been well-documented in ANN applications in the concrete engineering field [6,47,48].

3.3 ANN architecture definition using *k-fold validation*

To define the optimal hidden layer neurons, *k-fold* validation combined with the average root mean squared error (RMSE) is employed [Eq. (1)]. Here, *k-fold* validation involves dividing the dataset into *k* equally sized subsets, or "folds," and then training the neural network on *k-1* folds while validating its performance on the leftover partition. This procedure is realized *k* times, with every partition utilized as the validation dataset once. The average RMSE, which measures the prediction error of the model, is calculated across all *k* folds [48].

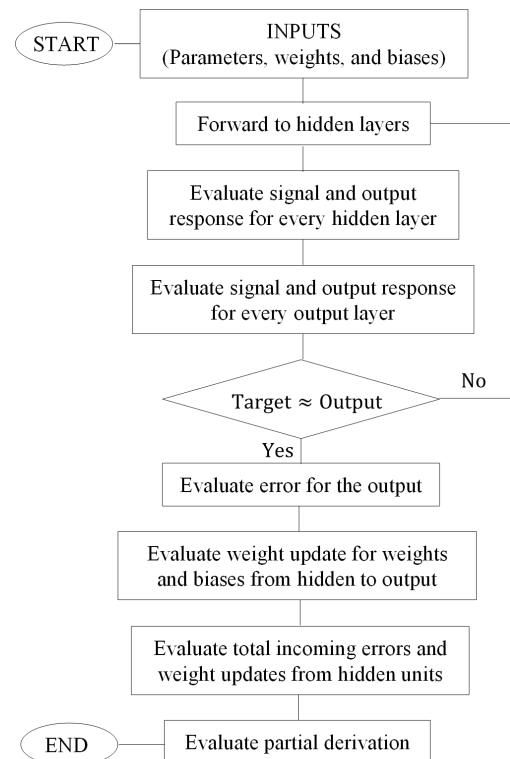


Figure 3. The RProp algorithm.

Source: The authors

By varying the hidden layer's number of neurons in the *k-fold* validation process, the performance of the ANN model is obtained for different configurations. The hidden layer's number of neurons is varied over a range of values, and the configuration that results in the lowest average RMSE is selected as the optimal number of neurons. In this manner, the most effective neural network architecture is identified to achieve a balance between model complexity and prediction accuracy for the current concrete engineering problem [6].

3.4 ANN performance evaluation

The capability of the model to calculate the targeted response was evaluated based on four parameters: (i) the RMSE; (ii) the coefficient of determination [R^2 , Eq. (2)]; (iii) the mean absolute error [MAPE, Eq. (3)], and (iv) the normalized mean bias error [NMBE, Eq. (4)].

$$\text{RMSE} = \sqrt{\frac{\sum_{i=1}^n (a_i - \hat{a}_i)^2}{n}} \quad (1)$$

$$R^2 = 1 - \frac{\sum_{i=1}^n (a_i - \hat{a}_i)^2}{\sum_{i=1}^n \hat{a}_i^2} \quad (2)$$

$$\text{MAPE}(\%) = \frac{100}{n} \sum_{i=1}^n \frac{|a_i - \hat{a}_i|}{|\hat{a}_i|} \quad (3)$$

$$\text{NMBE}(\%) = \frac{100}{n} \left(\frac{\sum_{i=1}^n (a_i - \hat{a}_i)^2}{\bar{a}_i} \right) \quad (4)$$

Where,

- n : the number of data points in the training and testing sets.
- a_i : the targeted response.
- $\hat{a}_i$: the predicted response.
- $\bar{a}_i$: the mean of the targeted response.

3.5 Connection weight approach

A CWA is a method used to interpret and understand the internal workings of ANNs [56], which are often called "black boxes" due to their complexity and non-linearity. This approach involves analyzing the weights assigned to the connections between neurons in the neural network. It is possible to gain insights into the relative importance of different input features or variables by examining the magnitude and direction of these weights. This approach is useful in interpreting and explaining the decision-making process of ANN used in the concrete investigation by recent research [6,48,57]. Engineers and practitioners in the cementitious materials field will better understand the effect of concrete's components on its characteristics.

4 Results and discussion

4.1 Model description and performance

This study developed an ANN model with a unique one-hidden layer by employing the R statistical language and the

neuralnet function. Sixteen different architectures were tested for each activation function, and 100 models were computed for each architecture to mitigate the effect of the connection's initial weight allocation. As a result, a total of 3,200 ANN approaches were established to forecast the slump flow of fresh UHPC utilizing the earlier mentioned 793 test result records. These networks consisted of an input layer containing the input nodes, a hidden layer of computational neurons, and an output layer. The input signals were grouped into two classes:

- The volume ratio of UHPC-making ingredients: including cement (PC), silica fume (SF), fly ash (FA), ground granulated blast furnace slag (GGBFS), waste ground glass powder (GP), rice husk ash (RHA), fluid catalytic residue (FC3R), metakaolin (MK), limestone powder (LP), water (W), polycarboxylate-based high-range water reducer admixture (HRWR), quartz powder (QP), and total aggregate (A).
- UHPC's features: the maximum size of aggregate (MSA), water-to-binder ratio (WB), water-to-total powders ratio (WP), and virtual packing density (VPD), which represents the relationship between components.

The VPD is not typically included in scientific articles but was estimated using the available data, particularly the mean particle size (d_{50}) and the mixture proportion. The calculation of VPD was based on the compressive packing model theory [58-60]. Fig. 4 depicts the average RMSE obtained in the most favorable initial weight allocation versus the hidden layer's number of neurons. It is evident that three neurons in the hidden layer of the ANN result in the minimum RMSE. Therefore, the ANN configuration shown in Fig. 5 was selected for implementation.

The performance of the ANN model was measured using the metrics listed in Table 1. Based on these results, it can be concluded that the ANN approach predicts UHPC slump flow reasonably well, with R^2 values of 0.97 and 0.91 for training and testing subsets, respectively. The regression plot shown in Fig. 6 also shows the good performance of the ANN model. Furthermore, the performance metrics on train and test data subsets are in the same order of magnitude, indicating proper implementation of the *k-fold* validation method [6,47,48].

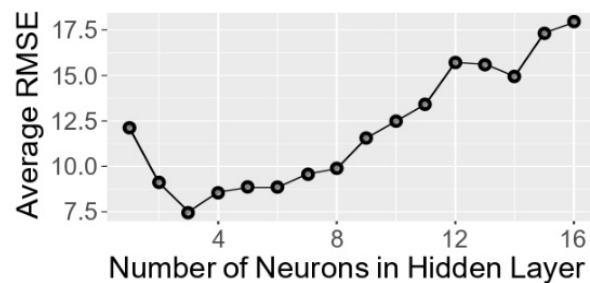


Figure 4. Average RMSE obtained during the *k-fold* validation training versus the number of neurons in the hidden layer.

Source: The authors

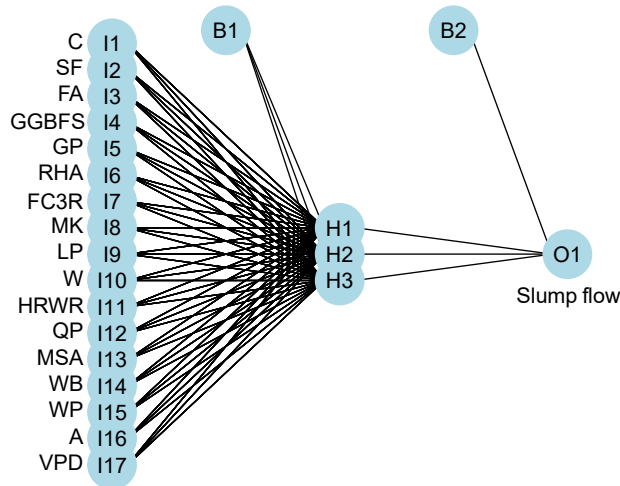


Figure 5. Chosen ANN architecture for predicting the UHPC slump flow.
Source: The authors

Table 1.
Performance metrics of the ANN regression model.

Subset	RMSE	R ²	MAPE	NMBE
Train	7.509	0.971	4.477%	-2.175%
Test	9.603	0.909	5.372%	-0.137%

Source: The authors.

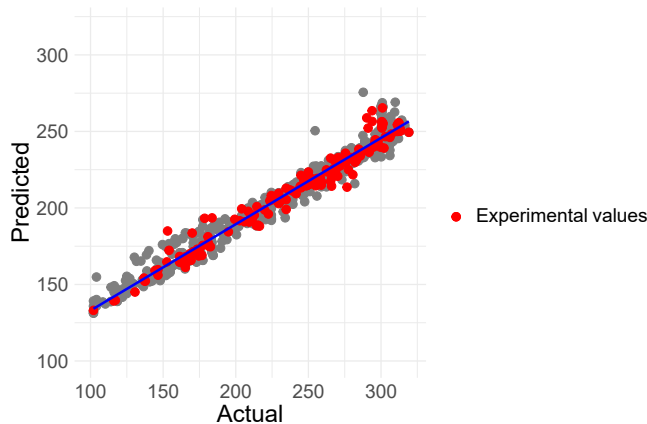


Figure 6. ANN regression plot discriminating the experimental UHPC's slump flow values.
Source: The authors

4.2 CWA findings and discussion

A summary of the findings obtained by the CWA is shown in Fig. 7. The results of the CWA analysis were consistent with expectations, indicating that water content (W) had the highest positive importance in predicting slump flow, followed by HRWR dosage. Other variables that positively influenced slump flow were those related to the water amount (WP, WB), demonstrating relative importance. The dosages of LP, FA, and GP also show a positive influence on the flowability of the mixture. A similar pattern of results was observed in previous studies in this area [6,61].

The significance of LP dosage in the improvement of UHPC rheological performance has been well-established in

previous research. Yu, Spiesz, and Brouwers [62] concluded that LP utilized as a partial substitution for C could significantly enhance the flowability of UHPC, emphasizing its importance as a supplementary material in UHPC production. Furthermore, recent studies [63,64] have highlighted the positive impact of LP on the UHPC's mechanical durability features, making it a promising addition to modern concrete technology. Additionally, LP has shown the ability to mitigate the cement-polycarboxylate incompatibility in UHPC, which poses a serious concern in the application of this excellent cementitious material [65-67].

The fly ash, on the other hand, significantly affects the rheological properties of UHPC. Its particles' spherical shape improves the concrete mixture's flowability, workability, and cohesion. It reduces internal friction, allowing for smoother movement of particles. This results in enhanced stability, reduced segregation, and improved overall rheological performance of UHPC [48]. On the other hand, fly ash is still an ultra-fine powder that demands water in concrete. Therefore, the fly ash addition produces a limited positive effect as shown in Fig. 7.

The positive influence of GP on concrete can be attributed to its remarkably low water absorption characteristics [7,30,68], which in turn improves the rheology of the concrete. Furthermore, the incorporation of GP in the mixture leads to an augment in alkaline concentration due to its high Na₂O concentration [69,70]. Consequently, the liquid phase's higher alkalinity results in the paste's lower shear strength, contributing to increased flowability [7,71,72]. Moreover, it is also relevant to glass particles having almost zero water absorption. Therefore, when partially replacing other components, the inclusion of GP provides more free water to contribute to the rheology properties of concrete [70].

Moreover, MSA has a slightly positive influence on the rheological features of the fresh-state UHPC. In this sense, sand's maximum size and gradation are critical factors influencing the rheological behavior of this high-performance cementitious composite. Typically, UHPC employs manufactured crushed and classified quartz as micro sand with an MSA value of 600 μm, which may necessitate

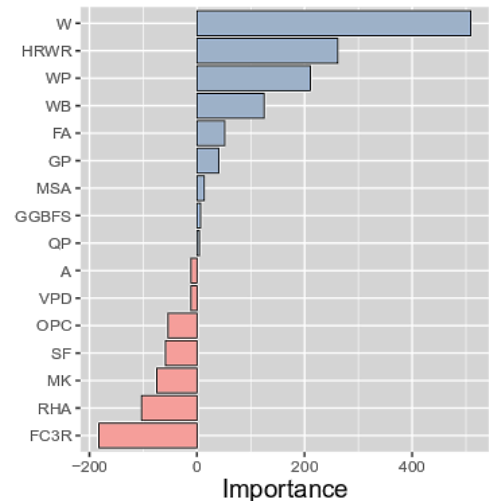


Figure 7. Findings depicted in the CWA analysis.
Source: The authors

an increase in binder proportion to ensure adequate flowability [73]. This is due to the fact that smaller sand grains lead to a larger specific surface, requiring a higher amount of paste to achieve the desired workability. Consequently, when the sand volume is fixed, the utilization of sand with a larger maximum particle size can be considered to improve rheological performance and mitigate shear thickening behavior [73,74]. Thus, the larger the particle size, the larger the slump flow of UHPC.

Continuing with the analysis of the CWA results, the following list of UHPC-making materials appears to have a positive but non-significant influence on the rheological features of the UHPC: GGBSF, QP, and VPD.

On the one hand, the collective findings of several recent studies shed light on the significant impact of GGBFS on the rheology and mechanical properties of concrete, supporting the results depicted in Fig. 7. Bature et al. [75] conducted experiments revealing that the addition of GGBFS to concrete resulted in a notable reduction in its dynamic yield stress, leading to improved workability and pumpability. Gokce [76] corroborated these findings, demonstrating that incorporating GGBS into self-compacting concrete notably enhanced its flow consistency. For its part, Torres et al. [77] conducted a comprehensive study examining the impact of different superplasticizers on the reactive powder concrete's workability and compressive strength when this SCM was incorporated. The results underscored the significant role of superplasticizer type and composition in influencing concrete spread, viscosity, and compressive performance. This effect was found to be far more significant than the GGBSF. Moreover, as per Zang et al. [78], finer particles of slag with sizes up to 30 microns negatively influenced the rheology of concrete, while coarser particles with sizes between 30 and 45 microns had the opposite effect.

To sum up, the above paragraph highlights the findings from recent studies that collectively emphasize that the impact of GGBFS on the rheology of concrete is limited and depends upon its particle size more than chemical reactions [75-79]. The latter supports the results observed in the CWA analysis.

For its part, QP is a constituent of a typical UHPC mixture proportion whose main objective is to contribute to obtaining the desired concrete packing density [79,80]. Similarly, to what we will see occurs with VPD, the CWA analysis shows that this component has a positive effect but is of limited relevance to the UHPC's slump flow value.

The case of the influence of the VPD on the UHPC's rheological features can be a little bit controversial when comparing it to other typologies of concrete. The studies reviewed in the field of concrete engineering indicate that particle packing density plays a significant role in the rheological properties of concrete. Ghoddousiet al. [81] demonstrated in their work published in 2014 that exists an optimal packing density for self-consolidating concrete mixtures, which leads to improved velocity and rheological properties. In general, higher packing densities can result in mixtures that require less water, thereby reducing the amount of cement needed. For its part, Chateau [82] provided an overview of the impact of particle properties on packing characteristics and presented predictive models for packing

density in particle mixtures. Mehdi pour & Khayat [83] conducted a review on the influence of packing features of colloidal and non-colloidal particles on the rheo-physical properties of cementitious suspensions and concluded that the rheological features are mainly influenced by the relative solid packing fraction. Collectively, these studies suggest that optimizing particle packing density can enhance the concrete rheological features and potentially reduce the amount of cement required. However, in the case of UHPC, this situation is negatively compensated by the necessity of ultra-fine particles to obtain the high packing density values that reach values over 0.8 when conventional concrete's around 0.6 [70]. These ultra-fine particles, such as SF with an average particle size of about 0.15 microns, thereby augmenting drastically the specific surface of the mixture [84,85]. This balance could be the explanation for why VPD appears to be positive but with non-relevant importance in the slump flow of UHPC, contrary to what happens in other concrete types.

The CWA analysis indicates the little adverse effect of aggregate (A) on UHPC's workability. In this sense, Yang et al. [86] found that the addition of angular manufactured sand, the typical aggregate utilized in UHPC, can negatively affect the flowability and volume stability of this special concrete. According to this research work, the incorporation of quartz angular micro sand might disturb the UHPC particle packing skeleton, leading to a deterioration of the slump flow values.

The next component to be commented on is cement (C), which, as expected, displays a negative influence on the UHPC slump flow. Portland cement clinker's mineral composition, which includes C_3S , C_2S , C_3A , and C_4AF , is a significant factor that affects the workability of any type of fresh concrete. Gypsum is incorporated into the clinker to grind the cement, and each mineral composition reacts with water at different rates and requires different amounts of water. As such, the mineral composition can affect the cement paste's rheological properties. Ions like SO_4^{2-} , OH^- , Na^+ , and K^+ may be released into the water when cement comes into contact with water, which can influence the adsorption of the superplasticizer onto cement particles, thereby influencing cement paste rheological performance [87]. The cement's fineness also impacts the cement paste's rheological performance since fine cement particles hydrate faster than coarser ones and require more water for a given flowability. Many researchers have extensively studied cement's chemical and physical features, and the results indicate that an increase in cement dosage can reduce the flowability of fresh concrete [88]. For instance, Hope et al. [88] found that cement with high Al_2O_3 or C_2S contents requires more water, while cement with high ignition loss, C_3S content, or high carbonate concentration demands less water for a given slump. Mork et al. [89] noted that reducing the gypsum-to-hemihydrate ratio can decrease the yield stress of concrete for cement with high C_3A and alkalis content, but the effects were less pronounced for cement with lower C_3A and alkalis content. Dils et al. [90] examined the impact of cement's chemical composition and refinement on the rheological properties of UHPC and discovered that cement with a high C_3A and specific surface, a high alkali content, and a low SO_3 content provided poor flowability.

For its part, Chen & Kwan [91] showed that an increase in cement dosage could decrease the fresh concrete's workability, increasing the yield stress and apparent viscosity, particularly at higher water-to-cement ratios. At lower water content, the addition of superfine cement can improve the rheological properties of cement paste by filling the voids, increasing the packing density, and releasing the water between cement particles, leading to a thicker water film coating the particles in the cement paste. However, at higher water dosages, the addition of superfine cement may not have an obvious influence on the water film thickness due to the high specific surface area, which can increase plastic viscosity and yield stress [87,91]. Hence, the aforementioned pieces of research support the obtained CWA results (Fig. 7).

Regarding the SF, which is UHPC's most common SCM to enhance mechanical and durability properties. However, excessive dosage of SF can worsen the flowability of UHPC owing to the SF's small particle size. SF particles are so fine that they augment the specific surface area of the mixture, leading to a greater demand for water and superplasticizers to maintain the required workability. The WB in UHPC is closely linked to the SF content because of the aforementioned reasons [28]. These explanations are in line with the findings presented in Fig. 7.

Incorporating metakaolin (MK) into the UHPC leads to a reduction in slump flow, as the replacement ratio of this SCM increases. This reduction in flowability can be attributed to the accelerating effect of MK on the hydration process, which is supported by the high pozzolanic activity index observed at the early ages of this concrete-making ingredient. Additionally, the high content of amorphous SiO_2 and Al_2O_3 , as well as the porous non-spherical particles of MK contribute to the negative impact on workability [92,93]. Moreover, these pieces of research also suggested that the chemical reaction of reactive SiO_2 and Al_2O_3 content of MK can generate enormous heat during the hydration process, which can worsen flowability. Therefore, it should be noted that previous studies have demonstrated that incorporating MK into concrete requires more water or superplasticizer to achieve the desired level of flowability [94,95].

For its part, the incorporation of RHA in concrete results in a decrease in the slump flow value of UHPC, and this effect becomes more significant with an increase in the amount of RHA used (i.e., as the percentage of partial substitution of RHA increases, the factor A value decreases). The negative impact on the rheology of the concrete can be attributed to the non-spherical shape and porosity of RHA particles [48]. The use of materials with higher surface area and water absorption reduces the availability of free water in UHPC. This lower free water content increases friction between the solid particles in the bulk paste, resulting in highly viscous concrete with a lower slump flow. Additionally, replacing cement with RHA by weight leads to a higher paste volume due to RHA's lower density, which reduces the amount of free water available. Therefore, incorporating RHA necessitates greater water and/or superplasticizer contents to achieve the desired workability, as previously reported by [96-97].

Finally, the highest degree of importance is attributed to FC3R. This can be ascribed to the increased formation of

ettringite with higher levels of FC3R substitution for C in the concrete, as evidenced in previous studies [48,92], resulting in decreased flowability. Additionally, it has been demonstrated in several investigations that the incorporation of FC3R in concrete necessitates higher water content to achieve the desired workability [48,92,93].

5 Conclusions

The present study proposes a novel approach for predicting the UHPC slump flow using ANN. During the *k-fold* validation of the training process, the initial weight allocation and number of neurons in the hidden layer were chosen to minimize the RMSE between the actual and predicted values. Accordingly, 3,200 ANN models were constructed using the 793 observations to predict the slump flow of UHPC. The optimized ANN model consisted of seventeen nodes in the input layer, three computational neurons in the hidden layer, and an output layer. The ANN paradigm showed proper accuracy in the prediction of the considered response, achieving an R^2 value in the testing subset of 0.91. The CWA approach demonstrated that water content (W) had the highest positive importance in predicting slump flow, followed by superplasticizer content HRWR. Other factors that positively influenced slump flow prediction were the water-to-powder ratio (WP), water-to-binder ratio (WB), limestone content (LP), and recycled glass powder (GP), all of which demonstrated relative importance. The study also found that the maximum size of aggregate (MSA) was a critical factor influencing the UHPC's rheological performance. Cement displayed a negative influence on the UHPC slump flow. In this sense, the mineral composition of Portland cement clinker, gypsum, and the fineness of cement were factors that affected the rheological behavior of this cementitious material. It is also relevant to highlight that the findings depicted by the CWA analysis were well-correlated with experimental works around the world, which supports the models created.

6 Impact, limitations, and future research

In this study, we have introduced a novel, optimized one-hidden layer ANN model for the accurate prediction of UHPC slump flow, thereby contributing to the advancement of computational methodologies in civil engineering. The ANN model was rigorously tested against a comprehensive dataset of 793 observations, which were further validated through *k-fold* cross-validation. The resultant ANN demonstrated remarkable accuracy, achieving an R^2 value of 0.91 in the testing subset. Beyond mere prediction, the study also employed the CWA analysis to identify critical factors influencing the slump flow of UHPC, thereby providing a comprehensive tool for both prediction and understanding the underlying mechanics of UHPC flowability.

Although the ANN approach presented in this study showed promising results in predicting the slump flow of UHPC, some limitations must be acknowledged. First, the dataset used for training and testing the model was limited to the components listed in the manuscript. Therefore, future research should aim to include a broader range of UHPC-

making materials (i.e., other SCM, mineral admixtures, and so on) to validate the performance of the ANN approach across a wider range of UHPC compositions.

Second, while the CWA approach identified important factors that influence the slump flow of UHPC, it is important to note that the analysis was based solely on the data used in this study. Therefore, future research should include additional factors and variables that may impact the rheological behavior of UHPC. For instance, the mixing procedure or the addition of ice to the mixture.

Lastly, the current study focused solely on predicting the slump flow of UHPC in the fresh state. Future research should aim to extend this approach to predict other important properties of UHPC, such as compressive strength, flexural strength, and durability.

In summary, the results of this study provide a promising approach for predicting the slump flow of UHPC using an ANN model and identifying important factors that influence its rheological behavior. However, further research is necessary to validate these findings across a broader range of UHPC compositions and to extend this approach to predict other important properties of UHPC.

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Simulation analysis of school road traffic characteristics

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Abstract

This study aims to identify key factors and sensitive intervals affect the school road traffic characteristics. We collect traffic data from the parking area and the school road (400-700 meters). The simulation is calibrated to ensure the error of outputs are within 1.5%. A sensitivity analysis method is proposed, it makes the multifactor comparable. The sensitivity factors of vehicle delay, queue length, and average speed are 1.44, 2.03, and 0.28 in school road, and the bottleneck road are 3.07, 4.44, and 0.65. The traffic indicators change more concentrated in bottleneck road but greater in school road. 6 scenarios are created to analyze school road traffic characteristics. Traffic flow (TF), number of parking spaces (NPS), and stopping time (ST) are selected as variables. Scenarios 1-3 are univariate, and scenarios 4-6 are bivariate. TF is the key factor with a sensitivity interval of [1300,1700].

Keywords: urban traffic; traffic characteristic; simulation analysis; sensitivity analysis; school commuting.

Análisis de simulación de las características del tráfico escolar

Resumen

El objetivo de este estudio es identificar los factores clave y las zonas sensibles que afectan a las características del tráfico de las carreteras escolares. Recogemos datos de tráfico de la zona de aparcamiento y de la carretera escolar (400-700 metros). La simulación se calibró y el error de salida se situó dentro del 1,5%. Se propone un enfoque de análisis de sensibilidad multifactorial. Los coeficientes de sensibilidad para el retraso de los vehículos, la longitud de las colas y la velocidad media son 1,44, 2,03 y 0,28 para la sección de los colegios y 3,07, 4,44 y 0,65 para la sección de los cuellos de botella. Las variables son el flujo de tráfico (TF), el número de plazas de aparcamiento (NPS) y el tiempo de parada (ST). Los escenarios 1-3 y 4-6 se establecieron como univariantes y bivariantes. TF fue el factor clave con un intervalo de sensibilidad de [1300,1700].

Palabras clave: tráfico urbano; características del tráfico; análisis de simulación; análisis de sensibilidad; transporte escolar.

1 Introduction

An important part of urban traffic travel is school commuting. The school has always been used as an important traffic generator and attraction point, crowding effect caused by private car pick-ups and drop-offs adds to school road traffic problems [1]. The number of private cars has a serious impact on the school road traffic status [2]. As the requirements of on-street parking, the resulting drive-in and drive-out process creates significant disruption to road traffic flow. This has resulted in a reduction in the capacity and worse evaluation indicators [2]. It also threatens student travel safety [3]. Hence, school roads have become a pain point for urban traffic during commuting hours. There is a

serious need for research on the traffic characteristics of school roads.

Traffic characteristics refer to the traffic system in traffic flow under different conditions of the change law and the interrelationship between the sum of the quantitative or qualitative descriptions. Thus, the study of traffic flow characteristics is the basis for an in-depth analysis of the mechanism of traffic problems on road sections, which can guide the proposal of improvement strategies and optimization of traffic design. Several countries (regions) have conducted early research on traffic flow characteristics and prepared corresponding road access manuals for road traffic conditions in their countries (regions), of which the most widely used is the U.S. Highway Capacity Manual.

Research experience has shown average speed is an effective indicator of traffic characteristics. There is a positive correlation between the road capacity (the maximum passing rate) and average speed in urban traffic, and the increase in input traffic volume will result in higher roadway density and a significant decrease in vehicle speeds [4]. And the more on-street parking behavior, the worse the maximum passing rate is [2]. The velocity-flow relationship can be divided into two parts. When the traffic flow is less than a certain value, the speed is approximately equal to the free-flow speed (roadway speed limit), while when the traffic flow is greater than a certain value, the relationship between the speed and the traffic flow is nonlinear [5]. And there are differences in the speed-density relationship at different traffic flows [6]. Vehicle delay and queue length are the key indicators for evaluating traffic efficiency and reflect stability of traffic flow [7,8]. Vehicle delay and queue length always have similar trends when traffic parameters are varied. And they are heavily influenced by traffic flow [9]. Queuing tends to occur when the first vehicle exhibits deceleration behavior [8]. During commute hours, when queue length is greater than a certain threshold, roadway capacity breaks down and impacts travel time [10]. Vehicle delay is strongly correlated with congestion zone length and congestion duration [11]. Therefore, when analyzing the vehicle delay and queue length, it is necessary to identify the key factors that contribute to the traffic problems of the study scenarios. This is also the requirement for proposing targeted optimization strategies.

The school and bottleneck roads are both similar and different in traffic characteristics. This is because One of the lanes in the school road is occupied due to on-street parking, but it still has capacity due to the short parking time. In this study, the bottleneck road is defined as a roadway with a reduced number of lanes in the urban scenario. Currently, few studies have compared the traffic characteristics between them. But extensive research has been carried out on bottleneck roads. Traffic efficiency of the bottleneck road is seriously affected by traffic flow [12]. As traffic flow increase, the evaluation indicators become terrible, e.g., the queue length increases and average vehicle speed decreases [13,14]. Traffic simulation is often used to develop further analysis of bottleneck road traffic status [15]. The bottleneck road traffic flow indicators can occur significant critical eigenvalues. This always appears when during traffic state transitions [16].

Acquisition of traffic data is the basis for the traffic characteristics study. Because of the high cost, difficulty, and low precision in actual data collection, traffic simulation is always used to study traffic characteristics. The simulation contains many parameters to describe traffic system operations, traffic flow characteristics, and driver behavior. The parameters directly affect the interaction between vehicles and lead to a fundamental difference in simulation results. Therefore, it is necessary to collect actual data to calibrate the simulation parameters [17]. Because some of them represent subtle features that are difficult to isolate, or that would require extensive data collection. The calibration problem for simulation is transformed into an optimization problem [18,19]. To minimize the error between the

simulated and actual values for evaluation indicators (e.g., queue length), the parameter values are continuously adjusted during the calibration process [20]. The traffic and geometric data used to develop and calibrate the simulation are based on actual roads, e.g., Field Survey and OpenStreetMap (OSM) [21]. Due to the obvious differences in traffic parameters such as vehicle speed between the upstream and downstream of the road, the locations of change in parameter values should be identified in the actual observation and a simulation detector should be set up [22]. The calibrated simulation outputs are reliable. This can provide a realistic reflection of the actual road traffic characteristics [23].

The study focuses on school road traffic characteristics by simulation. In the part 2, simulation is constructed. To reflect actual traffic characteristics, data observations are made at the stopping zone and starting and ending points of the school road. The simulation parameters are calibrated by collecting observations. In the part 3, the differences in traffic characteristics between the school and bottleneck roads are analyzed by sensitivity analysis. In the part 4, the school road traffic characteristics are analyzed in depth. Six scenarios are set to qualitatively and quantitatively analyze the relationship between variables (TF, NPS and ST) and evaluation indicators (vehicle delay, queue length and average speed). In parts 5 and 6, we discuss the reliability of the findings and summarize the study.

2 Traffic simulation build and driving behavior parameter calibration

For the reliability of the simulation output results, typical scenarios of school roads are selected for the collection of actual data. We describe the data collection process and observation data characteristics. Then, a microsimulation environment is built and driving behavior parameters are calibrated.

2.1 Study area and data collection

The selected scenes should satisfy the following requirements: (1) Number of road sections with two or more lanes in one direction. (2) Short-term aggregation of traffic flow (>1500 pcu/h). (3) Existence of on-street parking or other factors that interfere with the stability of traffic flow. We describe the data collection using the Northeast Normal University Elementary School at Changchun, China, as an example.

Rangefinders and unmanned aerial vehicle (UAV) equipment are used to collect data. The selection of data collection locations follows the principles: (1) No shooting angle or blocking problem, and the scanning range is large enough. (2) Significant changes in traffic status, e.g., upstream and downstream junctions with the school road. (3) Worst traffic areas, e.g., parking concentration areas. Fig. 1 illustrates our selected data collection locations. And the school road is the study area. The approximate length of the road is 1,000 meters, ranging from 0-400 meters upstream, 400-700 meters for the school road, and 700-1,000 meters for the downstream.

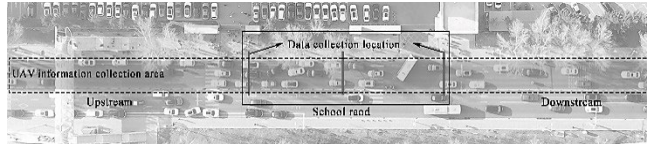


Figure 1 Data collection location.

Source: Own elaboration.

Table 1.

Basic data names and values.

Name	Unit	Value
Acceleration	km/h ²	4
Percentage of cars	%	90
Percentage of buses	%	10
Stopping vehicles	pcu	500
Lane number	-	3
Lane width	m	3.25
Length of parking space	m	6

Source: Own elaboration.

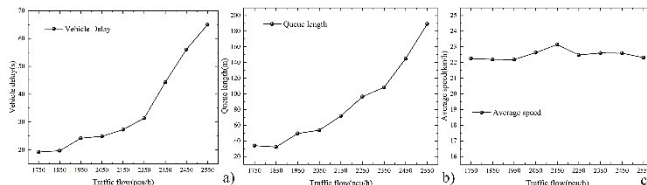


Figure 2 Actual data characteristic: a) Vehicle Delay; b) Queue Length; c) Average Speed.

Source: Own elaboration.

We have mined the video data with Tracker software. Due to the cold climate in Northeast China, the percentage of non-motorized vehicles is very small. Hence, the study focuses on motor vehicle flow. We categorize the collected data into traffic data and basic data. And the basic data are listed in Table 1.

Traffic data including vehicle delay, queue length, average speed, travel time, TF, NPS and ST. We count the observation data of evaluation indicators when TF varied between 1750 and 2550 (in steps of 100). Fig. 2 shows their changes. Vehicle delay and queue length increase quickly with TF, and queue length rises more rapidly. Smaller change range in average speed due to the road speed limit and traffic status. In actual observations it was found that when TF is at a low level, the vehicle speed is essentially equal to the roadway speed limit, vehicle delay and queue length values are small, and they have little variation, but when TF is greater than 1700, the vehicle delay and queue length values increase rapidly, and average speed maintained at low level.

2.2 Simulation build-up

PTV VISSIM 7.0 is used to build the traffic simulation, the steps are as follows:

Step 1: Establishing road. The study area is erected one-way three-lane. In China, the minimum distance between the main roads of urban intersections are 600 meters, so the length is set to 1000 meters. According to the regulatory requirements, the road within 150 meters radius up and downstream of the school entrance belong to the school road.

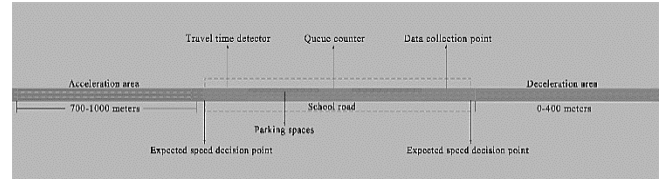


Figure 3 School road simulation scene.

Source: Own elaboration.

Therefore, the study section is divided into upstream (the range is 0-400 meters), school road (the range is 400-700 meters), and downstream (the range is 700-1000 meters).

Step 2: Upstream section settings. The speed limit value of the school road should not exceed 30 km/h. Hence, a deceleration zone is set up. It is located at 0-400 meters, and the deceleration is 4.

Step 3: School road settings. The expected speed decision point is set at 400 meters. It ensures that the vehicle speed is around 30km/h. Parking spaces are set at 400-700 meters, they set up lane close to the school.

Step 4: Downstream section settings. The acceleration zone is set at 700-1000 meters to simulate the vehicle speed recovery after leaving the school road. The acceleration is 4, and the desired speed is 60 km/h.

Step 5: Traffic parameter settings. We set TF, NPS and ST to variable traffic parameters. They are used for simulation analysis in different scenarios.

Step 6: Detector settings. The vehicle delay, queue length, and average speed can reflect the traffic characteristics well, and they are chosen as evaluation indicators. We set up the queue counter, data collection point and travel time detector in the simulation to obtain evaluation data. Queuing is considered to occur when the vehicle speed is between 5-10km/h.

According to the above process, we have built the simulation scenario, as shown in Fig. 3.

2.3 Driving behavior parameter calibration

In order to make the simulation output results reliable, we calibrate the microscopic driving behavior parameters. This work includes calibration parameter determination, calibration algorithm design and result analysis.

Calibration parameters are driving behavior parameters that are difficult to obtain from actual observations but have a significant effect on the simulation results. In Vissim, they usually refer to the max-forward-looking distance (MFLD), average stopping distance (ASD), additional part of the safe distance (APSD), multiplier part of the safe distance (MPSD), max-deceleration (MD), waiting time before disappearing (WTD), min-headspace (MH). We use the Pearson Correlation Coefficient by eq. (1) and consider that the parameter has a significant effect on the evaluation indicators when the significance index is less than 0.05. The calibration process requires repeated calls to the simulation. Filtering of calibration parameters not only ensures calibration results but also improves computational efficiency. Queue length and travel time are selected because the evaluation indicators need to meet the requirements of being easily accessible in real-world and directly exportable by simulation and reflect well on traffic running [8,24]. Table 2 demonstrates the correlation of driving behavior parameters with queue length and travel time.

$$P(X, Y) = \frac{\text{cov}(X, Y)}{\frac{\sigma_X \sigma_Y}{E(XY) - E(X)E(Y)}} \quad (1)$$

$$= \frac{\sigma_X \sigma_Y}{\sqrt{E(X^2) - E^2(X)} \sqrt{E(Y^2) - E^2(Y)}}$$

Where $P(X, Y)$ is Pearson Correlation Coefficient; X is the driving behavior parameter; and Y is the evaluation indicator.

The parameter calibration aims to minimize the error between the output results of the simulation and actual measured value. As shown in eq. (2), the root mean square relative error is used to construct the objective function. We used MATLAB R2016a and PTV Vissim 2021 to solve the problem using a GA. The computer hardware device used have an 11th Gen Intel (R) Core (TM) i7-11800H CPU, where the number of cores and logical processors is 8 and 16, respectively, and the RAM is 16 GB. The crossover probability is considered 0.8, the variance probability is considered 0.2, and the maximum number of iterations is 50. The calibration process is illustrated in Fig. 4.

$$\text{Min}F(x) = \sqrt{(Q_r - Q_s)^2} + \sqrt{(T_r - T_s)^2} \quad (2)$$

Where Q_r and Q_s are the observed and simulated values of queue length; T_r and T_s are the observed and simulated values of travel time.

Table 2.
Basic data names and values.

Parameter	Queue length		Travel time		Select
	P	S	P	S	
MFLD	0.483	0.187	0.561	0.116	N
ASD	-0.853	0.003	-0.902	0.001	Y
APSD	0.890	0.001	0.942	0.000	Y
MPSD	0.960	0.002	0.749	0.087	Y
MD	0.130	0.835	0.802	0.103	N
WTD	0.058	0.882	-0.055	0.888	N
MH	-0.037	0.931	0.011	0.979	N

P: Pearson Correlation; S: Significance; N: Not selected; Y: Selected.
Source: Own elaboration.

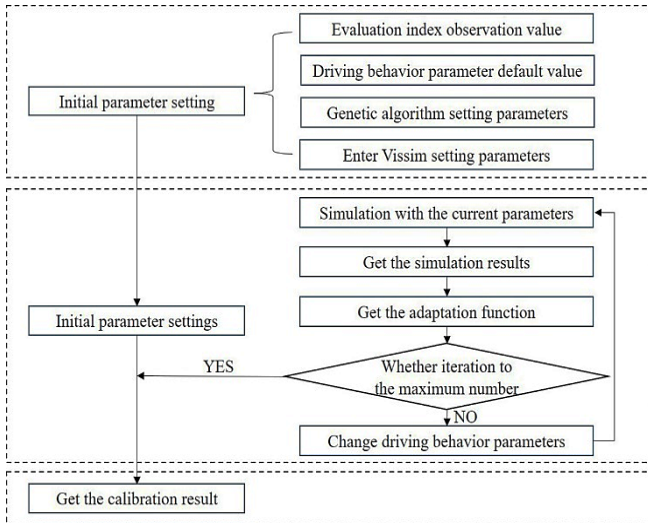


Figure 4 Parameter calibration flowchart.

Source: Own elaboration.

Table 3.

Calibration results.

Parameter	Result
MFLD	250
ASD	1.1
APSD	1.6
MPSD	3.5
MD	4
WTD	30
MH	0.5

Source: Own elaboration.

Table 4.

Comparison of simulation errors.

Evaluation indicator	Pre-calibration	Post-calibration
Queue length	7.2%	1.3%
Travel time	5.4%	0.7%

Source: Own elaboration.

Based on the results of the Pearson analysis, ASD, APSD, and MPSD are selected as parameters to be calibrated, the remaining parameters are adopted as the software defaults. The parameter calibration results are shown in Table 3.

To verify the reliability of the calibrated simulation outputs, we analyze it in comparison to using the software defaults, as shown in Table 4. The results show that the queue length and travel time output errors after simulation calibration are 1.3% and 0.7%, which are reduced by 5.9% and 4.7%. The simulation outputs after calibration are closer to the actual observed values.

3 Analysis of the school road and the bottleneck road

The most distinctive feature of traffic bottlenecks is the tendency to create congestion. In this study, bottleneck road is caused by the reduction of adjacent lanes. School road is caused by a strong traffic attraction source. This section focuses on the difference in traffic characteristics between the two types of scenarios.

3.1 Scene settings

The bottleneck road is 1,000 meters in total length and is divided into three parts: Upstream, mismatch section, and downstream. The upstream and downstream sections are three lanes. They are the same setting as the school road. The mismatch section is set up as a two-lane road. We set TF as a traffic variable. The range is [500-4500] and the step size is 400. The rest of the simulation settings are the same as the school scene, as shown in Fig. 5.

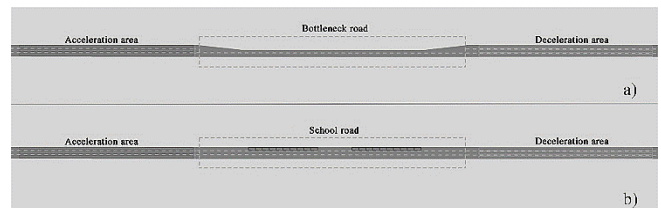


Figure 5 Simulation scene schematic: a) Bottleneck road, b) School road.

Source: Own elaboration.

3.2 Sensitivity analysis method

To compare the changes in the sensitivity values under the two scenarios, we propose a sensitivity analysis method based on the elasticity coefficient. The sensitivity function and the sensitivity factor are defined in dimensionless form, which make the multifactor sensitivity analysis comparable.

First, we establish the evaluation indicator-variable function relationship. Because cubic spline interpolation is not only characterized by excellent stability, guaranteed convergence, and smooth curves but also requires only function value information.

Second, the sensitivity function is established by eq. (3). By setting the cubic spline interpolation function as p and the variable as a_k , the comparison between the amount of change in the evaluation indicators and amount of change in the variable is defined as the sensitivity function $S_k(a_k)$.

$$S_k(a_k) = \left(\frac{|\Delta p|}{p} \right) / \left(\frac{|\Delta a_k|}{a_k} \right) = \left| \frac{\Delta p}{\Delta a_k} \right| \frac{a_k}{p} \quad (3)$$

Finally, the sensitivity factor is calculated by eq. (4). The nodes are selected to calculate the sensitivity function values according to the needs of study. Averaging them is the sensitivity factor.

$$S_k = \frac{\sum_{k=1}^n \left(\frac{|\Delta p|}{p} \right) / \left(\frac{|\Delta a_k|}{a_k} \right)}{n} = \frac{\sum_{k=1}^n \left| \frac{\Delta p}{\Delta a_k} \right| \frac{a_k}{p}}{n} \quad (4)$$

3.3 Data analysis

We analyze the traffic characteristics of two scenario types based on the method established in the previous section. The results are also compared with other methods to prove the reliability. In Fig. 6, the functional relationship between the evaluation indicator-variables is represented by the solid line, and the sensitivity function curve represented by the dotted line.

When TF changes, the changes in evaluation indicators of the school road and bottleneck road are shown in Fig. 4. From Fig. 6 (a)-(b), both scenarios show similar trends in delay and queue length. When TF increases at 500-1700, vehicle delay and queue length vary less, and the values of the sensitivity function are not above 3. The TF increases from 1700-3300 with large changes in the evaluation indicators and the maximum value of the sensitivity function is more than 10. After the TF is greater than 3300, the traffic status reaches the saturation state, and the value of the evaluation indicators fluctuate.

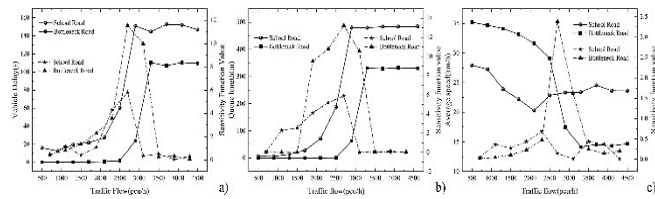


Figure 6 Comparative analysis of school road and bottleneck road: a) Vehicle Delay; b) Queue Length; c) Average Speed.
Source: Own elaboration.

Table 5.

Sensitivity factors under different methods.

Indicator	Method of the study		Common method	
	School	Bottleneck	School	Bottleneck
Vehicle delay	1.44	3.07	1.70	2.61
Queue length	2.03	4.44	1.93	2.64
Average speed	0.28	0.65	0.32	0.85

Source: Own elaboration.

From Fig. 6 (c), the average speed shows different trends with increasing TF in two scenario types. On the bottleneck road: When TF increases from 500-2000, the average speed values vary insignificantly, and the sensitivity values do not exceed 0.5. As TF increases from 2000-3300, average speed values change significantly, with sensitivity maxima exceeding 3, and then stabilizes. On the school road: As TF increases at 500-2500, the average speed values vary significantly, with sensitivity function values exceeding 0.5, and then tends to stabilize.

Extreme difference in average ratio is a common method for solving for sensitive values. Table 5 shows the sensitivity factors solved under two different methods. The results of both methods indicate a higher numerical sensitivity of the bottleneck road evaluation indicators. Ranked in order of indicator sensitivity: queue length, vehicle delay and average speed.

Comparing the two scenarios, TF has a remarkable impact on the evaluation indicators, and there are significant differences in the traffic characteristics between them. (1) Vehicle delay and queue length are experienced on the school road at low TF. (2) The school road has worse indicator values than the bottleneck road at same TF. (3) Significant differences in the sensitivity values. The bottleneck road evaluation indicators have a more concentrated change interval, which results in smaller sensitivity factors, although the school road evaluation indicators have wider change ranges.

4 Analysis of traffic characteristics of school road

The actual research found that: traffic congestion on the school road is mainly caused by changes in TF, NPS and ST. To investigate the traffic characteristics on the school road, this study analyses the impact of the individual and combined effects on the evaluation indicators.

4.1 Simulation scenarios

To analyze the relationship between research variables and evaluation indicators, 6 scenarios are created, as shown

Table 6.

Simulation scenario parameter setting.

Scenario	TF	NPS	ST
1	[500-4500] *	15	14.8
2	1700	[10-50] *	14.8
3	1700	15	[10-70] *
4	[500-4500] *	[10-50] *	14.8
5	[500-4500] *	15	[10-70] *
6	1700	[10-50] *	[10-70] *

*: Variable for the scenario.

Source: Own elaboration.

in Table 6. Scenarios 1-3 analyze the impact and sensitivity of univariate on evaluation indicators. Step sizes are 400, 4, and 6, respectively. The results of Scenario 1 have been described in the previous section. Scenarios 4-6 focus on the impact of bivariate on evaluation indicators.

4.2 Single-factor sensitivity analysis of school road

To analyze the impact of single variable on the evaluation indicators, we have described the changes and performed sensitivity analysis. In Fig. 7, 8, the solid line represents the process of evaluating indicator changes and the dashed line represents the sensitivity function.

Fig. 7 illustrates the changes in evaluation metrics as NPS increases. Vehicle delay and queue length first increase and then decrease. The change in average speed is reversed. The inflection point of evaluation indicators is when NPS is 18. When NPS varies from 10 to 18, the sensitivity means for vehicle delay, queue length, and average speed are 0.40, 2.56, and 0.18, respectively. While NPS varies from 18 to 50, the sensitivity means for them are 0.97, 2.61, and 0.33, respectively. Hence, less change in evaluation indicators at lower levels of NPS compared to higher levels.

When parking supply is at a low level, stopping demand cannot be met. As NPS is added, more vehicles can park. This has resulted in an increase in vehicle delay and queue length, and a drop in average speed. When parking supply is at a high level, stopping demand can be better met, vehicle delay and queue length begin to decline, as well as average speed subsequently increase.

NPS has a significant impact on the school road traffic operations. Rationalization of parking spaces can improve the efficiency of vehicular traffic on roads.

Fig. 8 shows the change in evaluation indicators as ST increases. Inflection points in rate of change for the evaluation indicators occurred at 52 and 64. Overall, vehicle delay and queue length continue to increase, and average speed is reduced. When the ST varies from 10 to 52, the indicators change greatly, and the sensitivity averages for vehicle delay, queue length, and average speed are 0.98, 1.12, and 0.29, respectively. The indicators tend to stabilize at

ST values between 52 and 64, with their sensitivity averages of 0.02, 0.78, and 0.04, respectively. When the ST is greater than 64, the indicators show renewed trends.

ST is disruptive to the school road traffic situation. The greater the stopping time, the worse the road traffic conditions are. Hence, ST should be minimized in context.

4.3 Multi-factor sensitivity analysis of school road

Analyzing the process of change in evaluation indicators from a multivariate perspective. We describe the process of the changes by combining trends and sensitivity factors and ranked the sensitivity magnitude of variables by comparing the sensitivity factors.

Table 7 shows the sensitivity factors for different variables. TF, NPS, and ST produce the greatest impact on vehicle delay, queue length, and average speed, respectively. In order of the impact on the evaluation indicators, from the largest to smallest, they are TF, NPS, and ST. In order of the sensitivity factors of the evaluation indicators, from the largest to smallest, they are queue length, vehicle delay, and average speed.

From Fig. 9, with changes in TF and NPS, vehicle delay and queue length show Z-shaped changes. When TF is less than 1700, little change in indicator values. This indicates that when TF is low, changes in NPS have less impact on the indicators. Once TF varies from 1700 to 2500, they increase significantly with NPS. While TF is greater than 2900, the change rate of the indicators starts to decrease. By the time TF reaches 3300, the road traffic volume reaches saturation, and these two indicators basically cease to change. Changes in average speed differ from the first two indicators. The inflection points are 1300, 1700, and 2100. When TF is less than 1300, as NPS changing, it varies little. Once TF varies from 1300 to 1700, regardless of NPS changes, it decreases sharply. At TF changes from 1700 to 2100, it increases with NPS. While TF exceeds 2100, it fluctuates.

In this scenario, vehicle delay and average speed are more sensitive to TF, and queue length is more sensitive to NPS. In general, a reduction in TF and an increase in NPS can improve the efficiency of vehicular on the school road.

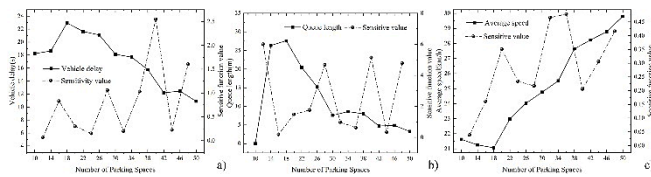


Figure 7 Evaluation indicators change with NPS: a) Vehicle Delay; b) Queuing Length; c) Average Speed.
Source: Own elaboration.

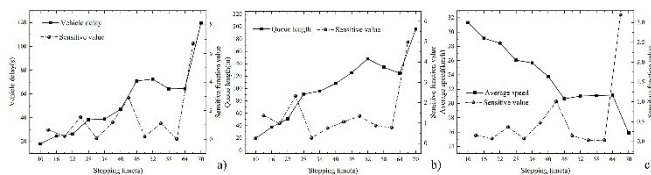


Figure 8 Evaluation indicators changes with ST: a) Vehicle Delay; b) Queuing Length; c) Average Speed.
Source: Own elaboration.

Table 7.
Sensitivity factors under different scenarios.

Variable	Vehicle delay	Queue length	Average speed	Average
TF	1.70	1.93	0.32	1.32
NPS	0.80	2.60	0.29	1.23
ST	1.45	1.47	0.56	1.16
Average	1.32	2.00	0.39	1.24

Source: Own elaboration.

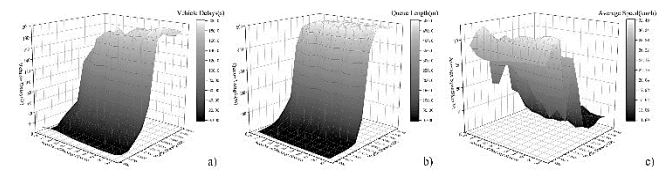


Figure 9 Evaluation Indicators change with TF and NPS: a) Vehicle Delay; b) Queue Length; c) Average Speed.
Source: Own elaboration.

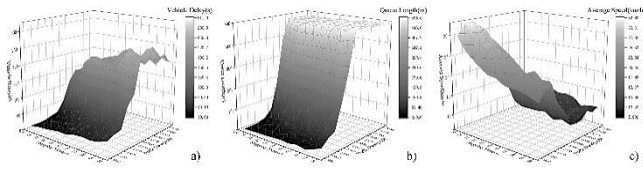


Figure 10 Evaluation indicators changes with TF and ST: a) Vehicle Delay; b) Queue Length; c) Average Speed.
Source: Own elaboration.

Fig. 10 illustrates the variation of evaluation indicators with TF and ST. Vehicle delays and queue lengths grow with increasing TF and ST overall, and average speed is reversed. When TF is less than 1700, the delay and queue length are relatively stable. This means that when TF is at a low level, ST increase has less impact on them. Once TF varies from 1700 to 2500, they increase dramatically as ST increases. By the time TF is greater than 2900, regardless of the changes in ST, they have changed very little. Average speed shows z-shaped changes with the changes of TF and ST. When TF is at a low level, ST has less effect on it. By the time TF is at 1700 to 2900, it decreases sharply as ST increases. While TF is greater than 2900, it fluctuates.

In this scenario, except for average speed, vehicle delay and queue length are more sensitive to the change of TF. In general, a reduction in TF and an increase in NPS can improve the efficiency of vehicular on the school road. The ST modulation is evident when the TF is changed at 1700 to 2500. Hence, school road traffic flow should be controlled within reasonable limits. The turnover efficiency of parking spaces can then be ensured by regulating vehicle stopping time.

Fig. 11 illustrates the variation of evaluation indicators with NPS and ST. Vehicle delay and queue length rise with increasing NPS and ST, and average speed is reversed. When NPS is less than 28, ST increases cause smaller changes in evaluation indicators. Once NPS is greater than 28, as ST increases, vehicle delay and queue length rise significantly, average speed decreases dramatically.

In this scenario, queue length is more sensitive to NPS, vehicle delay and average speed are more sensitive to TF. For NPS greater than 28, reasonable ST significantly improves the efficiency of traffic status. Hence, NPS should be rationalized according to parking demand. On this basis, ST is carried out. This can improve the operational efficiency of the traffic flow.

5 Results and discussions

To discuss the differences between simulated and observed values, we analyze the characteristics of the

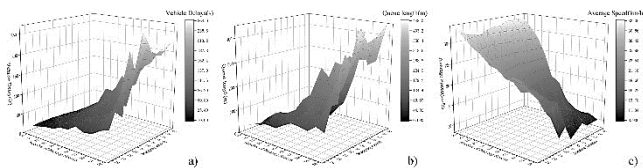


Figure 11 Evaluation indicators change with NPS and ST: a) Vehicle Delay; b) Queue Length; c) Average Speed.
Source: Own elaboration.

observations measured and simulation errors and compare the results with the relevant research.

The variables are factors that significantly interfere with traffic flow stability in the study scenario. Contributing to the traffic problems in the school scene are traffic volume short-term concentrations and on-street parking [2]. Hence, we select TF, NPS, and ST as variables. Increase in TF causes roads to be congested and traffic indicators to be worse [12-16]. The school roads are generally urban, with low vehicle speeds, and as TF increases, vehicle delay and queue length rise significantly and average speed drop or remain low. Research has shown that on-street parking, while mitigating the effects of insufficient off-street parking, has a significant impact on dynamic urban traffic [25,26]. And variations in NPS (parking area length) and ST are contributing to this effect [27,28]. In the school scenario, on-street parking behaviors are abundant. The large increase in NPS improves the level of roadway access, and the increase in ST makes the traffic indicators worse. The selection of evaluation indicators should reflect the change process of road traffic characteristics. We use vehicle delay, queue length, and average speed as evaluation indicators. Travelers are intuitively aware of the variation in vehicle speeds [5,6]. Even in school scenarios, average speed appears to vary, especially when ST changes. Vehicle delay and queue length are significantly correlated with traffic flow stability [7-11]. When the variables vary, they both change by a large amount. Vehicle delay and queue length are more sensitive to TF and NPS, respectively.

When the traffic flow is at a high level, vehicle delay and queue length are maintained at a high level and average speed is maintained at a low level [29-32]. Observational data demonstrates that when the road is congested, the relationship between speed and traffic flow is nonlinear and the speed tends to a fluctuating value [33]. During the observation and simulation of the school road, it is found that when the TF is small, the road is smooth and the evaluation indicators change little. When the TF increases to about 1700 pcu/h, the road is congested and the traffic indicators change rapidly. As the TF continues to increase, the indicators fluctuate and remain in poor shape.

Fig. 12 illustrates the simulation result errors under different traffic volumes, where ABS is the discrepancy between observed and actual values. The average errors in vehicle delay, queue length, and average speed are 0.67%, 1.26%, and 0.63%, respectively. The results show that the simulated output values after calibration have few discrepancies with the observed values.

Table 8 compares the sensitivity factors of the simulated and observed values. The ranking and trend of the evaluation indicator observations according to the size of the sensitivity

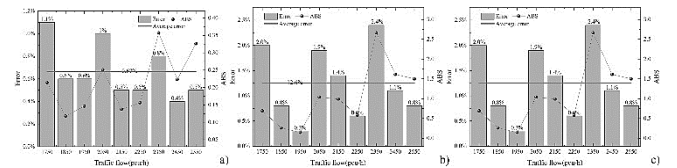


Figure 12 Simulation error: a) Vehicle Delay; b) Queue Length; c) Average Speed.
Source: Own elaboration.

Table 8.

Comparison of observed and simulated sensitivity factor.

Type	Vehicle Delay	Queue length	Average speed
Observed value	3.38	4.91	0.25
Simulated value	3.36	4.89	0.22
Error	0.36%	0.39%	15.29%

Source: Own elaboration.

factor is consistent with the simulated values. The findings for the observed and simulated sensitivity factors are consistent: when traffic flow changes, queue length is the most sensitive and average speed is the least. The errors in vehicle delay, queue length, and average speed are 0.36%, 0.39%, and 15.26%, respectively. Because of the school road speed limit (max 30km/h), the variation of the average speed is small, and the sensitivity factor error is large. The results show that the calibrated simulation outputs are basically consistent with the observed values in terms of the change in magnitude and the impact on the evaluation indicators.

Because traffic simulation can well reflect the actual traffic characteristics, it is widely used in actual engineering projects at present. The core task of simulation calibration is to reduce the error with the observed values, which requires that the simulation must be based on a realistic scenario [34]. The simulation parameter calibration process includes the selection of evaluation indicators, collection of observation data, determination of the parameters to be corrected, design of the experimental protocol, conducting simulation tests, determination of the intuitive function, determination of alternative parameters, evaluation of the simulation results, and testing the validity of the simulation. [34-37]. In this study, the data required for simulation building and calibration are collected in the field for the school scenario and the simulation calibration process is followed. For traffic efficiency simulation calibration, engineering practice often requires data errors within 5%, e.g. measurement errors in surveillance speed cameras [35]. This calibrated simulation output errors within 1.5%. They can reflect the actual road traffic characteristics properly. Microscopic traffic simulations (e.g., Vissim) also can be excellent for simulating pollutant emissions and identifying traffic conflict points [36,37].

This can be further studied from the following aspects: (1) Considering more complicated heterogeneous traffic flows. For example, the percentage of nonmotorized vehicles and pedestrians. The effects of variables on the traffic efficiency should be analyzed. (2) Based on the influence mechanism between different traffic elements, building a high-precision multiple regression model. (3) Proposing more specific optimization measures. The optimization effects should be verified.

6 Conclusions

This study focuses on the traffic characteristics of the school road, and VISSIM simulation software is used for analysis. It is found that there are significant differences in traffic characteristics between the school road and bottleneck road. The vehicle delay, queue length, and average speed reach fluctuating

states faster in the school road, indicating that parking behavior has a significant impact on road traffic. TF, NPS, and ST all have great effects on roadway traffic, but the effects are different. TF increase causes roadway congestion, NPS and ST affect the stability of traffic flow. The analysis resulted in the magnitude of the impact of each variable on roadway traffic indicators. That is, $TF > NPS > ST$.

The sensitivity function and sensitivity factor in a dimensionless form are proposed. They made the multifactor sensitivity analysis comparable. The method is used to describe the change process of school road traffic indicators and determine the sensitivity of the variables, determining the evaluation indicators most sensitive to that factor. In the school scenario, the sensitive intervals for TF, NPS, and ST are [1700,3300], [18,50], and [10,52] respectively. And in order of the sensitive factors of the evaluation indicators, from largest to smallest, they are the queue length, vehicle delay, and average speed.

We have followed the traffic simulation calibration process to calibrate the parameters of the school scenario simulation environment. A parameter calibration method for traffic simulation considering on-street parking is proposed. This method automates the calibration process, and the process is reasonable and actionable that can better reflect the actual road traffic status and play a crucial role in practical engineering. By comparing the observed data with the simulated data, the calibrated simulation outputs of average vehicle delay, queue length, and average speed have an error of 0.67%, 1.26%, and 0.63%, respectively, which reduce the error by 4.73%, 5.9%, and 4.77%, respectively. When the permissible errors in engineering practice are 1.5%, the method can fulfill the requirements.

In summary, this method can identify the key factors affecting the school road traffic status at a low cost. It also determines to set a reasonable range of traffic parameters based on the change process of the evaluation indicators and the results of the sensitivity analysis. This method can be extended to urban roadway on-street short parking scenarios, such as hospitals, shopping malls, etc.

Acknowledgements

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Factorial analysis of road infrastructure related to traffic accidents occurred in Neiva in the years 2017-2018

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Abstract

The transportation sector has been fundamental in Colombia and faces serious consequences in terms of traffic accidents. This paper examines the relationship between accidentability and most outstanding road infrastructure factors in ten urban stretches of Neiva in the period 2017-2018, following the inclusion and exclusion criteria of the International Road Assessment Program (IRAP) for developing countries in order to characterize the state of road infrastructure of the selected points. The results showed that the central sections of the city tend to be related to the day, time, type of vehicle and victim, attribute and direction of the road. The motorcyclist was the road actor most vulnerable to injuries and fatalities, Saturday and 8:00 am was where more crashes occurred. The road infrastructure factors contributing to accidents highlight the relevance of the environment in the city.

Keywords: road infrastructure; traffic accidents; factorial analysis.

Análisis factorial de la infraestructura vial relacionada con los accidentes de tránsito ocurridos en Neiva en los años 2017-2018

Resumen

El sector transporte ha sido fundamental en Colombia y se enfrenta a serias consecuencias en materia de accidentes de tráfico. Este trabajo examina la relación entre accidentabilidad y factores de infraestructura vial más sobresalientes en diez tramos urbanos de Neiva en el periodo 2017-2018, siguiendo los criterios de inclusión y exclusión del Programa Internacional de Evaluación de Carreteras (IRAP) para países en vías de desarrollo con el fin de caracterizar el estado de las infraestructuras viarias de los puntos seleccionados. Los resultados mostraron que los tramos centrales de la ciudad tienden a estar relacionados con el día, hora, tipo de vehículo y víctima, atributo y sentido de la vía. El motociclista fue el actor vial más vulnerable a lesiones y muertes, el sábado y 8:00 am fue donde más siniestros ocurrieron. Los factores de la infraestructura vial que contribuyen a los accidentes destacan la relevancia del entorno en la ciudad.

Palabras clave: infraestructura vial; accidentes de tránsito; análisis factorial.

1 Introduction

More than 1.25 million human lives are lost annually due to traffic accidents (TA) and public health problems that have mainly affected people between 15 and 29 years of age [1]. For Campos et al. [2], land transport has come to be considered one of the most dangerous means of transportation, where many pedestrians, cyclists and motorcyclists have been killed. It has been found that this major problem causes about 50 million serious damages on

citizens, where by the year 2020, in developing countries, it has come to be even within the top three of the major causes of disability; with a share of about 87% of the total events occurred [3,4], and it is predicted that by the year 2030 road accidents will be the fifth leading cause of death worldwide [5]. In addition to physical injuries, TAs cause psychological and social effects on families, impacting emotionally and economically between 1 and 3% of the Gross Domestic Product (GDP) of each nation [6].

For the year 2016, there were about 154,997 deaths

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caused by traffic in the Americas region, which came to represent about 11% of deaths worldwide due to this cause [7]. Similarly, Dávila et al. [8] pointed out that road safety in this region claims more than 154,000 lives per year, with an increasing trend, accounting for 12% of deaths worldwide due to this factor, where it has been estimated that TA are the ninth cause of death and by 2030 it is predicted to be the seventh worldwide, about half of these deaths correspond, as mentioned; to pedestrians, cyclists and motorcyclists. Motorcyclist deaths have increased from 15% in 2010 to 20% in 2013, reflecting great vulnerability and the need to further protect the lives of these road users [9].

In the country, for 2016, it was estimated that there were about 9.7 deaths per 100,000 inhabitants, which places it as the second country in South America with the second highest accident rate [10]. TAs cause approximately more than 7,000 deaths per year, for 2017, in Bogota about 32% of the TAs triggered in deaths to motorcyclists on the roads [11]. For the same year, to the National Institute of Legal Medicine and Forensic Sciences (INMLCF) [12] about 48,669 events entered by TA were reported; within this figure 15% corresponded to deaths, and, the remaining percentage to serious injuries. According to the National Road Safety Agency (ANSV) [13], in the country about 8,264 people died from road traffic in 2022, which represents a 13.67% increase over the previous year.

In the department of Huila, as described by the National Road Safety Observatory (ONSV), between the first and twelfth month of 2017, about 986 injuries were recorded with a total of 230 deaths [12]. Of these deaths, 114 and 116 occurred due to TA in urban and rural areas, respectively. It was found that Neiva was the city in the department that accounted for the highest percentage of fatalities for the year 2017 (26%) [14].

According to studies conducted by the Department of Transportation of the National Highway Traffic Safety Administration (NHTSA), they agree that the human factor is responsible for between 70 and 90% of accidents; road infrastructure, between 15 and 30%, and vehicle failure, between 5 and 12% [15].

On many occasions, the conditions and characteristics of the road infrastructure have been considered irrelevant to TA; however, it has been found that road conditions are actually significant on the occurrence of accidents, material losses and fatalities [16,17].

The municipality of Neiva remains as the seventh city in the country with the highest road accident rate, reflecting great weaknesses in the road safety system of the municipality, so it is clear that pedestrians and motorcyclists have been the most vulnerable road actors. It is important to recognize the role played by all road actors without underestimating the economic and social contribution that the city receives daily in terms of public and cargo transportation through the responsible use of road infrastructure; and although large investments have been made in the city, their condition has not been adequate.

In this research, we intend to factorially analyze the road infrastructure with respect to traffic accidents occurred in the city of Neiva during the years 2017 and 2018. The selection of the 2017-2018 period is based on the need to

perform a retrospective analysis covering recent years. This approach allows us to examine trends and patterns over two consecutive years, providing a more comprehensive view of accident rates in Neiva. This city was selected for this study not only because of its specific challenges in terms of traffic density, geographic characteristics and mobility patterns, but also because of its representativeness and relevance in terms of accident rates in the Colombian context, as it has been ranked as one of the top 10 cities with the highest road accident rates in our country.

2 State of the art

At the international level, B. Lin [18] developed an accident study in New York City on two-lane rural roads, concluding that "it is evident that curvature is an important determinant of accident rates when curvature exceeds 9°, the probability of a curve being dangerous is approximately 50% or greater (at a 95% confidence level) than straight sections of road. These characteristics suggest that curve flattening is considered a logical approach to improve road traffic safety. Speed reduction, when the vehicle moves from a straight section to a curve, has a significant impact on traffic safety. Á. Briz-Redón et al. [19] showed an analysis about TA in Valencia (Spain) during the years 2005 to 2017. The authors used binomial count models and specifically studied road crossings. The results showed that overdispersion of accident counts and disparate effects lie on road sections near intersections, generating high accident rates.

M. Pljakic and collaborators [20], analyzed the impact on infrastructure and road traffic on pedestrians, therefore, they used a geographically weighted regression to obtain and identify the significant factors on accidentability. The authors obtained about ten strong factors on pedestrian accidents: length of street networks, vehicle-kilometers traveled, length of roads, total population, number of bus stops, among others.

M. Tanishita and his team [21] investigated the impact of traffic control and road infrastructure on bystander severity in Japan. The authors applied logistic linear regression and determined that medians over intersections increased crash severity, on the other hand, they analyzed the intermittency of traffic lights (when the time to cross is about to end for the red light to turn on), and found an increase in severity over flashing traffic lights versus stop lights (stop sign).

D. Harwood et al. [22], who investigated the operational and safety effects of road geometry, found that geometric factors play an important role in defining the operational efficiency of any road and are key because they influence traffic operations and road safety. Among the most relevant elements are: the number and width of lanes, the presence and width of berms, the horizontal and vertical alignment of the road, and the signage".

Later, G. Karlaftis and Ioannis Golias [23], conducted their work on the effects of geometry and traffic volumes on road accident levels, finding that the results differed between two-lane and multi-lane (multi-lane) roads, and it was inferred that generally factors such as pavement type

and condition are the most relevant variables affecting TA rates.

At the national level, in the research conducted by F. Flórez et al. [24], the authors made a multicausal analysis of TA for the cities of Ibagué and Valledupar, using the method of reliability analysis and driving errors (DREAM) to categorize the causes associated with road incidents, for the first city, For the first city, up to 20 causes were found, 9 of which were recurrent, while for the second city, 18 causes were found, 12 of which were recurrent for accidents, where human factors (such as fatigue, vehicle failure, road geometry, among others) favor the constant frequency of accidents. N. Lopez et al. [25] analyzed the road conditions in terms of safety and road infrastructure for the city of Santa Marta, for this purpose, they conducted an exploratory and descriptive research under a survey of a sample of the population of the city, where they determined that the origin of accidents is due to factors such as speeding, lack of signaling and poor pavement condition.

P. Salcedo et al. [26] in their research, by means of network science studied the road accident rate in Bogotá, the authors spatially divided the city under Transportation Analysis Zones (TAZ) in 922 polygons. As materials, they used databases with information related to road accidents in the capital since 2011 and analyzed them using the free software GNU PSPP. It was found that the time, day, peak and plate, are significant on the pattern of accidents in the city.

In the research published by V. Cantillo et al. [17] and carried out for the city of Cartagena, the authors conducted an exploratory analysis on severe factors in TA in urban areas of the city. For the study the authors used seven factors (road infrastructure, traffic and control, victim, day and time, vehicle, and environmental factors) and three levels of crash severity (injury, fatal and only with property damage), in the study a discrete model was used to study the factors under the three levels mentioned, within the results obtained it was found that in streets with speed limit higher than 40 km/h, bridges or crosswalks, and at ages over sixty years; there is a high probability of an accident with fatal outcome.

H. Ospina et al. [10], analyzed a series of data about TA in motorcyclists in the city of Bogotá, the data were processed with information about weather and infrastructure and categorized into: weather conditions and schedule, road actors, road conditions, motorcyclists and people involved, and, location and characteristics of the accident. These five categories were found to be significant in terms of road safety in the city, which could recreate new scenarios for study and further research.

3 Materials and methods

The most distinctive feature of traffic bottlenecks is the tendency to create congestion. In this study, bottleneck road is caused by the reduction of adjacent lanes. School road is caused by a strong traffic attraction source. This section focuses on the difference in traffic characteristics between the two types of scenarios.

3.1 Type of study

In this research, a quantitative descriptive observational cross-sectional descriptive approach was used, as used by authors such as [27–29], under this approach, objective, quantifiable and analyzable data were collected about TA occurred in the city of Neiva for the years 2017-2018.

3.2 Geographical location

The study was conducted in the city of Neiva, capital of the department of Huila (Colombia). It was found that this city remains as the eighth in the nation with the highest accident rate exceeding even more than 20 fatalities per 100,000 inhabitants, managing to surpass capital cities such as Cali, Bogota and Medellin [13]. The city has 348,964 inhabitants according to the national population and housing census conducted in 2018 [30]. As of 2017, 27,439 vehicles, 20,411 motorcycles, 710 buses and 2,196 cabs were registered in the municipality.

According to data obtained from the city's Secretariat of Mobility, during 2017 and 2018 about 2,702 accidents occurred, of which 57% were reported in 2017 evidencing a decrease in the total number of accidents of 25%, compared to the previous year; although it is evident that the number of deaths increased by 150%.

3.3 Population

The study population contemplates the road sections of the city of Neiva with the highest occurrence of accidents during 2017 and 2018. In this sense, some criteria were taken into account: i) inclusion criteria, it relates the TA reported in the urban area of Neiva between January 01, 2017 and December 31, 2018, ii) exclusion criteria, it discards the report of accidents with missing information.

3.4 Sample

In this research, a non-representative sample was used, so the identification of the ten points with the highest occurrence of accidents in the period 2017-2018 was determined. Table 1 corresponds to the sample studied in this research, which, considers streets, races and avenues on which the events occurred.

Table 1.
Critical points with the highest occurrence of accidents.

Importance	Section of track	Accident	Injured	Deaths	Total
1	7 Street 55	11	10	0	21
2	Race 5 Street 48	16	2	0	18
3	Race 1 Street 48	8	7	1	16
4	Race7 Avenue Toma	11	4	0	15
5	Race 2 Street 21	9	5	0	14
6	Race 2 Street 4	5	8	0	13
7	Race 7 Street 21	7	4	0	11
8	Race 7 Street 10	9	2	0	11
9	Race 9 Street 4	3	8	0	11
10	Circunvalar avenueStreet 7	9	2	0	11

Source: Own elaboration.

3.5 Sampling

According to the sample referred to, a non-probabilistic and convenience sampling was carried out, authors such as Medina, Hincapié et al. and Gonzales et al. [31–33]; have used this type of sampling for the development of their research.

3.6 Collection of information

Based on data consulted from: i) Ministry of Transportation and Public Works (MTO), ii) ONSV, iii) INMLCF, and iv) the Neiva Mobility Secretariat; information necessary to describe how TAs behave in the city during the indicated period was obtained as input. All the information consigned in tables and figures were constructed from ITTH and INMLCF 2017-2018 data [12,34].

In this research, the methodology of the International Road Assessment Program (IRAP) for developing nations was used to characterize the state of the road infrastructure of the selected points. For this purpose, the most important factors of study on the safety and road infrastructure of Neiva's road users were determined in this research, as shown in Table 1. IRAP seeks to improve road safety by inspecting high-risk roads to encourage the prevention of TA fatalities; authors such as Lauragrazia Daidone et al. [35] have conducted similar studies.

For the collection of the information, a visual inspection was carried out by traveling in both directions of the determined roads, verifying the conditions of the infrastructure elements. The observations were recorded in the questionnaire designed for this purpose, which inquired about the characteristics, geometry, condition, flows and severity of the roads. Table 2 shows the structure of the instrument used for the questionnaire applied to the sample.

Table 2.
Structure of the questionnaire.

Road infrastructure	Variable
Track characteristics	Paved berm
	Unpaved berm
	Direction of traffic
	Number of lanes
	Auxiliary lanes
	Speed limit
	Lane width
	Pedestrian sidewalk
	Land use (lateral conflicts)
	Ciclovia
	Median
Track geometry	Traffic calming
	Track Surface
	Pavement condition
	Horizontal signage
	Vertical signaling
Track condition	Traffic light condition
	Public lighting
	Intersection control
Severity	Other conditions present
	Obstacle on the track
	Slopes
Flows	Ditches
	Ditches
	Pedestrian Cyclist

Source: Own elaboration.

3.7 Information processing

The data were tabulated and analyzed using Microsoft Excel. In this research, statistical analysis was performed by observing the behavior of the factors independently. Frequency distribution and measures of central tendency were used for qualitative and quantitative data, respectively.

4 Results and discussion

Fig. 1 corresponds to the frequency distribution of TA occurring between 00:00 and 24:00 hours per day for the study period. As can be seen, there were 3,178 TA, of which 2,807 met the defined exclusion and inclusion criteria. In relation to the time of occurrence of the accident, this figure shows that 60% of the TA occurred between 8:00 and 9:00 a.m. (1,688 accidents), 3.7% at noon (103 accidents) and less than 3.5% in the other hours. Records have shown that in countries such as Chile, the time at which the most accidents occurred during the period 2000-2009 was between 7 and 8 a.m., and that of the seven days of the week, Fridays and Saturdays had the highest incidence [36].

Table 3 corresponds to the total number of accidents that occurred during the study period according to the two aforementioned criteria. As can be seen, about 371 TA did not comply with detailed information or occurrence within the urban perimeter of the city.

Table 4 corresponds to the data obtained from the distribution of frequencies according to the type of outcome triggered by TA.

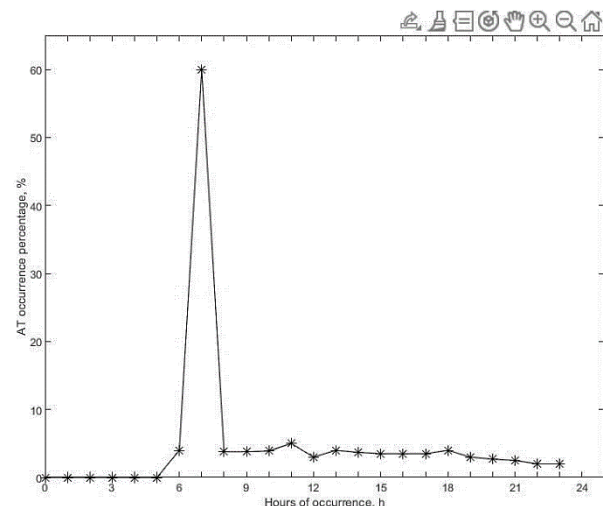


Figure 1. Hours of occurrence of TA.
Source: Own elaboration.

Table 3.
Total accidents according to inclusion and exclusion criteria

Year	Yes	No	Total
2017	1,634	214	1,848
2018	1,173	157	1,330
Total	2,807	371	3,178

Source: Own elaboration.

Table 4.

Frequency distribution by type of outcome in TA.

Unraveling	Number of accidents	Frequency (%)
Material damage	1,519	54.11
Wounded	1,232	43.89
Death	56.00	2.00
Total	2,807	100

Source: Own elaboration.

Table 5.

Frequency distribution of TA occurrence.

Day	Number of accidents	Frequency (%)
Monday	390	13.89
Tuesday	415	14.78
Wednesday	379	13.50
Thursday	401	14.29
Friday	447	15.92
Saturday	466	16.60
Sunday	309	11.01
Total	2,807	100.00

Source: Own elaboration.

Of the number of accidents that meet the above criteria, 54.11%, 43.89% and 2% correspond to TA that resulted in property damage, injuries and fatalities, respectively. As can be seen, in the 10 points of the city analyzed, property damage accounted for more than half of the TA.

Table 5 corresponds to the occurrence of accidents according to the day on which they happened. As can be seen, during January 01, 2017 and December 31, 2018, Saturday was the day of the week where the highest number of TA occurred (466), contrasting with what was obtained in [36], this great top 3 is complemented by, Friday and Tuesday which triggered a total of 447 and 415 of accidents, respectively, representing about 15.92 and 14.78% of the total accidents occurred during the period in the sections studied. It is evident that the percentage variation with respect to the day with the highest accident rate on Tuesday ($\Delta\%=1.82$) and Friday ($\Delta\%=0.68$) is lower compared to

Sunday ($\Delta\%=5.59$), a day on which the occurrence of TA was 11.01%. Although Sunday was the day with the lowest accident rate (considered a day of rest and not a working day in many places and companies), it has been found that it can never exempt citizens from the possible risks or hazards that can result in TA [37].

Table 6 corresponds to the distribution of TA frequencies according to the four daily shifts tabulated and classified as follows: i) early morning, between 00:00 and 06:00, ii) morning, between 06:00 and 12:00, iii) afternoon, between 12:00 and 18:00, iv) night, between 18:00 and 24:00. From the above table, it can be inferred that 70.12% of the accidents occurred in the morning. Also, it was found that the time range and day with the highest accident rate was Saturday morning, with about 11.62% of the total number of TA.

Table 7 corresponds to the percentage of accidents according to the type of vehicle and the outcome triggered. According to the type of vehicle involved in TA occurring in the city during the study period, it was found that the first place went to the private motorcycle (41.38%), the second to the private vehicle (23.98%) and the third to the cab with 14.79%. In relation to the type of outcome, it was found that the private motorcycle was the type of vehicle that caused the most damage, injuries and deaths in TA, with 19.70%, 67.05% and 64.29%, respectively.

Table 8 shows the type of victim involved in TA occurring in the city during the period analyzed. Of the total number of accidents reported, about 581, i.e., almost 21% involved victims (injured and deceased). Of this figure, 54.78% were vehicle occupants, 37.04% pedestrians and 8.17% cyclists. In terms of fatalities, pedestrians were the greatest fatalities (71.43%), followed by cyclists (17.14%) and vehicle occupants (11.43%). As for the injured, it was found that most of the victims were vehicle occupants (57.9%), followed by pedestrians (34.81%) and cyclists (7.59%).

Table 6.

Frequency distribution Daily days of TA occurrence.

Time range	Sunday	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Total
00:00-06:00	0.86	0.32	0.14	0.11	0.25	0.46	0.46	2.6
06:01-11:59	7.31	10.19	10.76	9.52	10.12	10.69	11.62	70.21
12:00-17:59	1.78	2.42	2.53	2.96	2.46	3.21	2.42	17.78
18:00-23:59	1.07	0.96	1.35	0.93	1.46	1.57	2.07	9.41
Total	11.01	13.90	14.79	13.51	14.29	15.93	16.57	100

Source: Own elaboration.

Table 7.

Type of vehicle and TA-related outcome.

Vehicle	Damage	Wounded	Dead	Total
Bicycle	0.07	0.08	1.79	0.11
C/tractor-trailer*	0.00	0.00	1.79	0.04
Public truck	8.04	2.60	5.36	5.60
Micro bus	14.43	5.28	7.14	10.26
Private motorcycle	19.77	67.21	64.29	41.60
Cab	17.52	11.93	3.57	14.79
Official vehicle	0.07	0.00	0.00	0.04
Private vehicle	39.33	5.76	8.93	23.98
Grand total	100	100	100	100

* Indicates a person who has suffered a TA while either as a driver or as a passenger.

Source: Own elaboration.

Table 8.

Type of victim involved in traffic accidents.

Victims	Injured (%)	Deaths (%)	Total (%)
C/occupant*	57.59	11.43	54.78
Cyclist	7.59	17.14	8.17
Pedestrian	34.81	71.43	37.04
Total	100	100	100

* Indicates a person who has suffered a TA while either as a driver or as a passenger.

Source: Own elaboration.

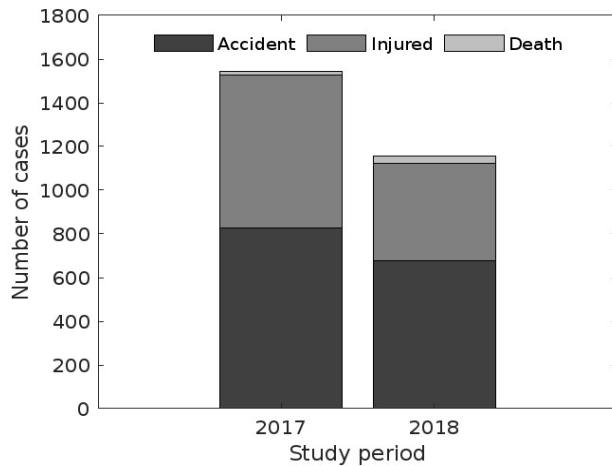


Figure 2. Number of cases reported by accident, injured and death during 2017 and 2018.
Source: Own elaboration.

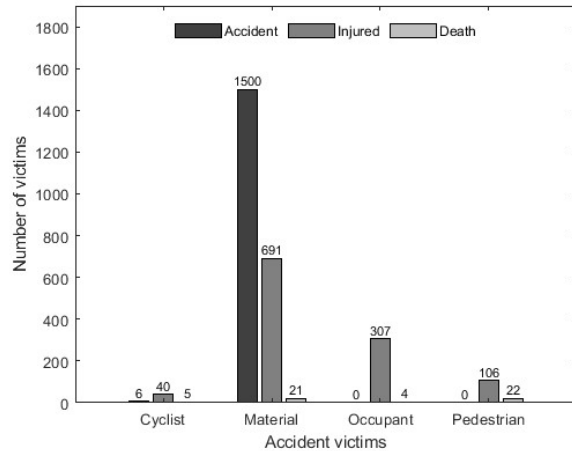


Figure 4. Cases for accident victims.
Source: Own elaboration.

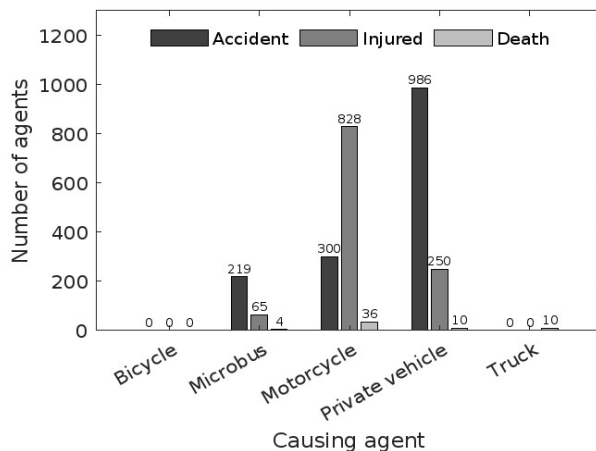


Figure 3. Cases by causative agent and type of event.
Source: Own elaboration.

Fig. 2 corresponds to the information discriminated by accident, injury, death and year of the event. As can be seen, in 2017 and 2018 there were 1,544 and 1,158 reported cases, respectively. It is highlighted that for 2018 there was a lower number of TA and injured, however, there were about 37 deaths, a higher figure than the immediately previous year (15 deaths), which allows inferring that of the fatalities does not necessarily depend on the number of accidents, but also, on the lethality and period of occurrence of the TA.

Fig. 3 shows the number of cases by causal agent and type of event. According to the agent causing the event, it was found that 46% of the cases were caused by vehicles, followed by motorcycles (43%) and minibuses (11%). In addition, it was found that private vehicles caused the greatest number of material damages with about 65% of the total number of events, while motorcycles accounted for the greatest number of injuries (72%) and deaths (75%), reflecting the great vulnerability of this means of transportation.

Fig. 4 corresponds to the number of cases per accident victim during the period studied. In terms of accident victims by TA, injury and death, it was found that property damage also dominated the first place with 82%, followed by vehicle occupants (11%) and pedestrians (5%). Similarly, it was observed that vehicle occupants had the lowest probability of death compared to cyclists and pedestrians.

Once the visual inspections were carried out and the road attribute registration forms were filled out, based on the IRAP, the following information was obtained:

Table 9 (which, because of its size, is at the end of the section of the document) represents the matrix of attributes of the sections indicated in Table 1 according to IRAP.

In this sense, according to the evaluation criteria used by IRAP to carry out the star rating of road safety by levels to the elements inspected in the road sections, and once the matrix analysis of the sections in Table 9 was performed, it was obtained as a result, that these sections maintain a level of 3 and 4 stars, this because the roads (at a general level) inspected have a sidewalk for pedestrians, wide lane, road in good condition, adequate signaling and dividing islands between lanes.

Table 10 represents the attributes associated with the accident rate during the period investigated. According to the information collected, a relationship was observed between the level of accident occurrence and attributes such as: speed, land use, berm width, intersection control, etc.

Table 9.
Matrix of attribute results according to IRAP of the sections in the ten sections studied.

			Accident hotspots in the city of Neiva (2017 - 2018)									
Categories	Track attributes	Criteria evaluated	1	2	3	4	5	6	7	8	9	10
Characteristic of the track	Number of lanes	One Two Three	X	X	X	X	X	X	X	X	X	X
	Direction of transit	Unidirectional Bidirectional	X	X	X	X	X	X	X	X	X	X
	Lanes	Does not exist One way In both directions	X	X	X	X	X	X	X	X	X	X
	Speed limit	Value	80	80	80	80	80	80	80	80	80	80
	Lane width	> 3.25 m <3.25 2.75-3.25	X	X	X	X	X	X	X	X	X	X
	Width of paved berms	No existe ≥2.4 1-2.4 <1,0	X	X	X	X	X	X	X	X	X	X
	Width of unpaved berms	Does not exist ≥2.4 1-2.4 <1.0										
	Pedestrian sidewalk	Does not exist Right Left	X	X	X	X	X	X	X	X	X	X
	Land use (lateral conflicts)	Commercial Industrial Housing Worship Education		X	X	X	X	X	X	X	X	X
	Ciclovia	Segregated barrier-free On the road Does not exist	X	X	X	X	X	X	X	X	X	X
	Median	Without median With median	X	X	X	X	X	X	X	X	X	X
	Quieting	Speed reducers velocidad None	X	X	X	X	X	X	X	X	X	X
	Horizontal curves	Very closed Closed Moderate										X
	Vertical curves	Concave Convex Flat	X	X	X	X	X	X	X	X	X	X
Track geometry	Track inclination	Wavy Mountain										
	Horizontal signage	Good Fair Poor	X	X		X	X		X		X	
	Vertical signage	Good Fair Poor	X	X	X	X	X	X			X	X
	Pavement condition	Good Fair Poor	X	X	X	X	X	X	X	X	X	X
Intersection characteristics	Intersection control	Signaled by fiscal						X				
		Traffic light				X	X		X	X	X	
		Stop	X	X	X							X
		No signage Not applicable										
		Detour				X			X			

	Other conditions present	Work on the road										
		Speed reducer Channelizer vehicle Other	X	X	X		X	X		X	X	
Flows	Pedestrians	None Density B,M,A	M	B	B	A	A	A	A	A	B	B
	Cyclist	None Density B,M,A	M	X	M	M	B	B	M	B	B	X
	Motorcyclist	None Density B,M,A	A	A	A	A	A	A	A	A	A	A
	Vehicle	None Density B,M,A	A	A	M	A	A	A	A	A	A	A
	Visual inspection rating with stars for each section		4	3	3	4	4	4	4	4	3	4

Source: Own elaboration.

Table 10.
Attributes with observable relationship to accidentability.

Track attributes	Result	Percentage
Speed	80	-
Land use (lateral conflicts)	8	80
Width of paved berm	9	90
Ciclovía	10	100
Unpaved berm width	10	100
Quieting	10	100
Track inclination	10	100
Horizontal signage	6	60
Vertical signage	8	80
Pavement condition	9	90
Intersection control	4	40
Motorcyclist	High	-
Vehicle	High	-

Source: Own elaboration.

As can be seen in Table 10, although there is evidence that the roads are acceptable, have a wide lane, a flat profile and a high-speed limit, this causes drivers to travel at high speed, creating complications and threats to pedestrians and road actors in the face of sudden events that could lead to threats and critical or catastrophic events in the face of relatively short response times. It has been found that speeding has been the main cause of TA involving fatalities on urban roads, and the second cause of fatalities on rural roads [36]. In addition, it is evident that the high mobility of motorcycles and vehicles overloads the roads, generating a large increase in the accident rate.

From this table, it can be inferred that the road signaling is not adequate in the studied sections, according to the road level, and that intersection control is less than 50%, which induces great vehicular congestion, increased accident rate, difficulty and threats to cyclists and pedestrians.

In view of this situation, authors such as Y. Asprilla et al. [5] have involved the concept of sustainable mobility through mass transportation where the use of motorcycles and vehicles with few passengers is minimized, and therefore, high road traffic is minimized leading to the reduction of AT. Likewise, as pointed out by the same author, but by means of [38], The inclusion of mass public transportation systems guarantees not only a safer transportation, but also a more

complete one, according to the complementarity and organization of schedules established for the common transportation of citizens.

5 Conclusions

Road accidents involve all actors, pedestrians, cyclists, motorcyclists, passengers and vehicle drivers. In the urban context of the city of Neiva, through this research it could be determined that in 2017 there were more TA compared to 2018 (1,544 vs 1,158), however, for the latter there were more lethal deaths (about 37). Likewise, at a general level there were cases in which there are factors that have really been significant on the TAs, such as: the environment and type of soil, time of occurrence, type of transport and victim, road section and speed. The latter has become a worrying factor for society, considering its high level of threat and weakness in terms of compliance with the regulatory system by the authorities and road actors. The results showed that, for the study period in question, the highest number of TA occurred around 8 a.m., and that the day with the highest accident rate was Saturday. Likewise, it was found that out of the ten stretches analyzed, the one comprising Carrera 7 between 54th and 55th Streets had the greatest number of occurrences; these results are truly representative for the identification of critical stretches in terms of TA. It was found that motorcyclists are the most vulnerable road actors in the city for the time range studied, highlighting also that, until now, as transportation, this means of transport has been a tool for informal work as a growing phenomenon. As pointed out by Y. Lara et al. [39], motorized urban mobility has always been the most vulnerable, where the implementation of AT mitigation policies will be essential.

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Correcting misinterpretations on the distribution of feasible solution lengths in the traveling salesman problem

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Abstract

The traveling salesman problem (TSP) is the canonical combinatorial optimization problem famous throughout literature. There exists an objective function associated with every feasible solution. However, the increase in the number of possible solutions makes this an NP-Hard problem. We show that the central limit theorem (CLT) applies to the problem. We then conduct extensive computational testing to show that the cycle lengths tend to a normal distribution as the problem grows large. When the size of the TSP problem exceeds computational power, better understanding solution distributions allows us to save resources. This is a non-trivial result as understanding solution distributions in huge TSP problems helps us to minimize computational effort that may not lead to significantly better results.

Keywords: traveling salesman problem; distribution fitting; graph theory

Corrección de interpretaciones erróneas sobre la distribución de longitudes de solución factibles en el problema del viajante

Resumen

El problema del agente viajero ("Traveling Salesman Problem" o TSP) es el problema canónico de optimización combinatoria usando en la literatura. Existe una función objetivo asociada con cada solución factible. Sin embargo, la tasa de aumento en el número de soluciones posibles hace que este sea un problema NP Difícil. Mostramos que el teorema del límite central (Central Limit Theorem o CLT) se aplica al problema y luego realizamos pruebas computacionales extensas para mostrar que las longitudes de los ciclos tienden a una distribución normal a medida que el tamaño del problema crece. Cuando el tamaño del problema TSP excede el poder computacional, una mejor comprensión de las distribuciones de soluciones nos permite ahorrar recursos. Este es un resultado no trivial, ya que comprender las distribuciones de soluciones en problemas TSP enormes nos ayuda a minimizar el esfuerzo computacional que puede no conducir a resultados significativamente mejores.

Palabras clave: problema del viajante de comercio; accesorios de distribución; teoría de grafos.

1 Introduction

Our contribution is to dispel two widely held but incorrect perceptions regarding the Traveling Salesman Problem (TSP) in the Operations Research field. The first is that the set of feasible TSP solution objective function values is proven to not be Normally distributed. This assumption derives from the failure to prove that the cycle lengths tend

to normality in the general case using analytic means. A second misnomer is that feasible objective function values have a Weibull distribution. That inference derives from a misreading of Golden and a misinterpretation of extremal value theory [1].

The Weibull does work well to model the distribution of extremal values, but not necessarily entire populations. Derigs recounts Golden's work and then extends the

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application of the Weibull to estimate minima in problems with few locations [2]. A careful application of analytic methods enables us to construct the argument that the lengths of randomly generated feasible TSP solutions do indeed tend to normal distributions, as would be expected in light of the Central Limit Theorem.

This research corrects at least two widely held but incorrect perceptions in the operations research field. One is that the set of feasible traveling salesman problem (TSP) solutions objective function values is proven to not be normally distributed. This assumption derives from the failure to prove that the cycle lengths tend to normality in the general (including one-dimensional) case using analytic means. A second misnomer is that feasible objective function values have a Weibull distribution. That inference derives from a misreading of Golden as well as a misinterpretation of extremal value theory [1]. The Weibull does work well to model the distribution of extreme values, but not necessarily entire populations. Derigs recounts Golden's work and then extends the application of the Weibull to estimate minima in problems with few locations [2]. A careful application of analytic methods enables us to construct the argument that the lengths of randomly generated feasible TSP solutions do indeed tend to normal distributions as would be expected in light of the Central Limit Theorem.

The TSP is the best-known combinatorial optimization problem. While there are several versions of this problem, we consider the simplest. Here, the objective of the problem is to create a minimum length round trip through a set of locations. In its most common form, (1) the locations exist in a bounded space in R^2 ; and (2) the distances between locations are calculated using a Euclidean metric.

The problem has historical precedent predating its popularization among academics [3–6]. Extensive histories of the problem are found in literature [7, 8]. The problem continues to influence researchers in fields ranging from computational geometry [9,10] to statistical mechanics [11,12]

Beardwood et al. is a seminal work that strongly influenced later researchers' understanding of the problem [13,14]. Their main contribution was to apply analytic rigor to the TSP. They showed that there exists a limit to the rate of increase in the length (in the sense of Lebesgue measure) of cycles as the number of vertices in a problem increases. This relationship is usually reported as $\lim_{N \rightarrow \infty} \frac{L_E}{N^{1-1/d}} = \beta_E(d)$; the rate of increase in length of a cycle through "many" points approaches a constant value.

Beardwood asserts that the lengths of random cycles through a point set in R^1 are not asymptotically normal in all cases [13]. However, the behavior in R^1 is not the same as in R^k where $k > 1$. On account of this, they declared that they failed to prove that cycle lengths are not provably normal in the general case. They stated that conditions for convergence to the Normal distribution exist in the special case where $C = E$ while E is the set of points and C is a closed region of unit measure. The problems we address exist in R^2 .

Golden noted that an estimate on lower bounds on TSP solution values could be obtained using a Weibull distribution [1]. Derigs extended that work to place bounds

on a broader set of combinatorial optimization problems [15]. Other researchers reported the influence of Golden's work [16–18]. The Weibull distribution does have properties that would make it attractive for use in modeling feasible TSP solution values. First, it can be used to model distributions with specific lower values. Second, its parametrization supports multiple distribution shapes, such as the "bell shape" that we find during our computational experimentation.

Beardwood et al. cited that the probabilistic nature of locations in the data set could cause cycle lengths to not converge [13]. For instance, a point to be visited could exist at some position with some probability. We assert, however, that this concern does not apply to the set of locations in the test TSP data sets. The locations for the problem sets are given. Once the set of locations to be visited is fixed, there is no longer a question of the probable location of any given location. While most applications focus on exact solutions to symmetric TSP instances, recent work exists on "good enough" solutions [19]. Similarly, research has been published on finding maximum-length TSP cycles or as Barvinok [2007] writes, "...known informally as the "taxicab ripoff problem" [20].

We show, both through analysis and computational results, that cycle lengths for feasible TSP solutions tend to follow a Normal distribution as the problem size grows large. Other authors have alluded to this behavior but have not published computational evidence to support or disprove the tendency [7,21]. Consequently, research on potential opportunities to exploit the statistical properties of cycle lengths has gone undone.

2 Research Objectives and Analytic Basis

Our purpose is to show that (1) TSP objective function values can be expressed as random variables; (2) the Central Limit Theorem can be applied to TSP cycle lengths; and (3) computational experimentation supports the hypothesis that cycle lengths tend to a normal distribution as the problem size increases. Research on the TSP is central to the fields of operations research, theoretical computer science, combinatorics, and graph theory.

While there is a great deal of commonality in the terminology used in these fields, there are also some differences. We have tried to reduce any confusion that may arise from the differing backgrounds of readers. We use both the terms "vertex" and "location." In general, "vertex" is used when the context of the passage derives from graph theoretic sources. The terms "distance" and "length" refer to a Lebesgue metric rather than the number of edges transited as is common in graph theory.

Definition 2.1 A walk is a nonempty sequence of edges $(uv, vw, \dots)$ such that the tail of an edge is the head of the next edge if the sequence contains more than one edge.

Definition 2.2 A closed walk is a walk such that the number of edges equals the number of vertices and the degree of each vertex is 2.

Definition 2.3 A cycle is a closed walk $(v_1, v_2, \dots, v_n, v_1)$, $n \geq 3$, in which then points v_i are distinct [22].

Definition 2.4 A permutation is "The arrangement of

different objects into a linear order using each object exactly once” [23].

Lemma 2.1 *A cycle can be constructed from a permutation of the vertices of K_n .*

A random variable is a variable quantity whose values depend on chance and for which a distribution function of probabilities has been defined [24]. Similarly, a function defined on a sample space is called a random variable [2]. Thus, the distance between randomly generated locations is itself a random variable. The Central Limit Theorem states that sums of Independent Identically Distributed (IID) random variables with finite variance approach a Normal distribution as the number of random variables (RVs) grows large [25]. As Hogg and Tanis state: “Given a random experiment with an outcome space S , a function X that assigns one and only one real number $X(s) = x$ to each element s in S is called a random variable [26]. The space of X is the set of real numbers, where $S\{x : X(s) = x, s \in S\}$, where $s \in S$ means that the element s belongs to the set S .”

The position of each vertex in the tour is dictated by a random number associated with that particular vertex as will be shown in Section 3. As the traveler transits the cycle, the distance between two successive vertices (say the first and second vertices visited) is a function on two random variables (the vertices). In this case, the distance between the each successive pair of vertices is a random variable. The total distance traveled is the sum along the respective edges the traveler transits in a cycle.

Lemma 2.2 *The distance between two locations having finite coordinates is finite. If we assume the lemma is false, then one of the end points must be infinitely far from the other. But each location has finite coordinates. Since the difference between finite numbers is finite, the distance between the points cannot be infinite. This is a contradiction. Thus the lemma is proven.*

Lemma 2.3 *The variance of the distances between locations having finite coordinates is finite. The sum of finitely many finite quantities is finite. Here we define variance as $\sigma^2 = \frac{\sum_i (\mu - x_i)^2}{\sum_i 1}$ where, $\mu = \frac{\sum_{i=1}^n x_i}{n}$. Thus, μ must be finite. The definition of variance is a squared sum of finitely many finite quantities. Therefore, the variance of the distances between locations, σ^2 , is finite*

3 Methodology

While the usual objective of the problem is to find the minimum length cycle through the locations, a feasible solution can be derived from any ordered list of locations [27]. The cycle length is the sum of the distances between each location in the round trip that constitutes the cycle. Assuming that the locations are chosen randomly, the cycle length is the sum of random variables.

We now show how to generate a cycle whose edges are constructed from IID random variables. The methods used coincidental similarity to that of Tercariol et al. but were developed independently [27]. The weight for any arc in this case is the Euclidean distance between the arc endpoints.

To generate a random cycle: let there be a cycle along the elements of the newly created ordering of P_r .

The Euclidean distance between successive vertices in the

new list is a random variable. Each element in v exists at a specified location and is addressed using Cartesian coordinates. Therefore, the distance between any two elements is finite. Since every element in the set of distances is finite, the variance of the distances must also be finite in the strictly numerical sense. It is well to remember that the TSPs we consider exist in the real world and that we treat the subject in an engineering context rather than in a solely abstract mathematical space. In the engineering sense it makes no sense to consider vertices located infinitely distant.

Lemma 3.1 *A cycle constructed as shown above is a sequence of IIDs with finite mean and variance. There is a bijection between each location and a uniformly distributed random number. That random number is a random variable. In each instance the generated random comes from the same distribution without regard to any possible previous trial. Therefore, these random variables are IID. The locations are then sorted in order by the generated random. The resulting ordering is a random variable. This ordered list constitutes a permutation and thus defines a cycle.*

Algorithm 1 Random Cycle Generation

- 1: Where, P is a set of indices mapped to locations (A)
 - 2: $R : P \rightarrow A \ni A \cup (0, 1)$. R is a bijection on P
 - 3: Input: Generate R^{-1} as a mapping of the elements of A
 - 4: $P \ni |A| = |P|$
 - 5: Sort: A to produce an ordered list, A_r
 - 6: Condition: let $P_r \subset P : A$
 - 7: Output: Generate A as a randomized ordering of locations where A maps to P
 - 8: Result: The position in which every element of P appears in P_r is the result of a random process.
-

The distances between any pair of locations is finite by Lemma 2.2. The variance of the distances is finite by Lemma 2.3. Thus is constructed a cycle composed of IID random variables with finite mean and variance.

Theorem 3.1 The length of cycles created as above tend to a Normal distribution as the number of locations grows large without bound.

Proof 3.1 The Central Limit Theorem states that sums of Independent Identically Distributed (IID) random variables with finite variance approach a Normal distribution as the number of random variables (RVs) grows large [25]. Lemma 4 showed that cycle lengths are composed of the sum of IID random variables with finite mean and variance. Therefore, the cycles so constructed satisfy the requirement of the Central Limit Theorem.

To illustrate a short example of cycle generation, we assign random deviates (r,s) generated for five locations labeled a through e. The resulting sequence of locations is then a random variable. Since the distances between successive locations are dictated by random variables, those distances are also random variables. The total cycle length is the sum of random variables. See Table 1 for an example of five data points using this method.

Table 1.

Example of five randomly generated locations and mappings

Location	rv	v	r_v	v
1	0.997	a	0.284	d
2	0.825	b	0.312	c
3	0.312	c	0.825	b
4	0.284	d	0.941	e
5	0.941	e	0.997	a

Source: the authors.

The resulting sequence of locations is then a random variable. Since the distances between successive locations are dictated by random variables, those distances are also random variables. The total cycle length is the sum of random variables.

The remainder of the paper describes our computational methodology, results, conclusions, and recommendations for further work. Computations were executed on an AMD Ryzen 7 4800H 8-core CPU with 32 GB RAM using code written by the authors in Python 3.5.

4 Results and Discussion

Standard data sets for the TSP can be found in the TSP Library [28]. Those problems are labeled T in the Problem Source column in Table 2. Data sets motivated by human population centers (denoted as N) and Very Large-Scale Integrated circuits (denoted as V) are available from the Waterloo University, Department of Computer Science site. Results for problems containing as few as 25 locations are displayed in Table 2. For each of the test problems the null hypothesis is that the distribution of cycle lengths is Normal. To test that hypothesis, we generated closed paths containing each location in the problem. The resulting cycle lengths were then subjected to three tests to check for normality.

Those tests include: D'Agostino, Jarque-Bera, and Anderson-Darling. Our use of these tests are consistent with current literature regarding tests for normality [29–32]. Similarly, we did not use Kolmogorov-Smirnov (KS) tests or similar tests due to sensitivity to large data sets [32]. In all instances the confidence level was 99%. Anderson-Darling test statistics that do not exceed the 99% certainty critical value (1.092) result in rejection of the null hypothesis. We highlight the results of our tests in Table 2.

In all instances the confidence level was 99%. Anderson-Darling test statistics that do not exceed the 99% certainty critical value (1.092) result in rejection of the null hypothesis. We highlight the results of our tests in Tables 2 and 3 in the Appendices.

Table 2.

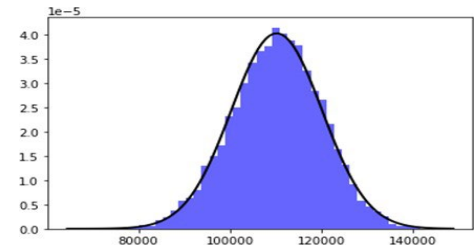
Summary of datasets tested

Vertices	Datasets Tested	Jarque Failures	Anderson Failures	D'Agostino Failures
>5000	28	0	0	0
4999-1000	45	0	0	0
994-226	45	0	0	0
<226	96	56	42	55

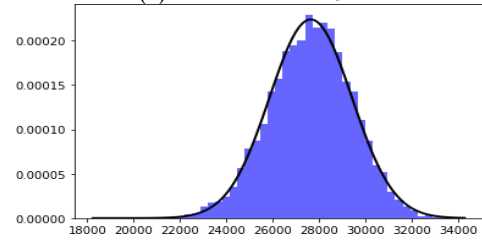
Source: the authors.

Results from a subset of the tested data sets are displayed in the table below. Statistics for each of the three the tests are shown for each data set. The test statistic or p-value is displayed in bold for instances in which the null hypothesis is rejected. For example, the null hypothesis for the CH150 data set is rejected on account of Jarque-Bera and D'Agostino tests. In Table 2 we see no failures to reject the null hypothesis for problems exceeding 1000 vertices. Consistent with our theory, we see multiple rejection of the null hypothesis where the number of vertices drop below 225.

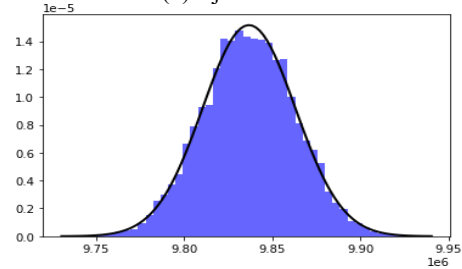
Fig. 1 display histograms of the cycle lengths produced through experimentation. While these histograms “look” Normal, statistical testing shows this is not always the case. Results from testing shows that the null hypothesis is rejected for the test problems. This is more easily shown in the Q-Q plots depicted in Fig. 2.



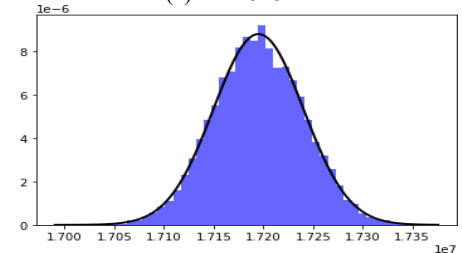
(a) Western Sahara29



(b) Djibouti38



(c) Bbz25234



(d) Xib32892

Figure 1. Histogram plots for small (1a, 1b) and large (1c, 1d) TSP problems
Source: the authors.

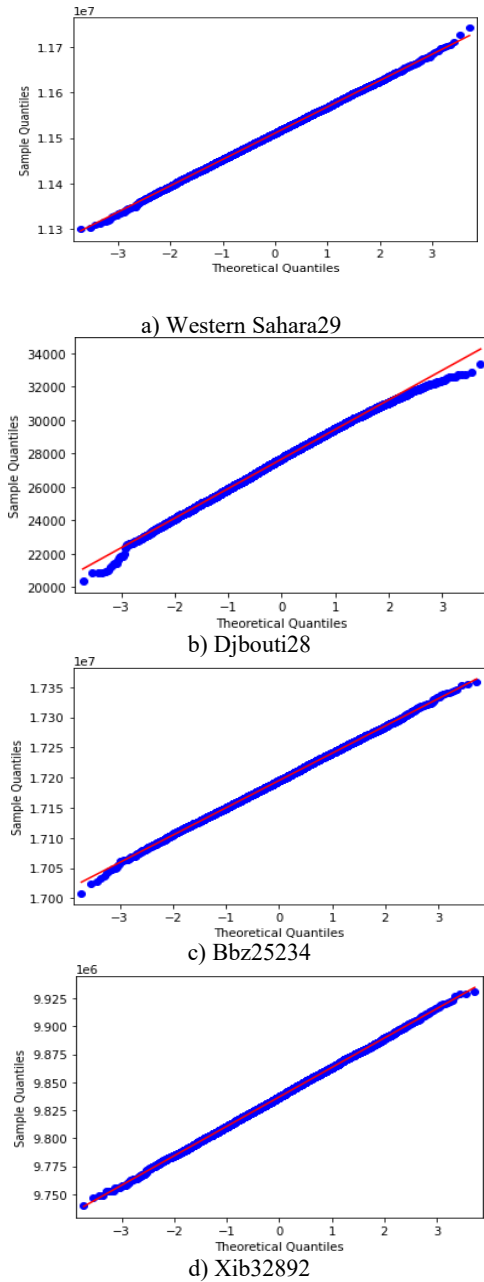


Figure 2. Q-Q plots for small (2a, 2b) and large (2c, 2d) TSP problems. Source: the authors.

Problem sizes varied from 25 to 85,900 locations. In general, the null hypothesis was rejected more frequently in problems having fewer vertices. The null hypothesis was not rejected for any problem having over 225 vertices.

In this research paper, we did the following:

1. We showed a generative mechanism to generate IID random vertex orderings that create cycles that produce feasible TSP solutions. Since the resulting inter-vertex distances are the products of a random process, they are random variables. The overall lengths of the resulting cycles are, thus, the sums of random variables.
2. The CLT tells us that the sums of RVs tend to a Normal distribution as the number of summands grows large.

Consequently, we can say that as the problem size (in terms of vertices) grows large, the lengths of the so-generated feasible solutions tend to a Normal distribution.

3. Hypothesis testing on the experimentally generated routes failed to disprove the null hypothesis – that route lengths of feasible solutions do not tend to a Normal distribution.

The experimental results support our claim that the objective function values for feasible TSP solutions tends to a Normal distribution as the number of vertices increases. We are not aware of testing of this type in existing reported literature.

While only a relatively small portion of the total number of cycle lengths are represented by in the tails of the distribution, this still accounts for a very large number in absolute terms. The experimental results support our claim that the objective function values for feasible TSP solutions tends to a Normal distribution as the number of vertices increases. Testing of this type has not been reported in the literature.

The overall probabilistic nature of feasible TSP cycle lengths has considered and then largely ignored. Carling noted that Golden's work generated great interest but research on related topics went largely dormant [16]. Doubtless the restrictions on computational experimentation at the time hampered widespread study of the topic. The technology now exists to enable much more experimentation.

While a cursory examination of the CLT suggested our results, some hurdles had to be overcome to produce these results. The highly influential paper from Beardwood et al. noted a failure to prove asymptotic convergence of cycle lengths to a Normal distribution. However, that research relied primarily on hand calculations and analytic methods. Beardwood's assertion that there exists an upper limit to the rate of increase in solutions has been positively received over the last six decades.

This research used some well-known tools and modern, if modest, computational resources to illustrate an interesting linkage between some combinatorial objects and probability theory. Knowing that the set of feasible solutions for a given problem yields paths whose lengths tend to a normal distribution should provide insight into the underlying structure of some combinatorial optimization problems. Since the TSP is NP Complete, we may be able to apply related analytic methods to other NP Complete problems. A natural direction of future work is to consider whether there might be statistical properties that optimal or good solutions share. Additional research might explore the use of this work to compute some relatively hard bounds on optimal solution objective values. We also recognize that while a two-dimensional TSP generates univariate random lengths, a higher dimensional TSP would require a multivariate test such as Mardia's Test. [33]. Because of the large size of the tests, we discounted the Kolmogorov-Smirnov test and focused our analysis with the Anderson-Darling, D'Agostino, and Jarque-Bera tests. In future studies it would be of interest to determine the robustness of each test with respect to random cycle lengths.

This work has significant potential to affect commercial and public logistics activities. One interesting question is whether problems with similar vertex counts covering similar spatial areas would have similar cycle lengths. Likewise, can we relate mean cycle lengths in problems having similar spatial properties and vertex counts. A positive answer to this question could be coupled with Beardwood's growth rate limit for length to produce cycle length estimates for different

data sets. This would be useful in capacity planning for commercial delivery companies as well as utility companies.

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Detection of white spot syndrome virus in seston from a coastal ecosystem and a shrimp farm in the Gulf of California

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Abstract

Three molecular assays were used to detect and quantify white spot syndrome virus (WSSV) in DNA extracted from seston size-fractioned (0.02, 0.2, 1.2, and 20 μ m) samples collected from a coastal lagoon and an adjacent shrimp farm. From 107 DNA extracts, only two from one sample tested positive for WSSV with nested PCR in the 1.2 and 20 μ m fractions. These results were confirmed by a semi-quantitative (IQ₂₀₀₀TM WSSV Detection and Prevention System) and a quantitative (IQ_{REAL}TM WSSV Quantitative System) detection system based, based, respectively, on nested PCR and real-time PCR. A first viral load reference value (6.54×10^4 WSSV copies/mL) was established in a seston size fraction (1.2–20 μ m). The results suggest that WSSV could be associated with both resuspension of fine clays and silts, and nanoplankton and organic colloids during infectious events.

Keywords: WSSV; seston size-fractions; nested PCR; real-time PCR; Macapule lagoon.

Detección del virus del síndrome de la mancha blanca en un ecosistema costero y una granja de camarón en el Golfo de California

Resumen

Con el fin de detectar y cuantificar el virus del síndrome de las manchas blancas (WSSV) en extractos de ADN de muestras de seston fraccionadas por tamaño (0.02, 0.2, 1.2 y 20 μ m) de una laguna costera y una granja camaronícola contigua se emplearon tres ensayos moleculares. De 107 extractos de ADN, solo dos de una muestra resultaron con detección positiva al WSSV con PCR anidada en las fracciones de 1.2 y 20 μ m. Estos resultados fueron confirmados por un sistema de detección semicuantitativo (IQ₂₀₀₀TM WSSV) y uno cuantitativo (IQ_{REAL}TM WSSV) basados, respectivamente, en PCR anidada y en PCR en tiempo real. Se estableció un primer valor de referencia de carga viral (6.54×10^4 copias WSSV/mL) en una fracción de tamaño de seston (1.2–20 μ m). Los resultados sugieren que, durante eventos infecciosos, el WSSV podría estar asociado tanto a la resuspensión de arcillas y limos finos, como a nanoplancton y coloides orgánicos.

Palabras clave: WSSV; fracciones por tamaño de seston; PCR anidada; PCR en tiempo real; Laguna de Macapule.

1 Introduction

Manuscript The White Spot Syndrome Virus (WSSV) is currently regarded as one of the most virulent pathogens

affecting commercial farming of various shrimp species and other marine crustaceans [1]. After being detected for the first time in China in 1992, its outbreaks were observed two years later in Texas [2] and four years later in Panama, Honduras, and Guatemala. Shrimp farms in Mexico and other Latin

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American countries have suffered substantial economic losses due to this virus [3]. Most efforts to address this disease have focused on developing early detection protocols, identifying potential transmission vectors [4], and, more recently, preventing outbreaks (e.g., [5]).

Some studies in Mexico have identified mechanisms through which the virus enters or remains latent in the farming facility system [6]. However, the possibility of the virus being present in the surrounding coastal environment and entering shrimp farms with seawater fed into reservoirs and ponds has been poorly assessed in the Mexican region. This hypothesis has been partially validated in several regions by the positive detection of WSSV in wild animals [7-10] by experimental tests. These evaluated viral infectivity through contact, ingestion of infected zooplankton (e.g., polychaetes, *Artemia*, copepods, and rotifers), or by virus attached to phytoplankton exopolymers that had been near sick or dying organisms [8,11,12]. Planktonic microorganisms and other seston elements are not completely filtered out of the incoming seawater stream; thus, this could be an entry pathway for disease-causing vectors into the ponds.

Even though annual technical reports of the Local Aquaculture Health Boards (JLSA, for its acronym in Spanish) of the state of Sinaloa show fewer WSSV infectious outbreaks occurring in 2019 and 2020 (27 and 8 cases, respectively) than those registered in previous periods between 2006 and 2010 (range: 115 and 273), the incidence of positive cases in shrimp farms is still currently high, mainly throughout the first and the most crucial cycle (up to 355 farms with outbreaks) of the three annual production cycles [13-15]. Therefore, time series recording and retrospective analysis of indicators of potential WSSV carriers can, even today, be of great use in local farming systems to understand patterns and address the contagion problems prevalent to date.

The present study aims to provide local evidence of the potential route of WSSV transport between shrimp ponds and its contiguous coastal system from the northern State of Sinaloa, Mexico, over a time series of viral detections on size-fractionated seston samples collected during an infectious event in June 2007 and from December 2007 to December 2008, analyzed through molecular testing based on nested, and real-time PCR assays. Viral concentration, in terms of WSSV copy number per milliliter, was estimated in the positive DNA extracts from the filtered seawater samples as an indicator of the detection limit, i.e., the minimum number of viral DNA copies in seawater detected with the methods used.

2 Material and methods

2.1 Sampling of seawater and shrimp pond water

Water samples were collected at two sites (reservoir and pond) within the Finca Doña Luisa S. de R.L. de C.V. shrimp farm and two sites (northern mouth and El Tortugón estuary) in the Macapule lagoon. The lagoon sampling stations were separated ~9 km from each other and 2.1 km and 10.8 km from the shrimp farm, respectively (Fig. 1).

Water samples between 4 and 10 L at the lagoon were collected monthly from December 2007 to December 2008 using a segmented tube; ~1 L samples at the farming facility were collected manually from the surface (0.5 m depth) in June 2007, and monthly from March to November 2008.

2.2 Seston separation by size fractions and DNA extraction

Samples were sieved through a 200 µm-mesh net and then separated into size fractions using a series of graded filters: Nuclepore polycarbonate membranes (20 and 0.2 µm), GF/C glass microfiber filters (1.2 µm), and Anodisc aluminum oxide membrane filter (0.02 µm). The volume of seawater filtered ranged from 20 mL for the smaller pore sizes to 1000 mL for the larger ones.

DNA was extracted from seston retained in the filters using DNAzol™ reagent (Invitrogen™), following the manufacturer's instructions; a total of 107 DNA extractions were obtained.

2.3 Polymerase Chain Reaction (PCR) and documentation

To assess the quality of DNA extracts, we amplified 16S rDNA with the universal primers F2C (5'-AGAGTTTGTATCATGGCTC-3') and C (5'-ACGGGCGGTGTGTAC-3') in those available extracts from both lagoon and pond, collected from December 2007 to July 2008 [16]. PCR amplification thermal conditions consisted of 94 °C for 4 min (initial denaturation) and 32 cycles at 94 °C for 30 s (denaturation), 60 °C for 30 s (annealing), 72 °C for 2 min (extension), and 72 °C for 5 min (final extension). The WSSV was initially amplified using a standard nested PCR assay [17], following the thermal conditions at 94 °C for 4 min (initial denaturation), 94 °C for 30 s (denaturation), 55 °C for 30 s (annealing), 72 °C for 1 min (extension), and 72 °C for 5 min (final extension), with 30 and 35 cycles for the one-step- and nested-PCR assays, respectively, from denaturation to extension step. These amplifications were confirmed with two commercial kits, namely IQ₂₀₀₀™ WSSV Detection and Prevention System (based on nested PCR assay) and IQ_{REAL}™ WSSV Quantitative System (based on real-time PCR assay) following the manufacturer's instructions (GeneReach Biotechnology Corp.).

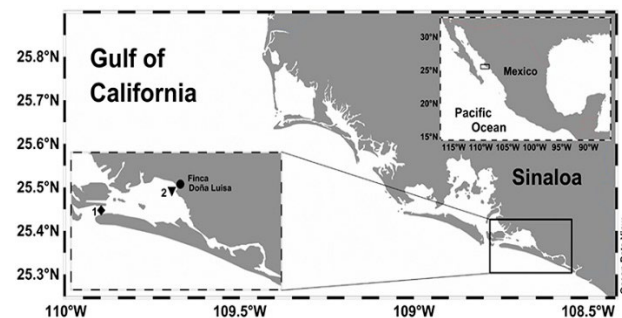


Figure 1. Location of the sampling stations at the Macapule Lagoon (Station 1: northern mouth, 25.37° N, 108.74° W, Station 2: El Tortugón estuary, 25.39° N, 108.67° W) and Finca Doña Luisa shrimp farm (closed circle).

Source: The authors.

All amplified products from IQ₂₀₀₀TM WSSV Detection and Prevention System were mixed with a loading buffer [0.25 % (w/v) bromophenol blue, 0.25 % (w/v) xylene cyanol F.F., 30 % glycerol in distilled water], separated by electrophoresis on 1 % agarose gel stained with ethidium bromide (0.5 mg/mL) in 0.5X T.B.E. buffer at 70 V, and then visualized using a U.V. trans-illuminator. A 1 kb molecular-weight size marker was loaded into the gel and the PCR products to identify the approximate size of the amplified fragments. Based on the viral load found in positive samples amplified with the IQ₂₀₀₀TM WSSV protocol, three possible migration patterns were expected on the agarose gel: three (910, 550, and 296 bp), two (550 and 296 bp), or a single (296 bp) band, which would indicate a high (>2000 copies/reaction), moderate (>200–2000 copies/reaction), or low (>20–200 copies/reaction) WSSV concentration, respectively. WSSV copies in the TaqMan IQ_{REAL}TM WSSV assay products were quantified (absolute values) with the equation generated from the threshold cycle that relates C_q values to the log template amount. The viral concentration in the WSSV-positive extracts, as viral copies per volume (mL), was estimated by considering the filtered volume of seawater for DNA extraction.

3 Results and discussion

3.1 WSSV detection in seston size fractions

Only two (1.2 and 20 µm fractions collected in the shrimp pond in June 2007 and July 2008) of the 107 DNA extracts tested with the standard nested PCR assay proposed by Kimura *et al.* (1996) were positive for WSSV (Fig. 2). Both nested PCR results were confirmed by IQ₂₀₀₀TM WSSV diagnostic kits, but the IQ_{REAL}TM assay returned a WSSV negative result for the June 2007 sample. When considering the filtered water sample volume for DNA extraction in the results of this quantitative assay, a viral concentration of 6.54×10^4 WSSV copies/mL was estimated for the July 2008 sample, which is 2 to 3 orders of magnitude larger than the semiquantitative kit IQ₂₀₀₀TM WSSV (Fig. 3).

This study applied methodological procedures commonly used to diagnose WSSV in animal tissues to seston samples from a shrimp farm and natural environments. Sample storing and handling (e.g., during the removal of potential inhibitors from seawater) may have affected DNA extraction, leading to our inability to detect the virus in most samples; thus, caution is advised in interpreting whether a sample was WSSV positive or not.

High concentrations of phenolic compounds, heavy metals, humic acid, or urea are the most common agents in environmental samples interfering with PCR detection (e.g., [18-20]. Of these compounds, only urea has been found in high and variable concentrations in the water column at Macapule Lagoon [21], although the significant levels of heavy metals in soft tissues of bivalves might be a potential pathway from sediments and settling seston [22].

Assuming that prokaryote DNA is ubiquitous and more abundant than WSSV DNA in seston size fractions, the results of the DNA quality test in extracts from both Lagoon and pond samples (n = 92) showed that only 50% of them

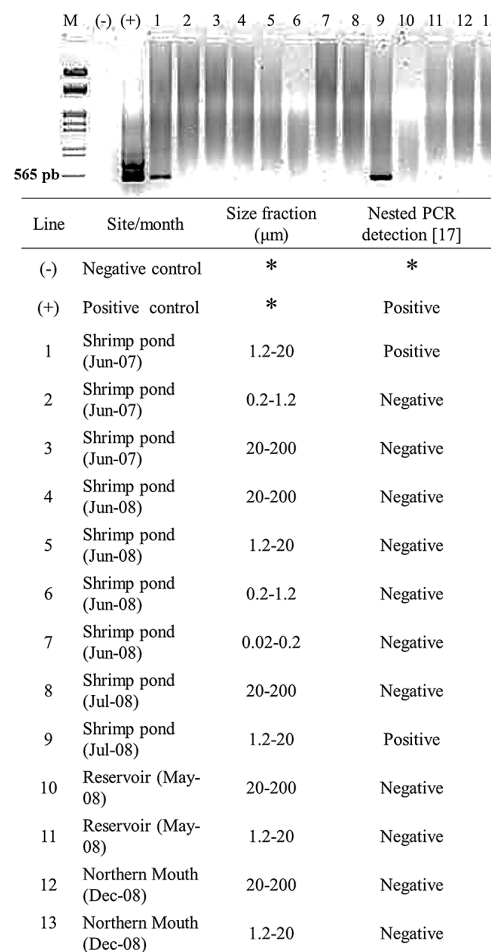


Figure 2. Photo-documentation of nested PCR (Kimura *et al.*, 1996) results for samples from the pond and reservoir sites at Finca Doña Luisa shrimp farm and the northern mouth of the Macapule lagoon. M: 1 kb molecular-weight size marker. The band at 570 bp indicates positive WSSV detection. * Not applicable.

Source: The authors.

produced clear single bands on the agarose gel electrophoresis. Thus, DNA preservation and inhibitory components in these samples were not likely to affect the WSSV test results obtained with nested PCR. The relatively low volume of filtered seawater may have been another contributing factor in the recurrent negative detection of WSSV. However, water samples (~20 L, collected at the estuary in March 2009) that had been pre-concentrated by tangential filtration (>0.02 µm) tested negative for WSSV with nested PCR.

The WSSV positive results showed that the 1.2 and 20 µm fractions could be a potential route for transmitting this virus to crustaceans by either direct contact or ingestion by filter feeders. Inert and biological particles in this size range present in coastal lagoons mainly include resuspended sediments, self-assembled organic colloids (microgels), and nanoplankton. It is known that WSSV can remain viable in shrimp pond sediments for up to 19 days under sun-drying conditions and up to 35 days in undrained sediments [23,24].

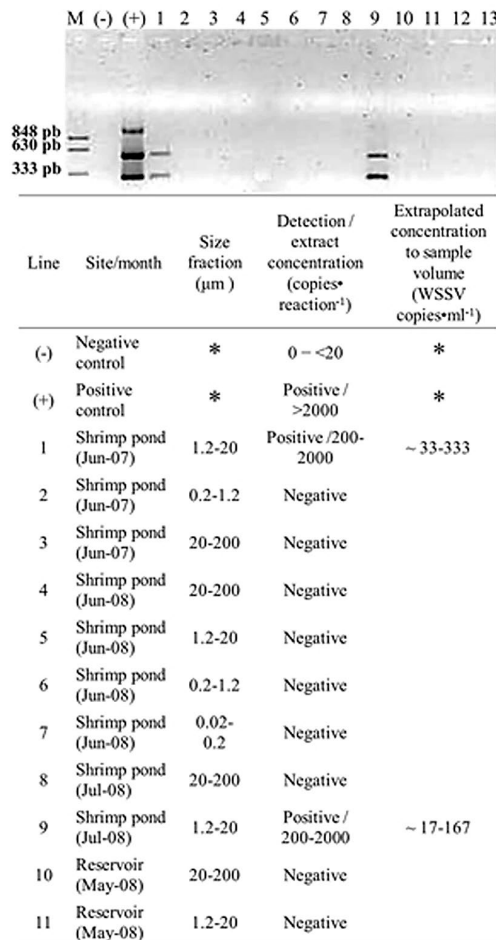


Figure 3. Photo-documentation of nested PCR results and WSSV range concentration as estimated from the IQ₂₀₀₀TM WSSV assay for some samples from the pond and reservoir sites at Finca Doña Luisa shrimp farm and the northern mouth of the Macapule lagoon. M: 1 kb molecular-weight size marker; migration bands of 848 bp, 630 bp, 333 bp. *Not applicable. Source: The authors.

Clay and very fine silt are the dominant sediment fractions in the Macapule Lagoon [25], and their resuspension into the uppermost water layer is facilitated by wind-induced turbulence, currents, and tides flowing over the topographic features [21,26,27]. Consequently, WSSV attached to sediments may play a significant role in the outbreak dynamics when they become resuspended or, indirectly when they come into contact with eggs of planktonic organisms and invertebrates that shrimp consume [23].

Self-assembled microgels are abundant in productive systems and act as microbial activity hotspots and reservoirs of detritus, small cells, and viable viral particles [28]. Highly “sticky” fractions of such microgels, which were retained by 0.4 μm pore polycarbonate membranes and quantified with the Alcian Blue staining method, were found in high concentrations (range 0.11 to 49 μg GX eq. mL⁻¹; for methods see [29] in seawater samples from Ohuira coastal lagoon, near our study site. However, no experimental data are currently available to support the potential association between self-assembled microgels and the viability and transport of WSSV.

A wide range of planktonic organisms (e.g., microcrustaceans, rotifers, and microalgae), benthonic crustaceans, and Polychaeta worms that are not WSSV infected have been reported as carriers [30,31]. Some life stages of these organisms may be present in both plankton and benthos, increasing the probability of acquiring and spreading the disease. In shrimp farms and other Mexican coastal systems, including the Macapule lagoon, the most frequently observed potential vectors of WSSV in meso- and macro-zooplankton belong to non-crustacean groups, such as chaetognaths and fish larvae [32,33]. Esparza-Leal et al. [6] monitored 12 ponds in a shrimp farm at Guasave City for two weeks after a WSSV outbreak and found WSSV-positive results in the >10 μm and >0.45 μm plankton fractions from one (#7) and three (#2, #7 and #10) ponds, respectively. The same study conducted infectivity assays on healthy shrimp differentially exposed to ten-sized fractions (0.1 to 100 μm) of filtered water and particulate material from a pond after a WSSV outbreak. They found positive detection after 216 h in shrimp that had been exposed to the liquid fractions: <40 μm, <10 μm, and <0.65 μm; and the particulate fractions: >100 μm, >40 μm, and >5 μm. Moreover, not all replicates from the same fractions tested positive for WSSV. This variability was attributed to the relatively high temperature (30–33°C) in the experimental systems, which might have inhibited WSSV replication [34].

Nanoplankton (encompassing phyto- and zooplankton) is one of the most prolific and essential components in the planktonic food web structure in natural and artificial systems influenced by enrichment conditions. The average nanophytoplankton abundance in the Macapule lagoon and the shrimp culture system during the study period was $7.90 \pm 5.52 \times 10^3$ and $2.13 \pm 1.14 \times 10^4$ cells/mL, respectively [21,35]. The environmental conditions in ponds favor autotrophic production and microbial abundance, thus increasing the probability of encounters between nanoplankton cells and hosts releasing WSSV particles. This association partially supports the empirical model of viral transmission to higher trophic levels by virus attached to phytoplankton [8,36], although this hypothesis has not been tested in samples from natural environments.

Moreover, the possibility that coastal ecosystems function as temporary or permanent WSSV reservoirs due to the discharges of untreated pond wastewater cannot be ruled out, as reported by several investigations elsewhere [9,10,37,38]. Discharge operations are carried out during the shrimp harvesting season with no wastewater sanitization/treatment. Besides potentially affecting the local diversity of crustaceans, the virus could likely be reintroduced and infect animals in the aquaculture system during seawater supply. Moreover, post-tropical storm conditions — i.e., high temperature and high ammonia concentration, low density of heterotrophic bacteria, and low oxygen concentration — have been identified as triggers of WSSV outbreaks [5,39]. Thus, the weather might play a key role by modifying currents, precipitation, and temperature conditions, among other ambient conditions.

4 Conclusion

DNA extraction methods should be improved to increase extraction efficiency (quantity and quality). These

improvements imply increasing filtered seawater volume by using tangential flow filtration systems to enable a higher sensitivity in determining the seston fractions involved in WSSV transmission between natural and shrimp pond ecosystems. It is also advisable to reassess the detection methodology to address the high haplotype diversity recorded, possibly due to a high viral mutation rate or the introduction of new viral strains [40]. Although advances in implementing biosecurity and contingency protocols have decreased mass mortalities produced by WSSV outbreaks in recent years, continuous monitoring and retrospective analysis of environmental and biological variables, including potential pathways of infection, is essential to discern a pattern in the recurrence of WSSV outbreaks for further prevention its spread along natural and aquaculture systems.

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Effects of saline and water stress on sweet sorghum

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Abstract

Sweet sorghum (*Sorghum bicolor* [L.] Moench) is a plant that can be an alternative for the production of bioethanol in semi-arid regions. The objective of this work was to evaluate sweet sorghum 'BRS 506' under salt and water stress. The experimental design was in randomized blocks, in a factorial scheme (4x4), with the first factor referring to the electrical conductivities of the irrigation water (1.5; 3.0; 4.5; and 6.0 dS m⁻¹) and the second refers to irrigation depths (53, 67, 85 and 95% of crop evapotranspiration). Gas exchange, leaf water status, leaf sugars and plant growth were evaluated. Salt and water stress cause negative effects on the growth of sweet sorghum 'BRS 506'. Salt stress causes disturbances in gas exchange and sugar levels. Sweet sorghum 'BRS 506' is tolerant to combined salt and water stress.

Keywords: *Sorghum bicolor*; water deficit; salinity; gas exchange.

Efectos del estrés salino e hídrico en el sorgo dulce

Resumen

El sorgo dulce (*Sorghum bicolor* [L.] Moench) es una planta que puede ser una alternativa para la producción de bioetanol en regiones semiáridas. El objetivo de este trabajo fue evaluar el sorgo dulce 'BRS 506' bajo estrés hídrico y salino. El diseño experimental fue en bloques al azar, en esquema factorial (4x4), siendo el primer factor referido a las conductividades eléctricas del agua de riego (1.5; 3.0; 4.5; y 6.0 dS m⁻¹) y el segundo a las aspersiones de riego (53, 67, 85 y 95% de la evapotranspiración del cultivo). Se evaluaron el intercambio de gases, el estado hídrico de las hojas, los azúcares de las hojas y el crecimiento de las plantas. El estrés salino e hídrico provoca efectos negativos en el crecimiento del sorgo dulce 'BRS 506'. El estrés salino provoca alteraciones en el intercambio de gases y en los niveles de azúcar. El sorgo dulce 'BRS 506' es tolerante al estrés salino y hídrico conjunto.

Palabras clave: *Sorghum bicolor*; déficit de agua; salinidad; intercambio de gases.

1 Introduction

Sweet sorghum (*Sorghum bicolor* [L.] Moench) is a C4 plant widely cultivated in the world, having high concentrations of soluble sugars (sucrose, glucose and fructose) contained in its stems [1]. Most of the world's ethanol production is extracted from corn and sugarcane [2]. However, sweet sorghum presents itself as an alternative for the production of bioethanol of plant origin from its sugary stem [3,4]. Since it has greater drought tolerance and requires less water compared to the other two crops [5].

Sorghum is generally cultivated in arid and semi-arid regions, where there are often limiting factors for the development of agriculture, such as irregular rainfall and water with inferior qualities [6,7]. However, it is a plant adapted to these regions and produces even under adverse conditions of low water availability and brackish water [8].

Salt and water stress cause a variety of problems in sorghum plants, which can unbalance cellular homeostasis, leading to morphological, physiological and molecular changes [9,10]. These changes have a negative impact on plant growth and development, with a decrease in production [11,12].

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Some studies were carried out to evaluate the physiology and growth of sorghum under saline stress conditions. The authors reported that the variables of: membrane damage [13], relative water content [14-16], gas exchange [11,17] and growth [15] are negatively affected.

On the other hand, other studies addressed the effects of water stress in sorghum, where the results showed that membrane damage, relative water content, sugars [12], gas exchange and growth [18] suffered reductions as water stress was high. However, plants develop some protective mechanisms to reduce the harmful effects of stress [10,13], such as the accumulation of sugars in response to salt and water stress [11,19].

Increasingly, water resources, whether by quality or quantity, are becoming limited for agriculture, and it is essential to understand plant responses to saline and water stress, in order to develop alternatives for the production of agricultural crops in adverse conditions [20,21]. Increasing tolerance to abiotic stresses (saline and water) in sorghum is of great importance, and it is essential to obtain information on how stresses influence physiological and growth processes in sorghum plants [10,19].

In general, the studies have focused on the development of research on salt and water stress in isolation and not jointly. Thus, the objective of this work was to evaluate the variables of leaf water status, sugars, gas exchange and growth in sweet sorghum (*Sorghum bicolor* [L.] Moench) 'BRS 506' under salt and water stress.

2 Material and methods

2.1 Experimental area

The experiment was carried out between September and December 2020, in the experimental area of the Cumaru farm (5°33'30" S, 37°11'56" W), located in the rural area in Upanema, Rio Grande do Norte, Brazil (Fig. 1).

According to the Köppen classification, the climate in the region is BSh – hot semi-arid with autumn rains and monthly average air temperature consistently above 18 °C [22]. During the experimental test, the temperature and relative humidity averaged around 28 °C and 60%, respectively (Fig. 2).

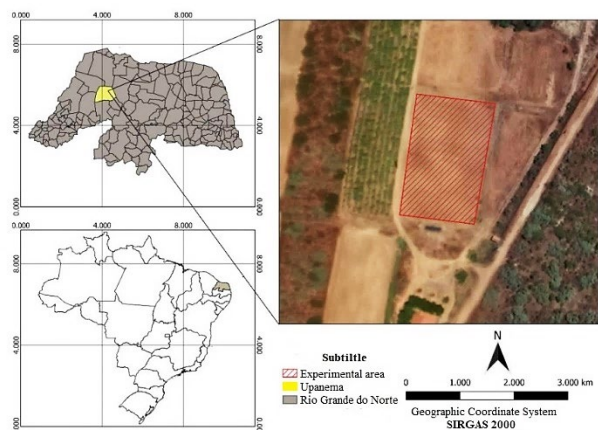


Figure 1. Location of the experimental area at the Cumaru farm, Upanema, Rio Grande do Norte, Brazil.

Source: The authors.

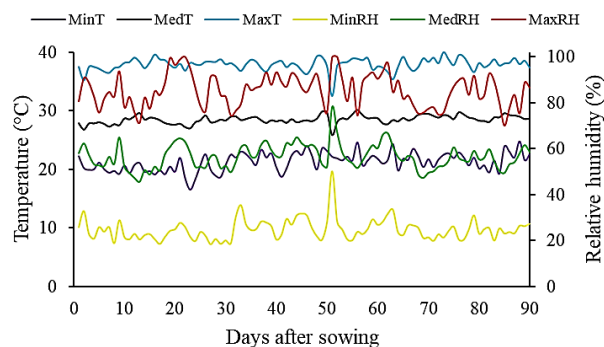


Figure 2. Climatic conditions of temperature and relative humidity during the experimental test period.

Source: The authors.

The soil of the experimental area is classified as Cambisol [23], before the installation of the experiment, composite soil samples were taken, where physical and chemical soil analyzes were carried out. For the 0-20 cm layer, the following physical characteristics were presented: sand = 71.77%; silt = 6.54%; clay = 21.69%. While for the 20-40 cm layer, the results were: sand = 61.67%; silt = 4.95%; clay = 33.38%. For the 0-20 cm layer, the following results were obtained for the chemical characteristics: pH = 7.56; ECs = 0.57 dS m⁻¹; organic matter = 1.87%; P = 0.05 cmol_c dm⁻³; K⁺ = 0.20 cmol_c dm⁻³; Na⁺ = 1.11 cmol_c dm⁻³; Ca²⁺ = 7.00 cmol_c dm⁻³; Mg²⁺ = 1.91 cmol_c dm⁻³; and SB = 10.22 cmol_c dm⁻³. For layer 20-40 cm the chemical characteristics obtained were: pH = 7.28; ECs = 0.36 dS m⁻¹; organic matter = 1.40%; P = 0.03 cmol_c dm⁻³; K⁺ = 0.18 cmol_c dm⁻³; Na⁺ = 0.95 cmol_c dm⁻³; Ca²⁺ = 5.96 cmol_c dm⁻³; Mg²⁺ = 1.77 cmol_c dm⁻³; and SB = 8.86 cmol_c dm⁻³.

2.2 Plant material and soil preparation

The sorghum cultivar [*Sorghum bicolor* (L.) Moench] used in the experiment was the saccharin cultivar 'BRS 506'. This cultivar can be used to complement the production of ethanol, having as characteristics succulent stems and a high concentration of sugars, with emphasis on its short cycle (90 to 130 days), with wide edaphoclimatic adaptation and high efficiency in water use [3,24].

Before the installation of the experiment, the soil was prepared, consisting of plowing and harrowing and a foundation fertilizer with 104 kg ha⁻¹ of P₂O₅ and 22 kg ha⁻¹ of N, using MAP as a source. In addition, cover fertilization was carried out via fertirrigation, applying 30 kg ha⁻¹ of K₂O, using potassium chloride as source and 40 kg ha⁻¹ of N, using urea as source.

2.3 Salt stress management

The application of saline stresses started 21 days after sowing. The water used in irrigation management was prepared as follows: the lowest concentration (1.5 dS m⁻¹) came from a tubular well that supplies the Cumaru farm, originating from the calciferous sandstone aquifer. The waters with the other electrical conductivities (3.0; 4.5 and

Table 1.

Chemical characteristics of the water used in the irrigation of the experiment.

EC	Na ⁺	Ca ²⁺	Mg ²⁺	K ⁺	Cl ⁻	SO ₄ ²⁻	HCO ₃ ⁻
dS m ⁻¹	mmolc						
1,5	5,0	8,0	2,0	0,12	8,1	0,3	7,0
3,0	19,0	8,0	3,0	0,12	22,1	1,3	6,9
4,5	28,5	12,0	4,5	0,12	35,6	2,8	6,9
6,0	38,0	16,0	6,0	0,12	49,1	4,3	6,8

EC: electrical conductivity of irrigation water; Na⁺: sodium; Ca²⁺: calcium; Mg²⁺: magnesium; K⁺: potassium; Cl⁻: chlorine; SO₄²⁻: sulfates; HCO₃⁻: bicarbonates.

Source: The authors.

6.0 dS m⁻¹) were prepared from the addition of NaCl, CaCl₂·2H₂O and MgSO₄·7H₂O salts [25]. The water with the highest concentration was based on the salinity tolerance of the sorghum crop for a potential yield of 50% [26], while the other waters had intermediate electrical conductivities (Table 1).

2.4 Water stress management

The application of the different irrigation depths started at 7 days after sowing (DAS). The irrigation depths were applied based on the maximum evapotranspiration of the sorghum crop (ET_c), adjusting the conditions of the experiment and the irrigation system (53, 67, 85 and 95% of the total estimated ET_c for the crop cycle). ET_c was estimated daily from the estimate of daily reference evapotranspiration (ET_o), by the Penman-Monteith method according to [27]. ET_o was estimated daily from data collected at a meteorological station installed in the experiment area. Whereas, the daily crop coefficient (K_c) was determined by the dual K_c method, assuming the length of phenological phases I, II, III and IV to be 28, 32, 20 and 10 days, respectively, and the crop coefficients baseline for phase III and end of the cycle, 1.00 and 0.70.

2.5 Experimental design

The experimental design was in randomized blocks (DBC), in a factorial scheme (4x4), with the first factor referring to the electrical conductivities of the irrigation water (EC_w - 1.5; 3.0; 4.5; and 6.0 dS m⁻¹), and the second factor refers to the irrigation depths (ET_c - 53, 67, 85 and 95%). Using two blocks with two replications within the blocks, totaling 16 treatments and 64 experimental plots.

2.6 Variables analyzed

2.6.1 Gas exchange

Leaf gas exchange was measured by a portable infrared gas analyzer (IRGA, GFS-300, WALZ, Germany). Measurements were made between 08:00 and 10:00 am, in two plants per plot on the flag leaf. The IRGA settings were defined as follows: temperature of 25 °C; relative humidity of 60%; flow rate of 750 μmol/min; light intensity of 1200 μmol m⁻² s⁻¹; impeller speed of 7; CO₂ concentration of 400 ppm and reading area of 8 cm².

The gas exchange variables were evaluated at 62 DAS. Leaf

temperature (LT - °C), vapor pressure deficit (VPD - kPa), stomatal conductance (g_s - mmol H₂O m⁻² s⁻¹), transpiration rate (E - mmol H₂O m⁻² s⁻¹), CO₂ assimilation rate (A - μmol CO₂ m⁻² s⁻¹), water use efficiency (WUE - A/E) and intrinsic water-use efficiency (WUEi - A/g_s) were measured.

2.6.2 Leaf water status

At 59 days after sowing (DAS), the end of phenological phase II, beginning of flowering, the leaf water status variables were evaluated: membrane damage (MD) and relative water content (RWC). MD was determined by the electrolyte extravasation method, according to the methodology proposed by [28].

Where:

$$MD = \frac{C1}{C2} \times 100 \quad (1)$$

MD: membrane damage, %;

C1: initial electrical conductivity, dS m⁻¹;

C2: final electrical conductivity, dS m⁻¹.

While, RWC was evaluated through leaf discs, by the equation proposed by [29]. Where:

$$RWC = \frac{FM - DS}{TM - DS} \times 100 \quad (2)$$

RWC: relative water content, %;

FM: fresh mass, g;

DS: dry mass, g;

TM: turgid mass, g.

2.6.3 Sugars

From leaf samples collected at 69 DAS, measurements of total sugars, reducing sugars, non-reducing sugars and starch were made. The samples were placed in paper bags and placed to dry in an oven with forced air circulation at 65 °C for 72 hours, and subsequently ground in a Willye-type mill.

Total sugars (TS): were determined by the Antrona method, according to the methodology proposed by [30].

Reducing sugars (RS): determined by the Somogyi-Nelson method [31].

Non-reducing sugars (NRS): obtained through the equation proposed by [32]. On what:

$$NRS = (TS - RS) \times 0,95 \quad (3)$$

Where:

NRS: non-reducing sugars, %;

TS: total sugars, %;

RS: reducing sugars, %.

Starch (ST): determined by the Somogyi-Nelson method [31], with values expressed in mg/g.

2.6.4 Plant growth

At 73 DAS, the following variables were evaluated: plant height (cm): measuring from the base of the plant to

the apex of the leaf meristem; and stem height (cm): measuring the entire length of the stem up to the last leaf insertion.

The leaf, stem, root and total dry mass (g) were evaluated at 69 DAS, where the parts of the plants were separated and then placed in paper bags and placed to dry in an oven with circulation of forced air temperature for 72 hours at 65 °C.

2.7 Statistical analysis

Data were submitted to analysis of variance by F test at a 5% significance level, in case of significant effects, regression analysis was performed using the R® software version 4.1.3 [33], and the graphics produced with SigmaPlot® software version 12.3 [34].

3 Results

According to the variance analysis (Table 2), for the leaf gas exchange variables, there were isolated effects of the data for the different electrical conductivities of the irrigation water (ECw) in the variables leaf temperature, water use efficiency and intrinsic water-use efficiency.

For leaf temperature (Fig. 3A), the highest values were observed in the lowest ECa of 1.5 dS m⁻¹, while the highest value was obtained in the treatment containing ECa of 3.0 dS m⁻¹, however there was no trend defined, although there was a statistical difference between the means.

Similar effects occurred for WUE and WUEi gas exchange variables, subjected to different ECws, with the highest values (23.96 and 0.41 $\mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}/\text{mmol H}_2\text{O m}^{-2} \text{ s}^{-1}$) being obtained in ECw of 4.5 dS m⁻¹, while the lowest values (20.16 and 0.34 $\mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}/\text{mmol H}_2\text{O m}^{-2} \text{ s}^{-1}$) were observed at an intermediate ECw of 3.0 dS m⁻¹, for WUE and WUEi, respectively. However, the values obtained did not fit the linear or quadratic model, despite the significant effects obtained (Figs. 3B and 3C).

According to the analysis of variance (Table 3), there was a significant isolated effect only for the variable of total sugars when subjected to different electrical conductivities of irrigation water (ECw).

Table 2.

Analysis of variance summary (ANOVA) for leaf temperature (LF), vapor pressure deficit (VPD), stomatal conductance (gs), transpiration rate (E), CO₂ assimilation rate (A), water use efficiency (WUE) and intrinsic water-use efficiency (WUEi) as a function of electrical conductivities of irrigation water (ECw) and irrigation depths (ETc) in sweet sorghum (*Sorghum bicolor* L.) 'BRS 506'.

Variables								
SV	DF	LF	VPD	gs	E	A	WUE	WUEi
F Statistic								
ECw	3	3,91*	2,10 ^{ns}	1,90 ^{ns}	2,60 ^{ns}	1,41 ^{ns}	3,82*	2,92*
ETc	3	1,42 ^{ns}	0,16 ^{ns}	0,03 ^{ns}	1,35 ^{ns}	0,78 ^{ns}	0,94 ^{ns}	1,16 ^{ns}
ECwxETc	9	1,95 ^{ns}	0,61 ^{ns}	0,55 ^{ns}	1,95 ^{ns}	0,59 ^{ns}	0,98 ^{ns}	0,91 ^{ns}
CV%	-	1,64	18,19	19,45	4,14	14,08	25,86	21,53

SV: source of variation; DF: degree of freedom; CV: coefficient of variation; ECw: electrical conductivity of irrigation water; ETc: irrigation depth; (^{ns}) not significant; (*) significant at the 5% level; (**) significant at the 1% level; (***) significant at the 0.1% level.

Source: The authors.

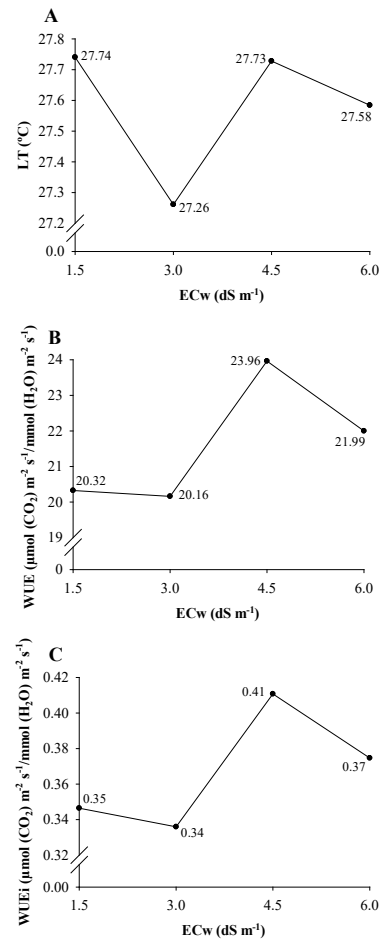


Figure 3. Leaf temperature (A), water use efficiency (B) and intrinsic water-use efficiency (C) as a function of electrical conductivities of irrigation water (ECw) in sweet sorghum (*Sorghum bicolor* L.) 'BRS 506'. Source: The authors.

Table 3.

Analysis of variance summary (ANOVA) for membrane damage (MD), relative water content (RWC), total sugars (TS), reducing sugars (RS), non-reducing sugars (NRS) and starch (ST) as a function of electrical conductivities of irrigation water (ECw) and irrigation depths (ETc) in sweet sorghum (*Sorghum bicolor* L.) 'BRS 506'.

Variables							
SV	DF	MD	RWC	TS	RS	NRS	ST
F Statistic							
ECw	3	1,43 ^{ns}	1,39 ^{ns}	2,96*	2,60 ^{ns}	1,29 ^{ns}	1,20 ^{ns}
ETc	3	1,24 ^{ns}	1,12 ^{ns}	0,23 ^{ns}	0,57 ^{ns}	0,57 ^{ns}	2,76 ^{ns}
ECwxETc	9	1,38 ^{ns}	1,81 ^{ns}	0,95 ^{ns}	1,16 ^{ns}	0,73 ^{ns}	0,96 ^{ns}
CV%	-	39,35	7,55	23,79	25,49	41,13	13,32

SV: source of variation; DF: degree of freedom; CV: coefficient of variation; ECw: electrical conductivity of irrigation water; ETc: irrigation depth; (^{ns}) not significant; (*) significant at the 5% level; (**) significant at the 1% level; (***) significant at the 0.1% level.

Source: The authors.

In Fig. 4, it is possible to observe that there was a significant effect for total sugars, with the highest value (4.75%) being obtained at the ECw of 4.5 dS m⁻¹, on the other hand, the lowest value (3.77%) was observed at ECw of 3.0 dS m⁻¹. Despite this, the values did not fit into a defined model, even with statistical differences between the means.

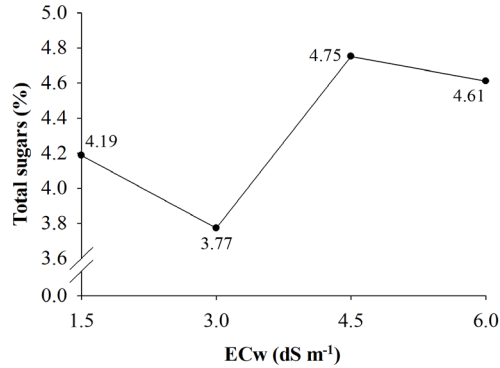


Figure 4. Total sugars as a function of electrical conductivities of irrigation water (ECw) in sweet sorghum (*Sorghum bicolor* L.) 'BRS 506'. Source: The authors.

Table 4.

Analysis of variance summary (ANOVA) for plant height (PH), stem height (SH), leaf dry mass (LDM), stem dry mass (SDM), root dry mass (RDM) and total dry mass (TDM) as a function of electrical conductivities of irrigation water (ECw) and irrigation depths (ETc) in sweet sorghum (*Sorghum bicolor* L.) 'BRS 506'.

Variables							
SV	DF	PH	SH	LDM	SDM	RDM	TDM
F Statistic							
ECw	3	1,63 ^{ns}	0,82 ^{ns}	1,99 ^{ns}	1,07 ^{ns}	1,50 ^{ns}	2,74 ^{ns}
ETc	3	1,98 ^{ns}	2,28 ^{ns}	0,67 ^{ns}	0,53 ^{ns}	0,20 ^{ns}	1,13 ^{ns}
ECwxETc	9	2,69*	2,12*	0,55 ^{ns}	1,06 ^{ns}	0,89 ^{ns}	0,78 ^{ns}
CV%	-	5,08	7,87	20,56	20,71	38,96	21,11

SV: source of variation; DF: degree of freedom; CV: coefficient of variation; ECw: electrical conductivity of irrigation water; ETc: irrigation depth; (^{ns}) not significant; (*) significant at the 5% level; (**) significant at the 1% level; (***) significant at the 0.1% level.

Source: The authors.

For the growth variables, there was a significant effect for the interaction electrical conductivities of irrigation water (ECw) x irrigation depths (ETc) for plant height and stem height (Table 4).

Plant height (Fig. 5A) was affected by combined abiotic stresses (saline and water), with the highest values being obtained in the combination ECw 3.83 dS m⁻¹ and ETc 87.76% (284.51 cm), by on the other hand, the lowest values (257.97 cm) were found in the combination ECw 3.98 dS m⁻¹ and ETc 53%.

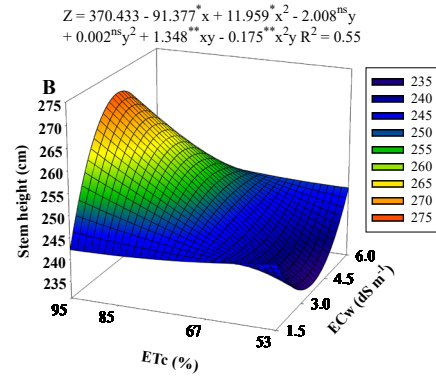
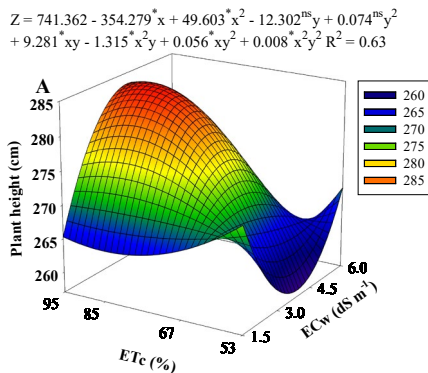


Figure 5. Plant height (A) and stem height (B) as a function of electrical conductivities of irrigation water (ECw) and irrigation depths (ETc) in sweet sorghum (*Sorghum bicolor* L.) 'BRS 506'. Source: The authors.

Similarly to plant height, for stem height the highest value (270.18 cm) was observed in the combination with ECw of 3.98 dS m⁻¹ and 95% of ETc, at the same time that the highest height (232.81 cm) was found in the combination of ECw of 3.67 dS m⁻¹ and 53% ETc (Fig. 5B).

4 Discussion

Plants subjected to high levels of abiotic stresses, such as saline and water, generally show damage to the water conditions of the leaves. In some previous studies in sorghum, increases in membrane damage were reported under conditions of water [12] and salt [13]. On the other hand, the relative water content is reduced in sorghum leaves under saline [14,16] and water [12] stress. However, in the present study, leaf water status variables (membrane damage and relative water content) were not affected by salt and water stress.

Salt and water stress cause reductions in soil water potential and leaf water potential, altering water relations and reducing plant turgor, leading to osmotic stress, and consequently reductions in leaf transpiration and gas exchange [35,36].

Generally, strategies for the mechanism of tolerance to abiotic stresses involve actions at the cellular level, such as maintenance of osmotic balance through ion absorption, preservation of hydrolase enzymes, accumulation of compatible ions, in order to maintain active photosynthesis [37-39]. In addition, these plants may have greater osmotic homeostasis compared to sensitive plants, through the accumulation of soluble sugars, in response to salt and water stress [10,15,19].

In our work, the total sugars showed an increase in the sorghum plants submitted to the highest electrical conductivities of the irrigation water. Corroborating the results found by [11], who reported greater accumulation of total soluble sugars in sorghum plants in response to salt stress. Total soluble sugars, especially non-reducing ones, are the main agents that contribute to the osmotic adjustment in sorghum leaves, being indispensable for the acclimatization of sorghum under conditions of abiotic stress [19].

Osmotic adjustment is essential for the acclimatization of sorghum to saline and water stress by maintaining turgor pressure and relative water content, as well as regulating physiological processes [15,17]. Changes in physiology and growth caused by salt and water stress generally depend on specific conditions, such as duration and intensity of stress, in addition to factors such as plant age and genotype [40].

In the present work, the gas exchange variables LT, WUE and WUEi were altered under salt stress, while the variables plant height and stem height were negatively influenced by salt and water stress together. However, there were marked reductions in both gas exchange variables and growth variables.

This behavior can be explained because the water potential in the leaves remained stable, not being affected by salt and water stress, resulting in the maintenance of gas exchange processes and the growth of sorghum plants. Showing that the sorghum cultivar 'BRS 506' can be cultivated under conditions of salt and water stress in semi-arid regions, without major losses in production [39].

5 Conclusions

The results indicate that combined salt and water stress cause negative effects on the growth of sweet sorghum [*Sorghum bicolor* (L.) Moench] plants. Salt stress generates disturbances in gas exchange and sugar content in plant leaves. The sorghum plants subjected to salt and water stress under the conditions of our work did not suffer major changes in the variables studied (gas exchange, leaf water status, sugars in the leaf and growth). Being able to show that the sweet sorghum cultivar 'BRS 506' is tolerant to the abiotic stresses studied.

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Quantification and analysis of flexibility in a power distribution network with penetration of non-conventional renewable sources

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Abstract

This work shows the quantification of the flexibility in power distribution systems in the scenario in which non-conventional renewable sources are connected to it. From a set of metrics available in the literature, one is selected based on its applicability to operational and distribution system planning scenarios. The theoretical foundation and detail of its computational implementation is shown. On the basis of this, its calculation is addressed for a distribution system in which non-conventional renewable sources and storage systems are present. From the results it is possible to identify quantifiable characteristics of flexibility to the variation in the operation of this type of systems.

Keywords: flexibility; power distribution networks; renewable energy sources; electrical energy storage systems.

Cuantificación y análisis de la flexibilidad en una red de distribución de energía eléctrica con penetración de fuentes renovables no convencionales

Resumen

Este trabajo muestra la cuantificación de la flexibilidad en sistemas de distribución de energía eléctrica en el escenario en el cual se tienen fuentes renovables no convencionales conectados al mismo. A partir de un conjunto de métricas disponibles en la literatura, se selecciona una basada en su aplicabilidad a escenarios operativos y de planeación de sistemas de distribución. Se muestra el fundamento teórico y el detalle de su implementación computacional. Con base en esta, se aborda su cálculo para el caso de un sistema de distribución en el cual se tiene presencia de fuentes renovables no convencionales y sistemas de almacenamiento. A partir de los resultados es posible identificar características cuantificables de la flexibilidad ante la variación en la operación de este tipo de sistemas.

Palabras clave: flexibilidad; redes de distribución de energía eléctrica; fuentes de energía renovable; sistemas de almacenamiento de energía eléctrica.

1 Introduction

On the planet Earth there are five main sources of energy: chemical reactions of natural resources, artificially induced nuclear reactions, the motion and gravitational potential of the earth, the sun and the moon, solar radiation and finally geothermal energy. Both conventional energy sources and Renewable Energy Sources (RES) are derived from these energy sources, but they differ from one another because RES primarily depend on weather conditions, causing their power generation to be highly variable but predictable with a certain

degree of reliability in the medium and long term [1,2]. It is generally accepted that renewable energy sources (RES) are more cost-effective compared to conventional sources, resulting in greater affordability and accessibility. The promotion and implementation of regulations in the technological field have resulted in a convergence [3]. Furthermore, to address the detrimental impacts of climate change, there has been a notable rise in the utilization of renewable energy sources (RES) that rely on solar radiation and wind speed.

According to [4], as of 2021, approximately 60% of global electricity generation relied on fossil fuels, while

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renewable energy sources (RES) accounted for the remaining 40%. The author's analysis includes a projection for the year 2050 regarding the sources of electricity generation based on the global perspective of various energy institutes and research centers. The projection emphasizes a notable diversification in the types of generation sources, with a prominent influence from solar and wind energy sources. Other works as [5], support these projections by observing that a 2°C increase in global temperature by 2050 would result in approximately 17% of energy production being derived from solar radiation systems.

In the context of Colombia, it has been reported by XM E.S.P [6] that the proportion of renewable energy sources (RES) in the country's installed capacity reached 68.7% in 2021. Of the total percentage, 66.9% is attributed to hydraulic generators, while approximately 3% is allocated to variable renewable energy sources (RES) such as solar, wind, biomass, and distributed generation. Among the latter group, photovoltaic technology holds a predominant position. According to projections, the integration of photovoltaic technology from renewable sources into the national transmission system is anticipated to occur by the year 2023. Moreover, Colombia's energy matrix is characterized by a significant reliance on hydropower, which has positioned it among the top 10 countries with the most environmentally friendly energy matrices globally.

1.1 Flexibility in power systems with renewable power sources

The increasing adoption and advancement of non-conventional renewable power generation technologies in interconnected and local power systems have resulted in the emergence of significant levels of volatility and unpredictability in power injection. These factors have had notable implications for the safety and reliability of these systems. Various instances have brought to light this particular circumstance, as exemplified in [1,5] respectively. This experience has led to the consolidation of a concept in the realm of traditional power systems known as "Flexibility". Flexibility can be defined as the capacity of an energy system to effectively manage the equilibrium between power generation and variable loads. In a similar vein, [7] and [8] provide a definition of grid flexibility as the capacity of an electricity system to effectively and economically handle the fluctuations in power demand and supply within a specified timeframe. A more expansive interpretation of flexibility can be described as the capacity of a power system to effectively address sudden instances of energy uncertainty, necessitating adjustments over an extended period of time. The latter definition enables the identification of two distinct temporal dimensions of flexibility: operational or short-term flexibility, and planning or long-term flexibility [9–11].

The incorporation of renewable energy sources (RES) into conventional power systems has become more prevalent. As a result, the assessment and measurement of flexibility across various timeframes have become crucial aspects of power systems planning and operation. With the proliferation of emerging renewable generation technologies, there is a growing need for networks that are more agile and flexible than ever before.

1.2 Quantification of flexibility in power electrical systems.

From the basic definition of flexibility set out above, three fundamental parameters for its quantification are derived; See Fig. 1.

Fig. 1 illustrates the power injection of a generator over a specified time interval. This behavior encompasses three primary components: the extent of power variation generated (Range), the rate at which the generator can modify the produced power (Ramp Rate), and the duration for which a specific generation level is sustained. In a typical situation, multiple generators will be interconnected within a single system, where the load experiences fluctuations over time. It is necessary to constantly maintain a balance between the generation capacity and the load demand, taking into consideration both technical and economic considerations.

Generators with a wider range of variation possess the capability to adapt their generation output to a broader spectrum of scenarios, thereby offering increased flexibility to the system. Some generators could quickly adjust their power generation and provide improved flexibility. In the long run, sources that have the capacity to maintain their production for extended periods of time will provide increased flexibility, allowing them to effectively manage fluctuations or prolonged changes within a system. It is imperative to acknowledge that the factors that contribute to variations in an electrical system are not exclusively ascribed to technical limitations, but also to economic decisions made during its operation. The aforementioned concepts are also addressed in the works referenced as [3,13]. In addition, taking into account additional elements like the frequency of load or generation variations over different time horizons and the sources' accessibility is necessary for quantifying flexibility in an electrical system [13].

The quantification of flexibility is accomplished across different time horizons. Operational flexibility pertains to the capacity to effectively respond and adjust to unanticipated fluctuations in load or generation circumstances within the span of a single day. This phenomenon has the potential to cause rapid fluctuations in the load, thereby requiring the

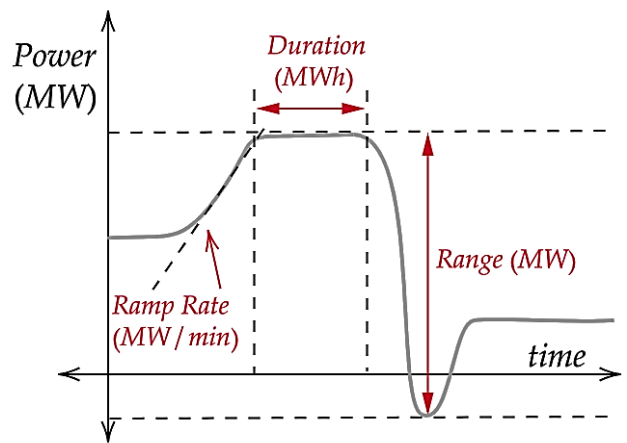


Figure 1. Key flexibility quantification parameters.
Source: The Authors.

deployment of sources that possess the capability to adjust their generation levels accordingly. Furthermore, these fluctuations can be attributed to changes in environmental variables such as solar radiation or wind speed, resulting in the need for additional generators to bear the burden that was initially not supported by renewable energy source (RES) generators. [11,14,15].

Flexibility in planning studies is related to the estimation of system's adaptability over long periods and frequently it includes the response to changing regulations, policies, and technological advancements. When developing this kind of studies, the concept of flexibility is commonly addressed through the establishment of indicators. These indicators serve as a basis for planning strategies and take into account periods of low flexibility, projected increases in power demand, among many others. In these studies, it is essential to be able to quantify and forecast hourly variations of demand, weather behavior, and net demand throughout the year, while also taking into account different timeframes. [13]

In the case of the short-term flexibility, some of the proposed metrics include the maximum and minimum residual demand [16], surplus energy [3,17], and instant power balance [18]. In contrast, the National Energy Reliability Center [13] has put forth a metric known as the "net charge" to evaluate the degree of flexibility. The net charge is defined as the immediate disparity between the overall load provided by the system and the load exclusively derived from renewable sources.

Various authors have put forth methodologies to quantify flexibility metrics based on these indicators. These metrics enable operational or planning decisions to be made in electrical systems. One instance of this approach is the methodology proposed by Lannoye et al. in [19], which will be one of the methodologies employed in this study.

1.3 Flexibility impact factors

Similar to an existence of flexibility metrics, there exist certain factors that exert a direct influence on the operational flexibility of a system. Several of these factors are associated with policies, such as demand response, while others are related to physical devices like energy storage [20]. Additionally, the presence of distributed generation on the network is another significant aspect to consider [3]. Another interesting example is the use of solar energy as a means of enhancing flexibility by generating green hydrogen via the process of hydrolysis. This enables the storage of energy in the hydrogen generated, which can be utilized for combustion purposes and other related systems or needs [21].

The adoption of policies or physical devices designed to enhance the flexibility of an electrical system allows for the conceptualization of flexibility as a service. The current implementation of this approach in a significant portion of Europe [7]. It involves modifying the generation dynamics in response to external signals originating from the energy market, network services, and the deliberate utilization of local compensation mechanisms.

Based on the aforementioned analysis, it is discernible that the integration of variable renewable energy sources into

electrical systems can yield either advantageous or detrimental consequences, contingent upon the interplay between demand and generation dynamics. The quantification, analysis, and evaluation of flexibility hold significant importance due to their ability to be applied and measured across various voltage levels and electrical systems. In the Colombian context, there has been a notable increase in the adoption of variable renewable generation technologies, such as photovoltaics and wind power, across different scales. Hence, it is imperative to quantitatively assess the adaptability of pre-existing electrical systems in relation to present and prospective circumstances. This evaluation is crucial for assessing the metrics associated with this adaptability and conducting an analysis of the power grid's supply and demand dynamics. The prevalence of photovoltaic system installations for the purpose of reducing energy consumption and billing is particularly evident in distribution systems [6].

Based on this discussion, the objective of this study is to assess the operational flexibility in an electricity distribution system that incorporates renewable energy sources, storage technologies, and demand management systems. Besides, to develop a flexibility estimation methodology that can be applied to a specific distribution network, taking into account the time series data of demand and generation. The modeling and simulation of power systems will be conducted using the open-source Python library known as PandaPower [22]. The repository will utilize time series databases to extract pertinent data from the Colombian Wholesale Energy Market API - XM SA ESP. The open-access library *pydataxm* is available in the official repository of the XM Analysis Team on GitHub Inc. [6]. Upon the conclusion of the study, an extensive analysis will be conducted to evaluate the chosen methodology and draw the most pertinent conclusions.

2 Methods

The literature contains a diverse range of proposals pertaining to the quantification of flexibility. Several methodologies have been proposed, including the Insufficient Ramping Resource Expectation (IRRE) [23], Lack of Ramp Probability (LORP) [24], Normalized Flexibility Index (NFI) and Loss of Wind Estimation (LOWE) [25], and Net Forecast Error (NFE) [26]. These are just a few examples among many proposals in this field. The assessment of an electrical system's flexibility is primarily determined by the anticipated or observed imbalances between power generation and demand, as well as the potential effects that corrective actions may have on the system. When determining these indicators, consideration is given to the fluctuating load's dynamic behavior and the variability in the timing of power injection from sources, commonly referred to as *ramps*. Furthermore, diverse metrics can be utilized to assess different timeframes, whether they pertain to operational or planning activities.

However, it should be noted that the methodologies and metrics discussed earlier are not limited to specific power systems, such as extra high, high, medium, or low voltage. The crucial factor lies in fulfilling the fundamental prerequisites for flexibility calculation. The study conducted

in [27] provides a comprehensive analysis of flexibility metrics in low voltage residential buildings. The author conducts a thorough literature review and establishes a classification of the most commonly used metrics for this voltage level. Various metrics encompass a range of calculation scenarios, ranging from straightforward calculations like maximum power reduction to more intricate ones that take into account economic variables, energy efficiency, and the impact of gas emissions. These metrics are instrumental in determining flexibility factors. In this study, the metric selected for implementation in a distribution system is the IRRE (Insufficient Ramping Resource Expectation) [23] as it can be used in short-term operation and also in the long-term planning of a distribution system. Its theoretical formulation will be presented in the subsequent sections.

2.1 The insufficient ramping resource expectation (IRRE)

The objective of the IRRE metric is to quantify the anticipated frequency of instances in which an electrical system is unable to effectively manage fluctuations in net load, regardless of whether these fluctuations were predicted or unexpected [23]. The calculation this metric involves the construction of an accumulated distribution of the flexible resources available for each increase or decrease in power injection or *direction*, and time horizon considered; this is known as the Accumulated Flexible Distribution (AFD). Furthermore, the determination of the likelihood that the system lacks adequate ramp resources in each observation, within each time horizon and direction, is derived from the cumulative distribution of available flexibility (AFD).

The information related to the production time series is used as the main input for calculating the IRRE, as detailed in [23]. The analysis ought to encompass data pertaining to the power output of each generation unit, encompassing both conventional and renewable sources. Furthermore, if accessible, the analysis may integrate time series data pertaining to losses and load consumption. The collection of the time series data is imperative within the specified time frame, typically spanning 24 hours, and at a predetermined level of detail, often measured in intervals of 15 minutes. The aforementioned values are employed in determining the temporal scope that is pertinent to the investigation. In addition, it is necessary to obtain data pertaining to the rated minimum and maximum output power, the startup time for power generation, and the maximum rate at which each unit can increase or decrease its output power.

In flexibility studies several time horizons can be considered based on the historical events related to the sudden increase or decrease of load or generation (ramps), the startup times for each generation type connected to the system under study or any forecast horizon of interest.

Based on the time series, the Net Load (NL) time series is obtained as its defined as the remaining load not served by variable generation. From it, the Net Load variation in time or Net Load Ramp curve is obtained as the difference between subsequent Net Load values for each time horizon considered i . This can be expressed as in eq. (1).

$$\begin{aligned} NLR_{t,i} &= NL_t - NL_{t-i} \\ 1 \leq t &\leq |NL| - i \end{aligned} \quad (1)$$

Eq. (1) expresses the variation of the Net Load Ramp (NLR) in time t and for a total of $|NL|$ observations. The values of the NLR exhibits both positive or negative thus two variables are introduced NLR_+ and NLR_- defined in eq. (2) for each time interval considered i and for each observation time t .

$$\begin{aligned} NLR_{t,i,+} &= NLR_{t,i} \quad \forall NLR_{t,i} > 0 \\ NLR_{t,i,-} &= NLR_{t,i} \quad \forall NLR_{t,i} < 0 \end{aligned} \quad (2)$$

The variables considered in this analysis encompass the load's behavior and its correlation with the production of generation units.

The other element considered in the calculation of the IRRE is the Available Resource Flexibility. For each generation unit u having a capacity of increasing its output power or having an upward ramp rate of $RR_{u,+}$, and a startup time S_u , it is possible to define the ability to respond to an increase in its output power or upward flexibility is given by eq. (3) for an interval i and observation time t .

$$Flex_{t,u,i,+} = RR_{u,+} * (i - (1 - Online_{t,u}) * S_u) \quad (3)$$

The variable $Online_{t,u}$ is binary variable that indicates whether or not unit u is operational at a specific time t . If the source is at maximum production, it has not upward flexibility at that time. Based on this, upward flexibility is bounded by this maximum production. Additionally, it is important to note that the startup time (denoted as S_u) is required for the resource to reach its desired power output once it goes online. Therefore, when considering the time horizon for analysis, it is necessary to account for a duration that is longer than the startup time. If a unit has the ability to increase its output during a specific time interval, its upward flexibility can be determined by multiplying the ramping up limit $RR_{u,+}$ with the difference between the time interval and the startup time, as indicated in eq. (3). Based on the aforementioned considerations, two restrictions are enforced to ensure upward flexibility.

$$\begin{aligned} Prod_{t,u} + Flex_{t,u,i,+} &\leq Gen_{MAX,u} \\ Prod_{t,u} + Flex_{t,u,i,+} &\in \mathbb{R}(0, Gen_{MIN,u}) \end{aligned} \quad (4)$$

Where $Prod_{t,u}$ is the unit production at a time t , and $Gen_{MAX,MIN}$ are the minimum and maximum production outputs of unit u .

The downward flexibility can be defined in a similar way and expressed as in eq. (5)

$$\begin{aligned} Flex_{t,u,i,-} &= RR_{u,-} * i * Online_{t,u} \\ 0 &\leq Prod_{t,u} - Flex_{t,u,i,-} \\ Prod_{t,u} - Flex_{t,u,i,-} &\in \mathbb{R}(0, Gen_{MIN,u}) \end{aligned} \quad (5)$$

Once the available flexibility of each unit is calculated, the upward and downward flexibility of the whole system can be calculated as the summatory of individual flexibilities as shown in eq. (6)

$$\text{Flex}_{t,\text{System},l,+/-} = \sum_{vu} \text{Flex}_{t,u,i,+/-} \quad (6)$$

Thus far, two components have been delineated, namely the NLR and the system's flexibility. It is important to acknowledge that these calculations can be performed in real-time using system measurements or short-term forecasts. These calculations could be subsequently used to make operational decisions within a distribution system.

When the long-term knowledge of system flexibility is available, it becomes possible to conduct a statistical analysis of its behavior by quantifying the cumulative distribution of available flexibility, also known as AFD (Available Flexibility Distribution). When considering various scenarios, it is imperative to accurately estimate this distribution as delineated in [23]. Formally, the $AFD_{l,+/-}(X)$ is obtained for upward and downward flexibility and indicates the probability that X MW or less will be available for a given time horizon i .

Finally, this methodology seeks for estimating the probability of a system to have insufficient flexibility at each point in time. The situation in question can be represented via a cumulative distribution, which illustrates the insufficient capacity of a system to adequately accommodate the necessary ramping for fluctuations in the net load at any given moment.

Based on the $AFD_{l,+/-}(X)$ distribution, the Insufficiency Ramping Resource Probability (IRRP) is calculated as shown in eq. (7).

$$\text{IRRP}_{t,i,+/-} = \text{AFD}_{i,+/-}(\text{NLR}_{t,i,+/-} - 1) \quad (7)$$

The sum of all IRRP values along the complete time series corresponds to the Insufficiency Ramping Rate Expectation (IRRE) and is given by eq. (8).

$$\text{IRRE}_{i,+/-} = \sum_{vt \in T_{+/-}} \text{IRRP}_{t,i,+/-} \quad (8)$$

This study exclusively focuses on the assessment of short-term flexibility within operational scenarios. This implies that the methodology is utilized to achieve the adaptability of the system and to analyze its statistical properties with respect to specific production and demand curves.

This assertion is grounded in the observation that the Net Load's behavior in planning studies diverges from that of the operational Net Load derived from nearly real-time data.

3 Results

The scenarios chosen to implement the quantification flexibility methodology (IRRE) were derived from the power network known as IEEE 33 Bus Case which is available in the open-source Python library called "PandaPower"; all details can be consulted in [22].

The network is modeled as a medium voltage distribution system as shown in Fig. 2.

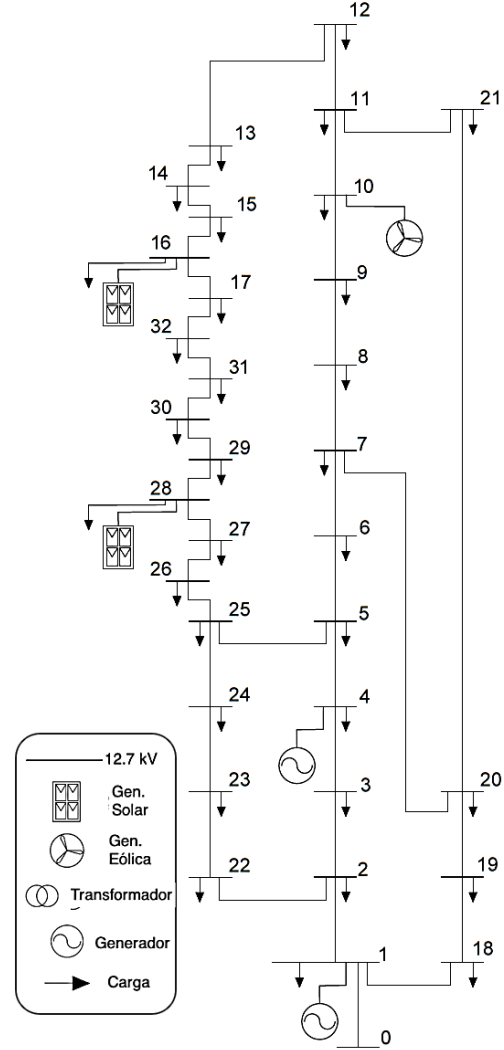


Figure 2. IEEE 33 Bus network.
Source: The Authors.

The time series associated to the generation units and load data was acquired using the XM S.A. E.S.P. API *pydataxm* [6]. To utilize the aforementioned data, a scaling procedure was conducted to retain the temporal behavior of the generation units, while adhering to the upper limits of production values identified in reference [22].

A total of four cases were examined for the same system. The scenarios for Case I involve a network without any storage devices. Conversely, Case II considers the existence of a storage device at Node 16 of Fig. 2. In both scenarios, the circuitual and optimal power flow methods were utilized to generate a 24-hour time series for production and demand. The flexibility methodology was implemented for each case, taking into consideration the data that was available.

The complete parameters of the network are shown in Table 1.

The following section presents a detailed examination of the outcomes achieved through the implementation of the IRRE methodology on the circuitual power flow of Case I. The findings pertaining to other cases are compared in section 3.2.

Table 1.
IEEE 33 Bus network parameters.

Network Element	Number	Details
Bus	30	Nominal Voltage: 12.66 kV Max. Voltage: 1.1 p.u. Min. Voltage: 0.9 p.u.
Loads	32	Total Power: 3.175 MW
Non-Conventional Units	3	PV: 1.13 & 0.56 MW WD: 0.86 MW
Conventional Units	5	Hydr: 0.83 MW Diess: 0.38 MW Power: -0.5 MW
Batteries	1	Soc: 100% Min Power: -0.125 MW Max Power: -0.625 MW
Lines	34	Length: 1km

Source: The Authors.

3.1 Case I – Circuital power flow

The network in this case had hydraulic, Thermal, Solar and Wind power; the load and generation data were obtained for 24 hours with a 15-minute resolution. The results obtained for the circuital power flow of this case are shown in Fig. 3.

In Fig. 3 it can be observed system's total generation (Total), the load consumption (Load) and the system losses (Loss). Generation units are divided in renewable (RNW) and conventional (Conv); according to the definition of Net Load, the NL curve was obtained for each time instant. From this NL curve, the Net Load Ramps (NLR) are obtained from eq. (1) and shown in Fig. 4 for the upward (positive) and downward (negative) changes in the Net Load for this system. As the Net Load is defined as the load not supplied by variable generation, this curve shows the changes in power of the conventional generation units.

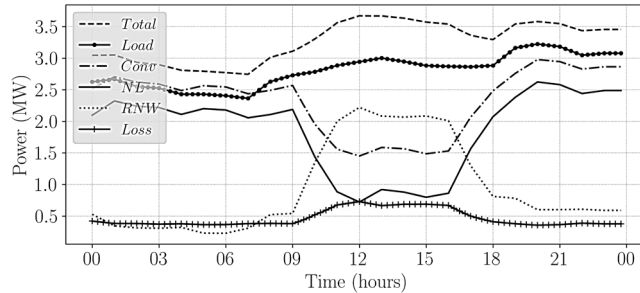


Figure 3. Circuital Power Flow - IEEE 33 Bus network.
Source: The Authors.

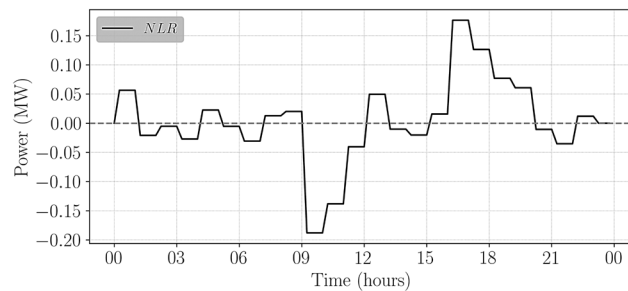


Figure 4. Net Load Ramp Curve.
Source: The Authors.

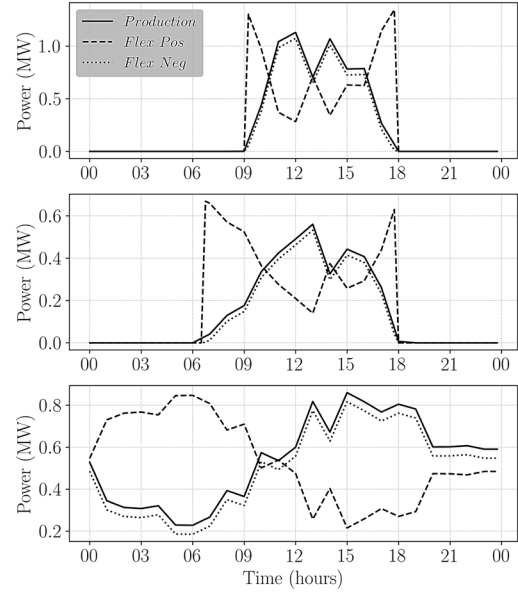


Figure 5. Upward and downward flexibility for renewable generation units.
Source: The Authors.

The upward flexibility (Flex pos) and downward flexibility (Flex neg) can be derived from eq. (3) to eq. (5) based on the production curves depicted in Fig. 3. These flexibilities are then illustrated in Fig. 5 for the renewable units and in Fig. 6 for the conventional units.

From Fig. 6, at a given time instant, two values can be obtained: the available power each renewable source could inject to the system (upward flexibility), and the power it could also cease to inject (downward flexibility). Depending on the type of input from each source (e.g. wind speed or solar radiation), its flexibility changes. For solar units this behavior is as expected; in morning hours its production is almost null but only in high solar radiation hours it could be integrated into the system and considered in the flexibility evaluation. Fig. 6 shows the same variables behavior for conventional units. The conclusions here are analog to those mentioned before for renewable sources.

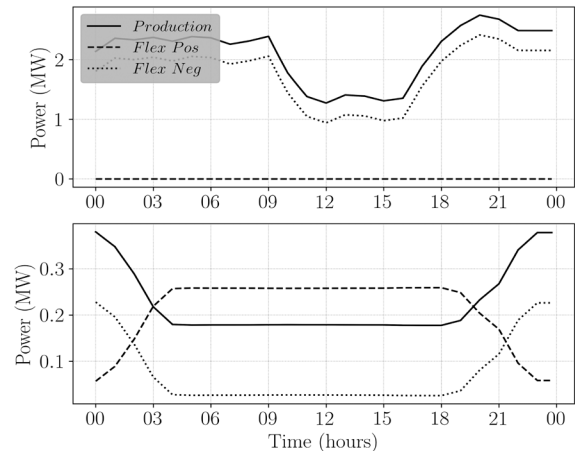


Figure 6. Upward and downward flexibility for conventional units.
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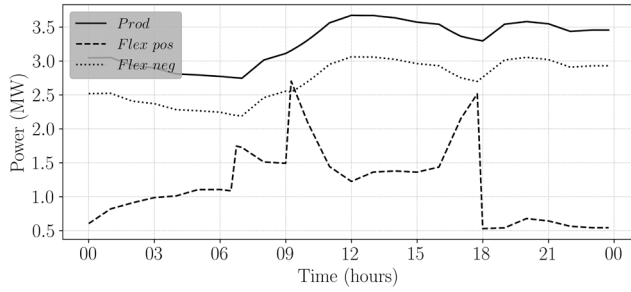


Figure 7. Upward and downward flexibility the complete system.
Source: The Authors.

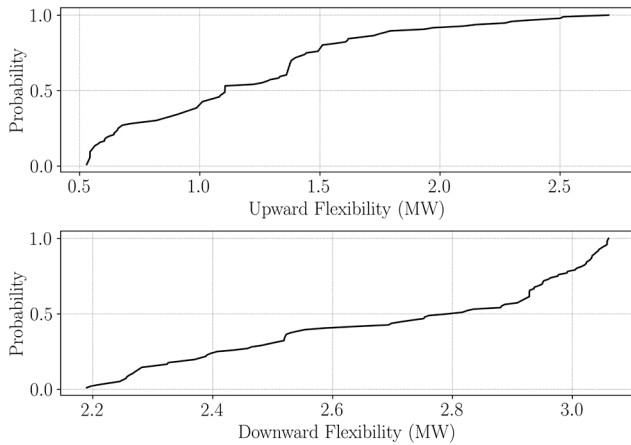


Figure 8. Upward and downward AFD.
Source: The Authors.

The total available flexibility of the system at each time instant is determined using eq. (6) and is visually represented in Fig. 7. In each of the flexibility curves presented, the positive value of available flexibility at a specific moment signifies the potential power that can be injected either at each individual unit or within the entire system. Conversely, the concept of negative flexibility pertains to the capacity of individual units to cease injection of power at any given moment.

The construction of the cumulative distribution of available flexibility (AFD) is based on the assumption that consistent production and load curves persist throughout a one-year period. The AFD is depicted in Fig. 8 using a distribution estimator.

Each point on these figures represents the probability that this system has of increasing (or decreasing) an amount or less of power a value.

Finally, the Insufficiency Ramping Resource Probability (IRRP) could be calculated from eq. (7) and IRRE from eq. (8) for long term planning scenarios and based on forecasted or estimated behavior of the net load.

3.2 Results comparison and analysis

As previously stated, four scenarios were taken into consideration. In Case I, a circuital and optimal flow were carried out in a system without any storage device (C1C and

Table 2.

Production Costs.

Generation Unit	Linear Costs	Quadratic Costs
	Cp1 (€/MW)	Cp2 (€/MW ²)
Hydroelectric	20.0	0.038
Thermal / Diessel	40	0.25
Photovoltaic	1	0.01
Photovoltaic	1	0.01
Wind	1	0.01

Source: Source: The Authors.

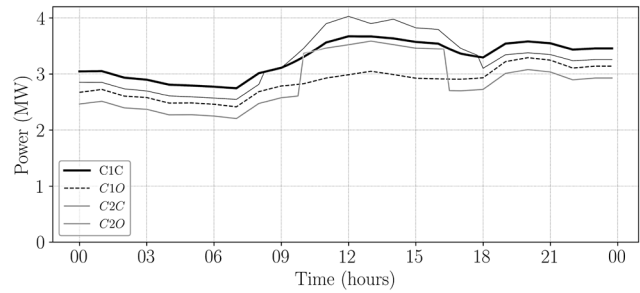


Figure 9. Total production for all cases.
Source: The Authors.

C1O respectively). In Case II, an analysis was conducted on the same two scenarios, but with the inclusion of a storage device within the system (C2C and C2O respectively). The selection of optimal power flow scenarios was motivated by an interest to incorporate the economic factor associated with a theoretical operation and planning of the network being studied into the estimation of flexibility. The generation costs that have been taken into consideration are presented in Table 2 [28,29]. In Table 2, the Cp1 column is related to linear costs per MW and the Cp2 column to quadratic costs per MW. This data is based on an n-polynomial cost function for order two and was used as input for the Optimal Power Flow algorithm. The total production time series for all cases is shown in Fig. 9.

The order of peak demand among different cases is illustrated in Fig. 9. The highest demand peak is observed in Case II C2C, followed by Case I C1C. C2O occupies the third position, while C1O exhibits the least peak demand. For all cases, the production curves obtained from circuital power flows are higher in the early morning (00 to 08 hours) and night (18 to 24 hours). In the cases of optimal power flows, the production curves order changes during late morning and afternoon hours (09 to 18 hours) due to the cost inclusion in the production of solar energy sources and the use of energy storage systems.

In order to obtain an analysis closer to the operation of a regional distribution power system, we will investigate the optimal flow scenarios, namely C1O and C2O. These cases include the cost factors as previously described.

Fig. 10 displays the net load for all scenarios, representing the load supplied by conventional generation. It is evident that this net load is closely linked to the aforementioned demand peaks. For instance, the minimum peak generation observed in case C1O is associated with the minimum peak net load. Moreover, the minimum values observed in all net load curves can be attributed to the substantial contribution

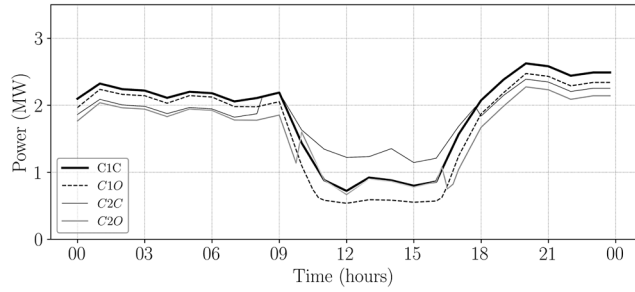


Figure 10. Net Load for all cases.
Source: The Authors.

of renewable energy sources during the late morning and afternoon period, specifically between 09:00 and 18:00 hours. This suggests that conventional generation units are anticipated to have a notable capacity for flexibility during this timeframe, in response to an unexpected change in variable generation.

The system's upward and downward flexibility are shown in Fig. 11.

The morphological similarities between the upward flexibility in cases C1O and C2O are quite apparent. Nevertheless, a significant distinction exists: Case C1O exhibits a greater capacity to introduce power into the system during specific time intervals. The enhanced injection capacity is influenced by the nominal parameters of the electrical generation equipment within a designated time frame, typically observed during midday. It is important to acknowledge that the enhanced injection capability in C1O can be mitigated in C2O due to the inclusion of storage units. In the given context of downward flexibility in cases C1O

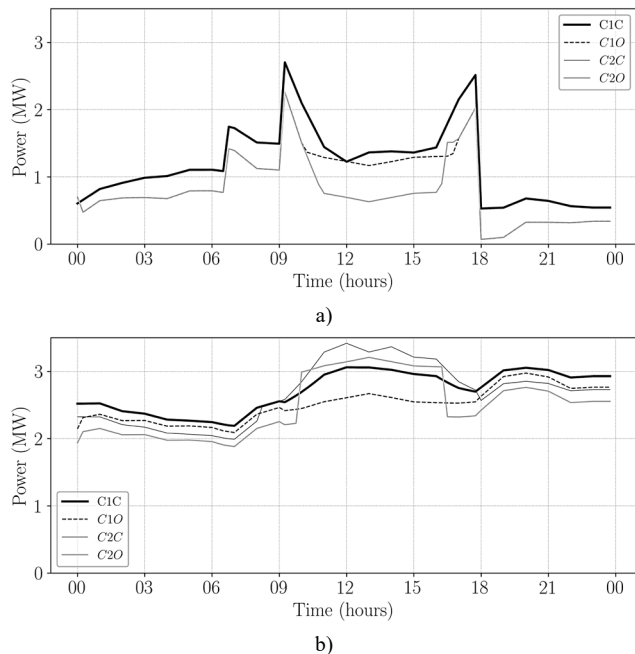


Figure 11. System's flexibility for all cases. a) Upward flexibility, b) Downward flexibility.
Source: The Authors.

and C2O, it is evident that case C2O exhibits a higher capability to impede power injection into the system. The rate at which this capacity operates is determined by the nominal parameters of the electrical production equipment and is typically limited to a specific time range, commonly around noon. The increased functionality of C2O is attributed to the coexistence of generation storage devices. The charging of these storage devices at specific intervals has resulted in a significant supply of downward flexibility.

Finally, the upward and downward distributions (AFD) are presented in Fig. 12.

Fig. 12 (a) depicts the AFD for upward flexibility cases. In a general sense, the cumulative distributions of these cases exhibit resemblances, except for one noteworthy deviation for optimal power flow cases. These cumulative distribution exhibits divergence in the range of $[0.6-1.5]$ [MW] in relation to upward flexibility. In the case of C1O, it can be observed that the cumulative probability stands at almost 0.55 probability, denoting the availability of about 1 [MW] or less of upward flexibility within a 15-minute timeframe. On the other hand, it is worth noting that in the C2O scenario, the cumulative probability exhibits a significantly higher value, reaching probability values of about 0.79. This suggests that within a 15-minute timeframe, there is a higher likelihood of C2O having upward flexibility of 1 [MW] or less.

In juxtaposition to the preceding instance, we are presented with a situation characterized by notably distinct cumulative distribution patterns. The distributions for cases C1O and C2O are illustrated in Fig. 12 (b), indicating a lack of similarity between the two, except for a common value related to downward flexibility. In both instances, there exists a shared value of downward flexibility, specifically 2.55 [MW] or lower, that can be utilized within a time frame of 15 minutes. The aforementioned value is correlated with a cumulative

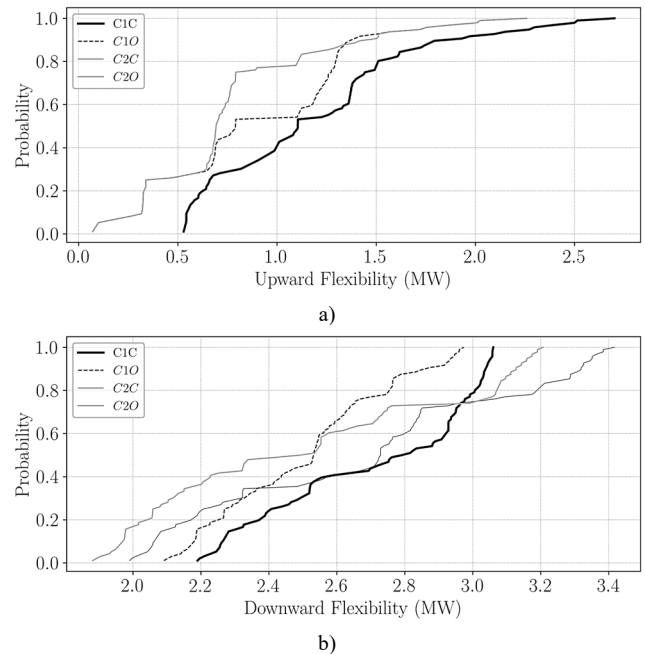


Figure 12. Systems AFD distributions. a) Upward flexibility, b) Downward flexibility.
Source: The Authors.

probability of 0.55. However, significant differences become apparent when analyzing the case C1O. In this particular case, the cumulative probability reaches 0.8, signifying that a maximum of 2.75 megawatts (MW) or less is accessible as downward flexibility within a 15-minute timeframe. In contrast, case C2O exhibits a greater value of 3.07 [MW] or lower as the downward flexibility that is available during the same time period. The aforementioned variations underscore the notable influence on the adaptability of a system when incorporating resources such as storage devices.

The results and analysis presented here gives the possibility to be used in a real-time or operational environment of a distribution system. The forecast based on measurements of environmental or power consumption/generation values could be used in order to evaluate the flexibility of a system at a given time instant. Based on it, the robustness of the system can be known, and control decision can be made to improve this situation.

4 Conclusions

The responsible integration of renewable generation sources, such as photovoltaic or wind power systems, necessitates a careful transition. This is due to their inherent volatility and the presence of high ramp rates in their technology. It is crucial to acknowledge that the migration to these new technologies extends beyond mere fashion or technological trends.

The various software applications available for power system modeling, incorporating the integration of renewable sources, may not inherently support flexibility calculations, and vice versa. Therefore, it is imperative that the objective of flexibility analysis is well-defined. One effective approach is to incorporate simulation and verification models, such as real-time models, which can greatly assist in quantifying and analyzing operational flexibility metrics. However, in the event that a reassessment of planning flexibility is deemed essential, it becomes imperative to utilize historical databases that possess a substantial influx of information pertaining to power systems. Consequently, it becomes crucial to possess the ability to discern the most suitable tool that aligns with the specific requirements.

The examination of flexibility metrics as instruments in the operation and planning of power systems encompasses a diverse array of models, procedures, and methodologies that can be applied, rendering it a potent and adaptable tool for analyzing both specific and general systems. This analysis does not differentiate between time scales, network components, or their physical dimensions.

The utilization of the flexibility metric in power networks has proven to be highly advantageous in providing a rationale for the adoption of regulations, policies, and economic models within frameworks that connect fluctuating renewable energy sources. This is done with the aim of ensuring energy security at the local or regional level. The concept of complete communities refers to the notion of creating urban environments that are self-sustaining and provide all necessary amenities and services.

The methodology for assessing the expectation of

insufficient ramp resource (IRRE) encompasses various metrics that facilitate the analysis of maximum power in flexible operation, characterization of net load curves, and statistical analysis of the probability of insufficient resources in flexible ascending or descending scenarios. These metrics serve as a basis for quantifying other related metrics and can also be utilized as a foundation for the development of more comprehensive methodologies. The project in question provided us with a tool that enabled us to gain insights into the benefits and drawbacks of demand management, specifically in relation to the economic aspects of operations.

The incorporation of battery banks into distribution systems characterized by a significant presence of variable renewable generation sources serves the purpose of not only mitigating the effects of low energy production periods but also addressing net load peaks during high production hours. This observation underscores the flexibility of energy storage banks as they effectively mitigate the inherent volatility associated with photovoltaic or wind generators, thereby contributing to the stability and reliability of the overall system operation.

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LoRa-based IoT platform for remote soil parameter monitoring

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Abstract

The objective of this work was to develop an innovative LoRa-based platform that provides a low-cost and customizable solution for real-time monitoring of soil parameters. The system architecture was based on four levels: environmental (rural), sensors and actuators, communication network, and application, with the code made available for operation. The collected data were transmitted to data collection points using LoRa technology. The application level allowed for data storage, analysis, and visualization, enabling end-users to remotely monitor and control environmental measurement operations. With LoRa technology range tests, results indicated the capability to cover a maximum area between 95 and 120 hectares in the studied areas. Additionally, the collected data were sent to ThingSpeak.com and a mobile application called Thingsview. This demonstrated the efficiency and viability of LoRa technology for industrial communication sensor and IoT applications in rural environments, offering automation, increased efficiency, and savings in human resources for environmental monitoring tasks.

Keywords: LoRa technology; rural environmental monitoring; sensors and actuators.

Plataforma IoT basada en LoRa para monitoreo remoto de parámetros del suelo

Resumen

El objetivo de este trabajo fue desarrollar una innovadora plataforma basada en LoRa que proporciona una solución económica y personalizable para la monitorización en tiempo real de parámetros del suelo. La arquitectura del sistema se basó en cuatro niveles: ambiental (rural), sensores y actuadores, red de comunicación y aplicación, con el código disponible para su funcionamiento. Los datos recopilados se transmitieron a puntos de recopilación de datos mediante la tecnología LoRa. El nivel de aplicación permitió el almacenamiento, análisis y visualización de datos, lo que permitió a los usuarios finales supervisar y controlar de forma remota las operaciones de medición ambiental. Con pruebas de alcance de tecnología LoRa, los resultados indicaron la capacidad de cubrir un área máxima de entre 95 y 120 hectáreas en las áreas estudiadas. Además, los datos recopilados se enviaron a ThingSpeak.com y a una aplicación móvil llamada Thingsview. Esto demostró la eficiencia y viabilidad de la tecnología LoRa para aplicaciones de sensores de comunicación industrial e IoT en entornos rurales, ofreciendo automatización, mayor eficiencia y ahorros en recursos humanos para tareas de monitorización ambiental.

Palabras clave: tecnología LoRa; monitorización ambiental rural; sensores y actuadores.

1 Introduction

The communication between humans and machines through the Internet of Things (IoT) has been routinely used

in various applications. Machine-to-machine and machine-to-human interaction using sensors has potential applications in various sectors [1-3].

When agriculture is associated with the application of the

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Internet of Things (IoT), it enables an approach aimed at optimizing the use of human and environmental resources with the goal of improving the efficiency and sustainability of agricultural activities [4]. In this context, Long-Range (LoRa) wireless communication technology has been used to develop monitoring networks in agricultural applications due to its data transmission capabilities over long distances with low power consumption [5].

Recent studies have demonstrated the use of LoRa technology for soil moisture monitoring as a highlight in Precision Agriculture. [6] proposed an IoT and LoRaWAN-based system for crop monitoring and irrigation control, emphasizing the efficiency of this technology in transmitting collected data. [7] also highlighted the use of LoRaWAN to implement intelligent irrigation systems in agriculture, contributing to water and energy savings.

Another relevant application is real-time crop monitoring. [5] developed a LoRa-based wireless sensor network for soil moisture monitoring in a coffee plantation, highlighting the reliability and low energy consumption of this technology. [8] also proposed an IoT and LoRaWAN-based system for soil moisture monitoring, emphasizing LoRa's long-distance coverage capability.

LoRa technology has also been applied to real-time weather monitoring to support decision-making in agriculture [9,10]. As highlighted by [11], the use of LoRa devices for transmitting agricultural data has shown promising results, enabling the acquisition of accurate information for crop management.

The use of LoRa in Precision Agriculture applications has proven to be a viable and promising solution for real-time monitoring of agricultural variables, enabling more informed decision-making, efficient resource management, and reduced operational costs [2,3,12].

To date, there are no known works that utilize sensors with RS-485 serial communication standards, Modbus serial communication protocol, real-time access, and simplified data visualization and processing capabilities for users. Thus, the objective of this work was to develop an innovative LoRa-based platform that provides a low-cost and customizable solution for real-time soil parameter monitoring.

2 Methodology

The development consisted of building a prototype using the Design Science Research methodology [13] for LoRa technology [14], with the potential for use in different environments. Subsequently, an IoT solution was implemented on the prototype using the Thingspeak platform. The following will demonstrate the steps for carrying out this work.

2.1 Proposed architecture

The development of the architecture was based on the one proposed by [2,15], consisting of four levels: Environmental (rural), Sensors and actuators, Communication network, and Application, as shown in Fig. 1.

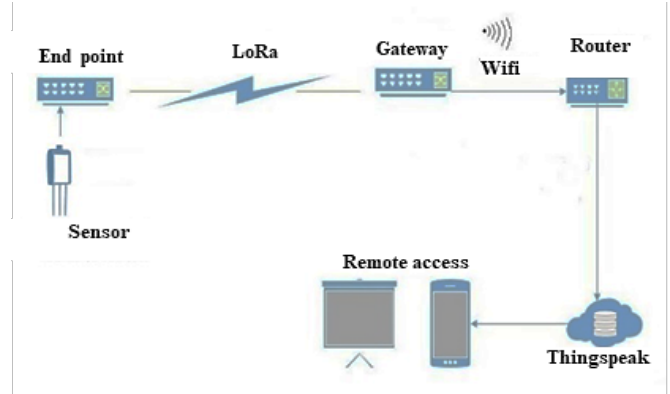


Figure 1. The proposed architecture.

Source: Adapted from Faria and Cavazzoti, 2019 and from Rudiger, 2021.

The characterization of the levels considered for execution starts with the rural environmental level, which includes various soil monitoring parameters, enabling data transmission with minimal human intervention. Subsequently, the sensor and actuator level can be observed. This level consists of different sensor nodes and soil parameter measurement devices that are installed to collect data on temperature, soil moisture, and electrical conductivity. The collected data is then transmitted to data collection points or gateways through wired or wireless communication.

Continuing with data acquisition, the communication network level enables data transmission from the environmental level to the application level using different long-range communication technologies such as LoRa. LoRa is used to exchange data with the assistance of a gateway located in an area with internet access in the rural environment.

Finally, the last level is the application level, where all the data received from the sensor nodes and devices through the communication network level allows for data storage, analysis, and visualization. This level enables end-users to remotely monitor and control environmental measurement operations. Thus, the application layer facilitates management, including planning and decision-making.

2.2 Transmitter-receiver set characterization

The operation of the prototype begins with the Arduino Pro Mini sending requests via Modbus RTU to the THC-S sensor through the RS-485 module. The sensor responds to the request by sending the collected data of soil moisture, temperature, and conductivity to the Arduino Pro Mini. The choice not to adopt the Heltec module to directly receive data from the sensor is due to the specific nature of the soil moisture sensor. This sensor requires a 5V power supply to operate correctly and, consequently, operates at a voltage of 5V. On the other hand, the Heltec module operates at 3.3V. Due to this voltage difference, the Heltec module is unable to directly read the data obtained from the sensor through the RS-485 module, making it necessary to use the Arduino Pro Mini as an intermediary to ensure accurate and reliable reading of the sensor data.

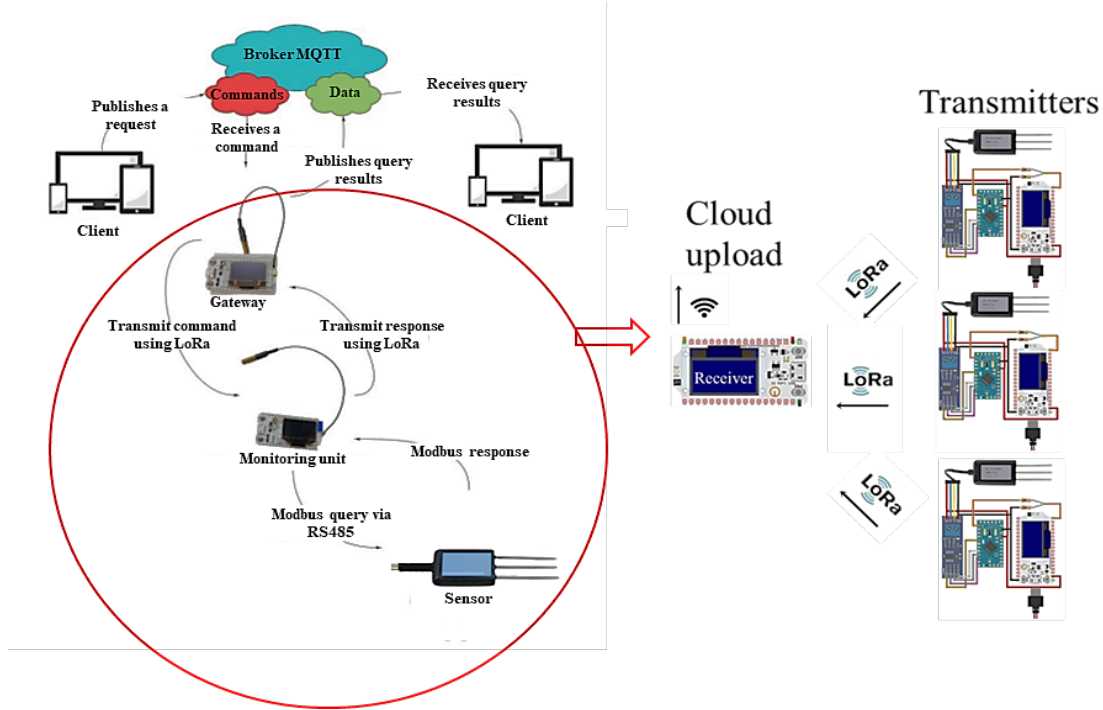


Figure 2. Transmitter-Receiver system details.
Source: Adapted from Rudiger, 2021.

To enable this serial communication, it is necessary to implement the use of the SoftwareSerial.h library in the code, where a new virtual serial port is created using two digital pins as TX (Transmitter) and RX (Receiver). After reading the data received by the Arduino Uno, it interprets it and converts the soil moisture, temperature, and conductivity values into real values.

After the Arduino Uno receives the data read from the sensor, it is necessary to send this collected information to another location. For this purpose, the Heltec Esp32 LoRa microcontroller is used, which has long-range communication capabilities. Communication between the Arduino and the LoRa was done via hardware serial port (UART), where this data will be sent via TX-RX.

Since the voltage levels of the Arduino Pro Mini and the Heltec Esp32 LoRa are different, they are not directly compatible for communication. The Arduino operates at 5 volts, while the Heltec operates at 3.3 volts, which could potentially damage the Heltec Esp32 LoRa due to the reception of a higher voltage.

To ensure that this serial communication is done safely, the use of a voltage divider is necessary to reduce the Arduino's voltage to a level compatible with the LoRa. This divider consists of two resistors connected in series, and the voltage at the midpoint between the two resistors is given by:

$$V_{out} = V_{in} \times \frac{R2}{R1 + R2} \quad (1)$$

To achieve a voltage of 3.3V, where $V_{in} = 5V$, and using resistors $R1=5k$ ohms and $R2=10k$ ohms, you would arrive at:

$$V_{out} = 5V \times \frac{10k}{10k + 5k} \rightarrow V_{out} = 3.33V \quad (2)$$

With all the data to obtain the necessary voltage, the transfer of information stored by the Arduino will be transmitted through the Pro Mini's TX pin, passed through the voltage divider, reducing it from 5V to 3.3V, and then received by the RX, pin 16, of the Heltec. Fig. 3 illustrates the serial communication between the Arduino and the Esp32 LoRa Transmitter with the voltage divider.

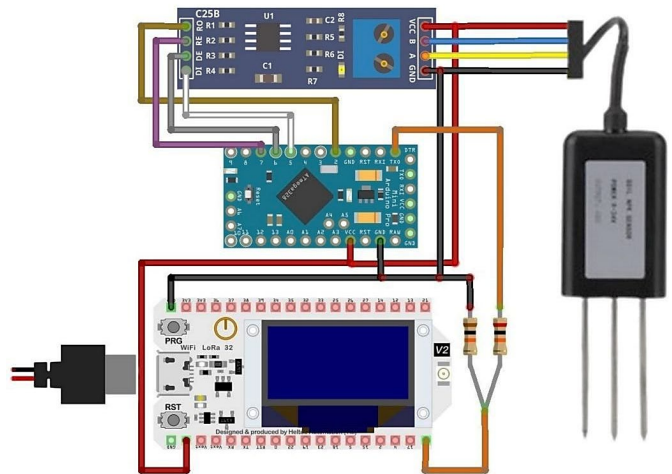


Figure 3. Serial Communication between arduino and Heltec Esp32 LoRa with voltage divider
Source: Author's Own.

The receiver is characterized by a LoRa unit, which functions as the gateway. Its configuration was designed to receive data from three different LoRa transmitters. Due to the nature of the transmitter-receiver communication, which processes one transmitter at a time, there was a need for a time-sharing strategy to ensure the integrity of the received data.

This strategy involved allocating specific periods where the gateway focuses on receiving data from one transmitter at a time. This was done to avoid conflicts and packet losses during transmission. Each transmitter was synchronized to send its data at predetermined times, ensuring that the gateway could capture all the information in an organized manner.

Additionally, the transmitters send an identification along with the packet, allowing the receiver to verify if the received messages are addressed to it. When destined, the gateway publishes its content to the data topic via the MQTT protocol. Thus, concluding the transmission of captured data to an IoT service, ThingSpeak.com, and to a mobile application, Thingsview.

2.1 Characterization of the Sensor (CWT-SOIL-THC-S)

According to the objective, the CWT-SOIL-THC-S sensor was used, designed to monitor soil conditions in agricultural, environmental, and crop monitoring applications. It is capable of measuring soil moisture, temperature, and soil electrical conductivity with high precision and reliability. However, the system has the capability to receive data from various sensors with Modbus communication via RS485. In other words, through the RS-485 module, it can establish an efficient serial connection between the Arduino and the sensors.

The CWT-SOIL-THC-S sensor has a measurement range of relative soil moisture from 0% to 100%, a temperature ranges from -40°C to 80°C, and a conductivity measurement range from 0 to 200,000 µS/cm.

The sensor can collect data on soil moisture, temperature, and electrical conductivity, enabling the transfer to a control system, which can be used to monitor real-time soil conditions and make informed decisions regarding irrigation and plant nutrition, similar to [10].

With its IP68 rating, the CWT-SOIL-THC-S sensor is protected against dust and liquids, indicating that the sensor is robust enough to withstand light impacts and vibrations, making it ideal for field applications.

Table 1.
Characteristics of the Sensor (CWT-SOIL-THC-S)

Parameters	Characteristics
Temperature	Measuring range: -40°C - 80°C
	Accuracy: 5%°C (25°C)
	Long-term stability: ≤0.1% °C/y
	Response time: ≤15s
Soil moisture	Measuring range: 0-100%RH
	Accuracy: 2% within 0-50%, 3% within 50-100%
	Long-term stability: ≤1%RH/y
	Response time: ≤ 4s
Conductivity (EC)	Measuring range: 0-200000µs/cm
	Accuracy: 0-10000 µs/cm range is ±3%; 10000-20000 µs/cm range is ±5%
	Long-term stability: ≤ 1%µS/cm
	Response time: ≤ 1s

Source: ComWinTop - Soil parameters measuring (<https://shre.ink/rQR1>)

With high precision, long-term stability, and a fast response time, the CWT-SOIL-THC-S sensor is a reliable and efficient solution for measuring soil moisture, temperature, and conductivity in various applications, from agriculture to environmental and scientific studies.

2.2 Simplified signal range

To validate the use of the developed system in locations where environmental data acquisition sites lack adequate infrastructure, such as for the installation and use of WiFi networks, Ethernet, or cellular networks, a range test was conducted. The purpose was to assess the distances at which the equipment could be installed.

The system operates at a frequency of 915 MHz. The signal evaluation metric for received messages was simplified, adopting only the RSSI (Received Signal Strength Indicator). RSSI is a metric of the relative signal quality that represents its power in dBm.

To evaluate the operational range of the system, the monitoring unit was connected to a power bank to provide the necessary power for its operation. The gateway was positioned in a location with elevation similar to the monitored area and with access to the internet via a WiFi network.

RSSI measurements were taken at three different spatially distributed points within each area. The locations for measurements were selected, including the Laboratory of Studies in Hydraulic and Hydrology of the Department of Agronomic Engineering at the campus of the Federal Institute of Bahia, in Bom Jesus da Lapa, and the Laboratory of Agricultural Instrumentation of the Postgraduate Program in Agricultural Engineering at the campus of the Federal University of Recôncavo da Bahia, in Cruz das Almas. The communication quality between the devices, operating distances, signal strength, and data storage system were determined.

The distances between the two points were calculated considering the flat distance between the points. According to the configuration described in the previous paragraph, the monitoring unit was positioned at one end of the indicated paths, while the gateway was positioned at the opposite end. RSSI of the signal received by the monitoring unit was evaluated throughout the distance between the transmitters and the receiver but was characterized only when the points reached their respective area boundaries.

3 Results and discussion

To validate the implementation of the system developed for its purpose, which is to monitor equipment in a rural environment, the following tests were conducted in temporarily deployed networks in the different climatology mesoregions of Bahia, Brazil.

The first test aimed to validate the functionality of the system as a whole, ensuring that it is possible to remotely acquire data from devices using ModBus communication via RS485 with the use of the LoRa protocol to transmit the data to a gateway.

The second test aimed to assess the range of communication via the LoRa protocol of the developed devices, as well as the effects of obstacles on the range.

Finally, the third test aimed to evaluate the availability of data through the MQTT protocol via WiFi to Thingspeak.

3.1 Prototype validation

To validate the integrated operation of the system as a whole, a test was set up as described in the previous methodology (see Fig. 2). The aim of this test is to demonstrate the system's capability to acquire and remotely transmit data. The system was entirely developed in the Arduino IDE and consists of three physical units, including the Arduino Uno for receiving data from the sensor and forwarding it to the LoRa transmitter, and to complete the LoRa receiver.

Before proceeding with the range and data transmission quality evaluation for the experimental fields, the entire system was already operational, receiving sensor data by the Arduino, which was then received by the LoRa transmitter and transmitted to the LoRa, as can be observed Fig. 4 below.

The system validation included testing the prototype under real "laboratory" conditions to verify if it meets the requirements and operates as expected. The following is a presentation of the operational and range test.

3.2 Field operation and range test

With the choice of the data collection and transmission scheme through the sensor, endpoint, gateway, and data storage location, the transmitters were moved away from the receiver and positioned at the boundaries of the properties at different points within the IF Baiano Campus Bom Jesus da Lapa area (Fig. 5A) and repeated at the UFRB Campus Cruz das Almas area (Fig. 5B). This was done to cover as much of the total area as possible, associating remote data acquisition. The geographical coordinates of each transmitter were recorded for distance reference purposes.

To collect data, the transmitters were programmed to send data from a probe-type sensor that collects soil moisture, temperature, and electrical conductivity variables at regular intervals. The messages contained a unique identifier for each transmitter, and the receiver was configured to record the received data, including the transmitter identifier and signal strength.

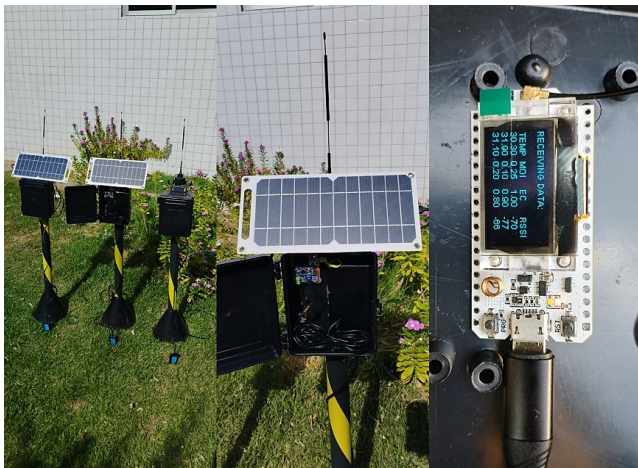


Figure 4. Prototype in operation.
Source: Author's Own



Figure 5. (A) Experimental area in Bom Jesus da Lapa, Bahia; (B) Experimental area in Cruz das Almas, Bahia.
Source: Adapted from Google Earth.

The receiver was positioned in a location with internet access. The central positioning of the receiver aimed to achieve better signal coverage throughout the area of interest. This, in conjunction with the potential location of an office on a rural property, aimed to minimize excessive personnel expenses for manual data collection.

Data was collected every 15 seconds with the goal of obtaining representative data from different locations within the campuses of different cities. After data collection, an analysis was conducted to determine the range achieved by the transmitter signal. The range was defined as the distance from the receiver at which data was successfully received, without data loss.

To determine the range, different scenarios were considered, including the presence of obstacles (trees, buildings) and atmospheric conditions (rain, fog). Signal strength data received by the receiver was also evaluated to assess signal intensity at different points in the field area.

The results allowed for demonstrating the quality of transmission, which did not study the maximum distance but achieved positive results ranging from 410 to 1514 meters with the reception of collected data. This differs from [12], who, through field tests in the rural sector between the municipalities of Sibaté and Granada in Colombia, established LoRa technology performance and its communication protocol within a radius of no more than 500 meters, under adverse terrain conditions.

The Received Signal Strength Indicator (RSSI) indicator was also obtained (Tab. 2), representing the signal strength received by the device in dBm. This is a measure of signal intensity and can be used to determine the device's proximity to the gateway or the number of obstacles along the path [2].

Table 2.
Distance and signal quality

Location	Transmitter	Distance (m)	RSSI (dBm)
Bom Jesus da Lapa - BA	LoRa 1	604	-123
	LoRa 2	948	-127
	LoRa 3	668	-115
Cruz das Almas-BA	LoRa 1	410	-91
	LoRa 2	1574	-123
	LoRa 3	1175	-132

Source: Author's Own.

The test was conducted using the antennas that came with the Heltec LoRa board. These antennas were connected to each Heltec LoRa board to improve signal transmission and reception capability.

The threshold of the boards is -139 dBm. So it is likely that greater distances could be achieved. [16] obtained better RSSI values when compared to those in the table above, which was associated with positioning based on field tests in rural and open environments. This differs from the environments in the present study, which had vegetation and structures in the line of sight. Values closer to 0 dBm are generally considered better when the device is close to the gateway [17].

3.3 Web monitoring

The system's operation test was conducted, involving the reading of sets of soil moisture sensors, data modulation to LoRa radio frequency by the endpoints, signal demodulation by the gateway, and data transmission to a web server with remote access in the cloud via ThingSpeak (Fig. 6).

After receiving the data, it was stored in channels, which are organizational units within ThingSpeak. Each channel was dedicated to a specific type of data and could contain multiple time series of information. The first channel was used to receive temperature data from sensor 1, the second channel for soil moisture from sensor 1, the third channel for electrical conductivity from sensor 1, and so on for sensor 3. The only exception was the electrical conductivity of sensor 3, as the free version of ThingSpeak only allows the simultaneous storage of 10 channels.

An ease of working with ThingSpeak leads to considerations similar to those of [18], who reported that IoT is becoming ubiquitous and universal, reaching all potential clients. The ThingSpeak IoT web service is unquestionably a fascinating web-based technology that has the potential to shape engineers' expectations.

With such a tool, data was stored as time series, which means it was organized by capture date and time. This facilitates trend analysis over time and the generation of dynamic graphs, as can be seen in the construction of auxiliary graphs with a 4-day period, as an illustrative example Fig. 7.

In general, considerations about the efficiency of LoRa technology in covering a large field area and its applicability in IoT applications can be made. Through the range test experiment with Heltec LoRa boards, it was observed that LoRa technology was capable of covering approximate areas of 90 to 120 hectares, although it did not achieve the

maximum range values. The results demonstrated the efficiency and reliability of LoRa technology in long-range communications, making it a viable solution for IoT applications, especially in agriculture.



Figure 6. Graphical and data visualization in web monitoring.
Source: Thingspeak.com.

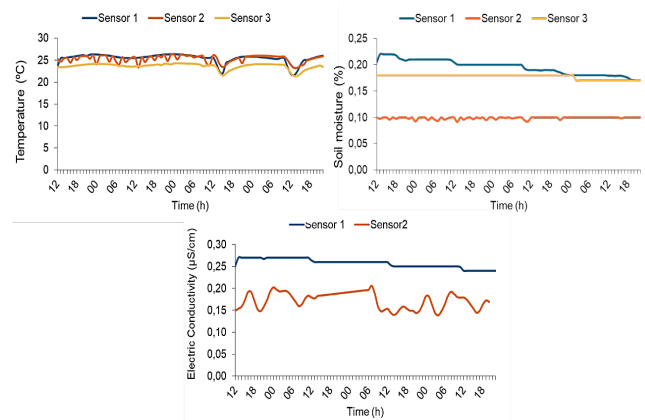


Figure 7. Graphs created with the stored database.
Source: Author's Own

The results are similar to those found by [19] suggesting that the IoT-based system developed using LoRaWAN technology can potentially be used for soil water monitoring applications and improve the sustainability of vegetable production systems, increasing marketable yield and saving irrigation water. However, there is an advancement in data transmission range, where the range presented by the respective authors does not exceed an application distance of 50 meters.

Noteworthy in all the presented results is the ability to replace manual labor with automation. Technology in rural environments has been a widely pursued goal in various industries and sectors over the decades. A significant result of this manuscript is the potential for increased efficiency, reduced human errors, and the release of human resources for more strategic and creative tasks, as also observed by [9].

4 Conclusions

In this case, it is achieved through embedded devices that collect soil parameter data and make it available to system users. This work presented applications of IoT and LoRa technologies, which are of great interest for their support of various applications in medium and large-scale agricultural farms.

The goal of implementing a soil variable monitoring system for agricultural fields has been achieved. Real-time data monitoring was conducted, and data was transferred to the ThingSpeak platform every 15 seconds. Various stages and corrections occurred before it was fully implemented because, in addition to being a new technology, the entire project needed to function perfectly, from the calibrated sensors providing accurate moisture readings to the endpoint devices sending data to the gateway and, finally, to the data cloud.

After numerous analyses, readings, attempts, and corrections, a definitive source code was developed, which proved to be efficient for the proposed application, thus achieving communication with the chosen cloud service.

It is necessary to bring rural areas closer to accessible and practical technological advancements. As evidenced in the state of the art, research in this field has been limited. Consequently, rural areas have not been able to fully leverage low-cost wireless network technologies.

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Modeling the impact of supplementary cementitious materials on compressive strength of recycled aggregate concrete forest-random approach

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Abstract

Recycled concrete aggregates (RCAs) and supplementary cementitious materials (SCMs) may substitute some cement and natural aggregates (NA) in concrete manufacturing. However, their effects on recycled aggregate concrete (RAC) compressive strength are difficult to model. Reactivity, silica, and alumina modulus were examined for cementitious materials' chemical complexity. Random Forest approaches were developed to predict and analyze RAC compressive strength. Even with RCAs and SCMs, the RF model accurately estimated concrete compressive strength. The Variable Importance (VI) research examined how input factors affected RAC compressive strength. VI indicated that silica fume contributes most to RAC compressive strength, followed by cementitious materials' reactivity modulus, cement content, silica modulus, fine natural aggregate content, and coarse natural aggregate dosage. The water dosage, water/binder ratio, and RCA content lower the RAC compressive strength. As a result, to highlight, the amount of SCM was not significant, but its nature was (i.e., hydraulic, silica pozzolanic, or alumina pozzolanic).

Keywords: Random Forest algorithm; compressive strength; supplementary cementitious materials; recycled concrete aggregate; reactivity modulus; silica modulus; alumina modulus; sustainability.

Modelación del impacto de los materiales cementantes suplementarios en la resistencia a compresión de los concretos con agregados reciclados - enfoque por bosques aleatorios

Resumen

Los agregados de concreto reciclado (ACR) y los materiales cementantes suplementarios (MCS) pueden sustituir parcialmente cemento y agregados naturales (NA) en la fabricación de concreto. Sin embargo, sus efectos sobre la resistencia a la compresión del concreto con agregados reciclados (CAR) son difíciles de modelar. Se examinaron los módulos de reactividad, sílice y alúmina para determinar la complejidad química de los materiales cementosos. Se desarrollaron enfoques de Random Forest para predecir y analizar la resistencia a la compresión de los CAR. Incluso con ACR y MCS, el modelo de RF estimó con precisión la resistencia a la compresión del concreto. El análisis de importancia de variable (IV) examinó cómo los factores de entrada afectaron a la resistencia a la compresión del RAC. IV indicó que el humo de sílice contribuye más a la resistencia a la compresión del CAR, seguido del módulo de reactividad de los materiales cementantes, el contenido de cemento, el módulo de sílice, el contenido de agregados naturales finos y la dosificación de agregados naturales gruesos. La dosificación de agua, la relación agua/cemento y el contenido de ACR reducen la resistencia a la compresión de CAR. Como resultado a destacar, la cantidad de MCS no fue significativa, pero sí su naturaleza (es decir, hidráulica, sílice puzolánica o alúmina puzolánica).

Palabras clave: Algoritmo de bosques aleatorios; resistencia a la compresión; materiales cementantes suplementarios; agregados de concreto reciclado; módulo de reactividad; módulo de sílice; módulo de alúmina; sostenibilidad.

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1. Introduction

1.1 Recycled aggregate concrete definition, application and main challenges

The construction and building material market remains dominated by concrete to this day, after becoming widely used since the turn of the 20th century [1]. Throughout most of the world, concrete is made using Portland cement as the major ingredient. During the past 20 years, Portland cement production has increased by three times (from 1.10 to 3.27 billion tons). In 2030, the expansion of the construction industry will lead to a staggering 4.83 billion tonnes of cement being produced [2]. In consequence, concrete production will increase, requiring an increase in natural aggregate (NA) consumption, including fine and coarse aggregates, since the NA constitutes 60–75% of concrete production. According to estimates, NA consumption reached 48.3 billion tonnes in 2015 and has grown at a rate of more than 5% every five years [3]. The current growth rates are expected to lead to a doubling of NA demand within 20 to 30 years [4]. The use of recycled aggregate (RA) from construction and demolition waste (CDW) can therefore conserve NA resources, reduce landfill demands, and contribute to a more sustainable built environment. Concrete produced by this process is referred to as RA concrete (RAC).

Following World War II, demolition waste from construction was used to produce the first RAC. The bombardment of German and English cities during that time generated a tremendous amount of rubble and debris [5]. Globally, 40 billion tons of aggregate grain are produced as a result of a large number of development projects being undertaken throughout the world [6]. The CDW consists of metal, concrete, minerals, and wood, as well as other unsorted fractions and miscellaneous waste. In the last 25 years, RAC has been extensively studied for its mechanical properties, durability, and structural performance. In general, the process of designing concrete mixes for RAC is the same as that used in conventional concrete [7]. A notable characteristic of recycled concrete aggregate (RCA) is that it is extremely water-absorbing, and therefore, it requires more water to be mixed into concrete. Additionally, Poon et al. [8] used scanning electron microscopy to examine the interfacial zone of RAC and conventional concrete. Their results showed that RAC contained predominantly loose and porous hydrate compositions, whereas conventional concrete consisted of dense hydrate compositions. Tam et al. [9] and Etxeberria [10] concluded that RAC microstructures were for the most part more complex than conventional concrete microstructures. RAC has two interfacial transition zones (ITZs): (i) one located between the old mortar matrix and the attached to the RCA (the former ITZ), and (ii) one located between the new mortar matrix and the RCA. RAC is susceptible to failure due to a weak link caused by the porous and cracked mortar.

According to several research reports [11–13], RAC has a significantly lower elasticity modulus than conventional concrete (ranging between 15 and 45%). In general, with

increasing RA content in RAC, its compressive strength will decrease [14–17]. The uniaxial compressive strength also decreases with an increase in RCA content [18]. In comparison with concrete produced with natural aggregates, RAC has approximately 81% compressive strength [19]. The low density in the transition zone between paste and aggregate plays a major role in the reduction of strength in RCA, but there are other characteristics of the recycled material that also contribute to this reduction [13]. Through the use of RCA, concrete properties can be improved in several ways, the most significant of which is the adoption of an extended curing cycle and the use of pozzolanic materials combined with an altered water-cement ratio [20]. Moreover, RAC concrete and conventional concrete provide comparable results in terms of uniaxial tensile strength [21]. In the study conducted by Li et al. [14], the researchers demonstrated that when mixing concrete, the proportions of cement and water can be adjusted fairly precisely to accomplish the targetted compressive strength (CS). This finding was corroborated by Buck's [22] experiments, which also demonstrated that RAC could be made stronger than the parent concrete that yields the RCA. Although RAC has a higher chloride ion permeability than conventional concrete [23], it still retains an acceptable resistance to chloride ion penetration [24, 25]. In the RAC, drying shrinkage increased with increased RCA replacement percentages and water-to-cement ratios; however, it decreased when fly ash and superplasticizers were applied [26,27].

In recent years, RCA has been demonstrated to be a promising technique for adding sustainability characteristics to traditional concrete mixtures [28]. Several benefits can result from the use of RA rather than natural aggregates, including a reduction of production costs and the ability to ensure a high level of availability. In comparison with conventional concrete, the cost of replacing RA in 100, 50, and 30% of a fly ash cement composite was compared by Wang et al. [29]. Despite having 2% less strength than its target strength (27.2 MPa), the 30 and 50% fly ash RCA was 15 and 26.5%, respectively, less expensive than conventional concrete. Although these savings may not seem significant, RA could be used to replace NA concrete by up to 100% [30]. Furthermore, the costs for the manufacture of cement composites are further reduced by accounting for the disposal income from construction waste.

Nevertheless, it is important to recognize that a major challenge lies in the perception of trustworthiness among users of these materials [31]. The environmental benefits of recycling concrete often outweigh the economic benefits of landfilling or disposing of it. Using this method will reduce pollution, transportation costs, and production costs of concrete, thereby reducing the consumption of natural resources. Since RCA originates from a wide variety of sources, its high degree of variability makes incorporating it into freshly cast concrete an extremely difficult process. The lack of specific guidelines regarding RCA specifications and their physical, chemical, and mechanical properties is another factor that needs to be addressed [32]. In concrete mixes containing RA, the negative chemical properties of the RA

can lead to deterioration during use, which can negatively affect the durability and performance of the concrete mix. As well, it is critical to pay attention to other concerns related to physical conditions, (e.g., size, type, angularity, and texture of RA) [33].

CDW can be recycled or reprocessed to replace a substantial proportion of construction materials in many developing countries. The problem is insufficient regulations and a lack of awareness of the advantages of these options. Developed countries are making efforts to promote the use of CDW globally. Therefore, it is likely that in the near future, RA derived from CDW will play a significant role in the commercial industry. The availability of landfill land is decreasing, and the aggregate demand for solid waste is approaching 40 billion tons per year. Due to this particular need, CDW can be viewed as a viable alternative to landfills. Nevertheless, research and development efforts will be required in order to find alternative materials that can be used for the production of concrete containing RA [34].

1.2 Random Forest models

Random Forest (RF) algorithm is a collective learning method that involves inputting data into an ensemble and developing decision trees during the training process to determine a regression model [35,36]. Breiman [37] developed the method by combining bagging sampling [38] and random selection of features [39,40]. A decision tree based on controlled variation has been developed by combining these two methods. The RFs approach utilizes trees as the basis for determining the classification label for every unlabeled instance in the ensemble. In the past decade, RF has become increasingly relevant across almost all disciplines, leading to numerous applications in almost every field, and many more are still in development.

The RFs method, for example, has been effectively utilized to model the properties of subsoils under a variety of conditions [41-44]. The effectiveness of this method has been demonstrated to be reasonable in predicting the behavior of various types of deep foundations [45-47]. A variety of construction management and engineering studies have also successfully applied the method in recent years [48-50]. This approach has also been successful in forecasting pavement material characteristics [51-53]. The modeling approach has been extensively used to model the characteristics of cement-based materials during their fresh and hardened states for the past few decades [54-63].

1.3 Research objectives, and significance

Despite its cost and carbon footprint advantages, RACs have not been used more in construction because of their inferior mechanical and durability properties. By including the appropriate SCMs, the harmful impacts of RCA may be mitigated in concrete. Owing to the vast chemical variety of SCMs and their combinations, material development research may need extensive testing, leading to costly experimental campaigns. This work provides a dependable

RF model for predicting and evaluating the CS of concretes incorporating RCAs, even when SCMs are present. This approach is efficient for decreasing development costs and timelines for novel doses.

2. Methodology

2.1 Database

2.1.1. Data collection

A total of 1181 dosages of RAC with and without SCMs, obtained from 116 literature sources, were gathered for use as train and test data for the model. The database mixture proportions encompassed a wide range of SCMs like silica fume, steel slag, fly ash, rice husk ash, and natural pozzolans, among others. Only those dosages with information on the oxide composition of the cement and all the cementitious materials that allow calculating the equivalent cementitious modulus of the concrete according to the studies by Xie and Visintin [64] were considered for the database. The reactivity of the cementitious materials was effectively assessed by those authors using a large experimental database. The moduli of critical oxides in any binder can be calculated based on their weight fractions, regardless of whether the binder is unary or blended [65]. In this study, the following cementitious indices were accordingly defined: (i) Modulus of reactivity [a RM value refers to the hydraulic reactivity of the binders], (ii) Silica modulus [SM, representing calcium silicate content in the binder (pozzolanic reactivity)], and (iii) Alumina modulus (AM, represents aluminate and ferrite phases in the binder (pozzolanic reactivity)). Before calculating the aforementioned indices, the relative modules of each cementitious material must be determined. These indices are computed for each cementitious material i using the Eqs. given (1-3):

$$RM_i = \frac{CaO + MgO + Al_2O_3}{SiO_2} \quad (1)$$

$$SM_i = \frac{SiO_2}{Al_2O_3 + Fe_2O_3} \quad (2)$$

$$AM_i = \frac{Al_2O_3}{Fe_2O_3} \quad (3)$$

Where RM_i is the reactivity modulus of cementitious material i and SM_i and AM_i are utilized to define the silica and alumina modulus of cementitious material i respectively.

With the relative reactivity modulus, it is possible to compute the cementitious modulus using Eqs. (4-6):

$$RM = \sum_{i=1}^n RM_i \times wr_i \quad (4)$$

$$SM = \sum_{i=1}^n SM_i \times wr_i \quad (5)$$

$$AM = \sum_{i=1}^n AM_i \times wr_i \quad (6)$$

Where n is the number of cementitious materials in the concrete dosage; and wr_i is the ratio by weight of cementitious material i to the sum by weight of all cementitious materials in the dosage.

Therefore, the gathered input variables are as follows: (I1) cement dosage in kg/m^3 ; (I2) silica fume dosage in kg/m^3 ; (I3) SCMs - except silica fume - also in kg/m^3 ; (I4) is the reactivity modulus (RM) as per Eq. (4); (I5) is the silica modulus (SM) as per Eq. (5); (I6) is the alumina modulus (AM) as per Eq. (6); (I7) represents the dosage of fine NA in kg/m^3 , while (I8) represents the dosage of fine RA; (I9) represents the dosage of coarse NA in kg/m^3 , and (I10) that of coarse RA; (I11) represents the water dosage in kg/m^3 ; (I12) represents the superplasticizer content in kg/m^3 (HRWR); (I13) represents the aggregate's maximum size (MSA) in mm; and (I14) denotes the water-binder ratio (w/b).

2.1.2. Outliers

The term outlier refers to a statistically significant data point that deviates significantly from what is expected, thus revealing an anomaly [66]. An outlier may be discovered in a data set as a result of a mistake made during the experiment, a problem with a measurement variable, or a signal that was detected in newly acquired data. Although outliers can provide insight into exciting possibilities, their presence can present serious challenges to statistical models and analysis, particularly when large datasets are involved [67,68]. There are several methods available for identifying outliers, depending on the type of data being analyzed. These methods can also be used for detecting the emergence of new phenomena as well as detecting anomalous behavior. It is possible to identify outliers using several methods, including Chauvenet's criteria, Grubb's test, ...etc., which rely on averages and standard deviations and assume the data is normally distributed [69].

Typically, outliers are the first factor to be addressed in a regression analysis, which can greatly influence the outcome [70]. The descriptive statistics applied to the variables in this study have been applied in order to detect any outliers among them, in accordance with [71,72]. The data were preprocessed using bivariate boxplots and Cook's distances in order to identify errors, outliers, and odd distributions. With the use of 2D patterns of graphed data in conjunction with robust methods and the use of ellipses to indicate possible errors, a bivariate boxplot can detect outliers as well as inconsistent data [73]. For this approach to be effective, it must, however, be complemented by a critical analysis of the data. It is possible that bivariate boxplots, which display data in two dimensions, would have portrayed some points as suspicious, whereas the rest might have been viewed as clustered, thus hiding the patterns that are actually present in the data [72]. The database was eventually cleaned up by removing 347 outliers, leaving 834 observations that could be used as training and validation data. Table 1 contains the statistical information of the database after the detection and treatment of outliers.

Table 1.

Statistical information of resulting database after outlier's treatment.

Input variable	Maximum	Minimum	Average	Standard deviation
I1 [cement (kg/m^3)]	578.00	117.00	345.12	87.52
I2 [SF (kg/m^3)]	35.00	0.00	0.64	3.83
I3 [SCM (kg/m^3)]	280.00	0.00	54.52	71.54
I4 [RM]	4.82	1.21	3.17	0.69
I5 [SM]	19.52	0.69	2.63	1.79
I6 [AM]	10.98	0.22	2.46	1.51
I7 [fine NA (kg/m^3)]	1066.00	180.00	678.24	163.84
I8 [fine RA (kg/m^3)]	611.25	0.00	28.64	94.60
I9 [coarse NA (kg/m^3)]	1470.00	0.00	610.69	442.97
I10 [coarse RA (kg/m^3)]	1280.00	0.00	424.15	395.27
I11 [water (kg/m^3)]	277.00	97.00	187.41	27.78
I12 [HRWR (kg/m^3)]	2.50	0.00	0.37	0.58
I13 [MSA (mm)]	31.50	5.00	18.94	4.62
I14 [w/b]	0.75	0.25	0.48	0.08
Compressive strength (MPa)	80.20	17.00	40.92	12.16

Source: The authors.

2.1.3. Data division: train data and test data subsets

We divided the data set randomly into two subsets for the purpose of training and evaluating the random forest prediction models. After outliers were removed, the training dataset contained 75% of the available data, whereas the test dataset contained the remaining 25%. Particular effort was made to ensure that all possible combinations of features and input variables were accounted for in the database before the division was also included in the resultant subsets. During the development of this algorithm, it was necessary to implement a verification filter in order to ensure this condition. During the random division of subsets, if any of the aforementioned criteria are not satisfied, the division is not considered legitimate, and a new division is performed until the condition is satisfied once again.

2.2 Classification and regression trees (CART)

Breiman et al. [74] introduced classification and regression trees (CART) in 1984, an innovative data analysis technique based on computational modeling. CART, sometimes known as a decision tree, has been used for classification and regression issues. A CART model conceptually resembles an inverted tree. This paradigm has both terminal and non-terminal nodes [75]. The solution to a query with two alternative answers should be a non-terminal node that indicates the direction in which two derivative nodes will progress.

The terminal nodes, on the other hand, offer a final forecast [75]. After the strategy has been modified, predicting a reaction is straightforward. With a given set of input variable values, following the tree's path from the root to the terminal nodes is sufficient, answering the questions presented at the non-terminal nodes up to the predicted response value of the response [75]. If the criteria at the non-terminal node is met, the CART model must go to the node on the left; otherwise, it must proceed to the node on the right. According to Genuer and Poggi [75], a CART model entails

dividing a space into rational and binary sections, then selecting the best out of both of these divisions that will produce the desired response. Thus, two phases are required to create this prediction technique. Initial construction of a comprehensive CART model must include all terminal and non-terminal nodes and their respective link routes. Then, it is required to prune the whole CART strategy in order to generate optimum subtrees which is picked as the best suitable tree that ensures there is no model overfitting concerns. See references [74-75] for further information on the CART algorithm's technique.

2.3 Random forest prediction models

A Random Forest technique is a machine learning paradigm that integrates numerous tree-prediction models, according to Dietterich [76]. In a regression problem, the ensemble technique estimates the response based on the midpoint of the forecasts from all tree models. The ensemble approach, on the other hand, utilizes a simple majority to solve a classification problem. Since the study given in this publication relies on regression methods, the following explanation focuses on this kind of analysis. The Random Forest regression model consists of m tree-based models $\{\hat{f}(\cdot, \theta_1), \dots, \hat{f}(\cdot, \theta_m)\}$. Each CART model is trained using a distinct subset of the total train data [37]. In order to adapt the tree-based techniques, a bootstrapping algorithm picks many random subgroups of data of the same size. As a result, the remaining dataset is not used for this model since each CART model is trained using just a subset of the complete data. Hence, the out-of-bag sample (OOB) data subset might be defined as the fraction of data not used to train a CART [55].

Furthermore, it is vital to specify the two characteristics that must be satisfied for the ensemble technique to be more successful than CART methods used individually. The first criterion is that the performance of any tree model must surpass that of random predictors. The second criterion is that each of the techniques included in the ensembled model must be distinct, i.e., there must be no connection between their mistakes [77]. As seen in Eq. (7), the forecasting approach employed by the Random Forest regression ($\hat{f}_{RF}$) can be computed as the average value of the forecastings of all trees that compound the ensembled model.

$$\hat{f}_{RF}(x) = \frac{1}{m} \sum_{i=1}^m \hat{f}(x, \theta_i) \quad (7)$$

where $\hat{f}(x, \theta_i)$ is the forecast of the response performed by the i regression tree approach, being θ_i the bootstrap sampling utilized to fit the individual model.

According to Oshiro et al. [78], increasing the number of trees does not guarantee that the Random Forest method would outperform the previous one (where the number of trees was lower), and increasing the number of trees by a factor of two is illogical. Hence, the Random Forest method takes into consideration an optimal number of CART models

[63,78]. References [37,63] can be consulted for a deeper knowledge of these machine-learning methodologies.

Using fourteen input variables, the current study proposes a Random Forest regression model designed to predict the compressive strength of RAC, even when utilizing SCMs. Table 1 contains the definitions of the considered input variables.

2.4 Performance metrics of the Random Forest approach

Using a cross-validation process, the Random Forest regression models were evaluated on the testing subset and modified using the test data. This sort of training aids in avoiding the overfitting and bias difficulties that these machine learning strategies often encounter [79]. In addition, to confirm the validity of the findings, this extra validation process and six statistical performance measures were applied to each of the generated models. Viz., the root of the mean squared error (RMSE), the mean absolute error (MAE), the normalized mean bias error (NMBE), the ratio of the RMSE to the standard deviation of measured data (RSR), the Nash coefficient of efficiency (E), and the coefficient of determination (R^2), whose formulations are presented in Eqs. (8-13) respectively. The use of multi-fitness criteria to ensure the correctness of the suggested techniques is made possible by the combination of different statistical indices that may overcome some of the limits of each individual one [79].

$$RMSE = \sqrt{\frac{\sum_{i=1}^n (a_i - \hat{a}_i)^2}{n}} \quad (8)$$

$$MAE = \frac{1}{n} \sum_{i=1}^n |a_i - \hat{a}_i| \quad (9)$$

$$NMBE(\%) = \frac{\frac{1}{n} \sum_{i=1}^n (a_i - \hat{a}_i)}{\bar{a}_i} \times 100 \quad (10)$$

$$RSR = \frac{\sqrt{RMSE}}{\sqrt{\frac{1}{n} \sum_{i=1}^n (a_i - \bar{a}_i)^2}} \quad (11)$$

$$E = \frac{\sum_{i=1}^n (a_i - \bar{a}_i)^2}{\sum_{i=1}^n (a_i - \hat{a}_i)^2} \quad (12)$$

$$R^2 = 1 - \frac{\sum_{i=1}^n (a_i - \hat{a}_i)^2}{\sum_{i=1}^n (\hat{a}_i)^2} \quad (13)$$

being a database's real value of the dependant variable; Whereas $\bar{a}$ represents the mean of the answers to the data, $\hat{a}$ is the result of the Random Forest regression method, and n is the total number of observations.

2.5 Variable importance in Random Forest approaches

With the Random Forest method, one approach to determine the importance of a variable is to observe how much the model's goodness-of-fit reduces if the variable is removed [37]. Since that each tree-based model has its own OOB data subset, this may be used to determine the

significance of a certain input component. Specifically, the OOB predicting performance is calculated for each particular CART technique. The OOB input variable is then randomly shuffled while maintaining the significance of the other components. The forecast accuracy decline resulting from the rearranged data is then calculated. Thus, the estimation of the factor significance of the j input component in the i CART method may be estimated as shown in Eq. (14):

$$I_{j,i} = mse(\hat{f}(x, \theta_i)) - mse(\hat{f}(x^j, OOB_i)) \quad (14)$$

being mse the mean squared error of the forecasting, and $\hat{f}(x^j, OOB_i)$ represents the forecasting estimated by the individual tree-based regression on the OOB_i data subset, removing the factor j .

In the end, the j input's variable importance metrics may be calculated for the Random Forest regression by determining the average variable relevance of each tree model, as shown in Eq. (15):

$$I_{j,RF} = \frac{1}{m} \sum_{i=1}^m I_{j,i} \quad (15)$$

where $I_{j,RF}$ represents the importance of the input variable j on the considered response as per the ensembled Random Forest regression approach, $I_{j,i}$ represents the importance of that input variable according to the individual tree-based model i , and m is the total number of trees in the Random Forest model.

3. Results and discussions

3.1 Random forest approaches

In this research, the Random Forest regression models were made with the help of the R statistical and programming language [80] and the *randomForest* package [75]. When the models were being trained, a limit of 1,000 CARTs per model was considered. The number of trees that led to the minor RMSE was used was chosen on the test data subset, as presented in Fig. 1. According to that analysis, a number of 563 CART models was selected for the RF approach.

Fig. 2 shows the first CART individual regression model for the Random Forest method to predict the concrete compressive strength.

The results of the performance metrics measured in both data subsets is presented in Table 2. Moreover, the regression plot is put forward in Fig. 3. From the analysis of these results, it can be concluded the good efficiency of the model in prediction the CS of RAC even with SCMs.

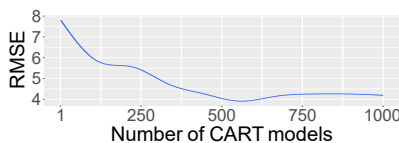


Figure 1. Measure on the RMSE on the test subset versus the number of CART approaches in the RF model.
Source: The authors

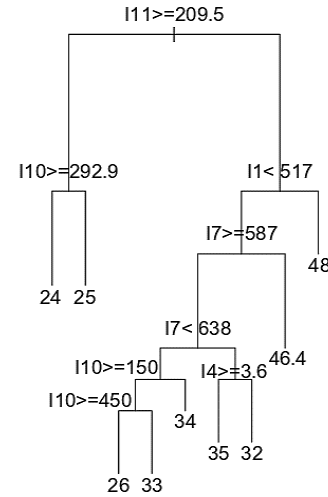


Figure 2. First of the 563 CART models that from the RF approach.
Source: The authors

Table 2.

Performance metrics of the RF regression model.

Subset	RMSE	MAE	NMBE	RSR	E	R ²
Train	3.548	2.047	0.424%	0.292	0.915	0.919
Test	3.846	2.869	-0.397%	0.317	0.899	0.901

Source: The authors.

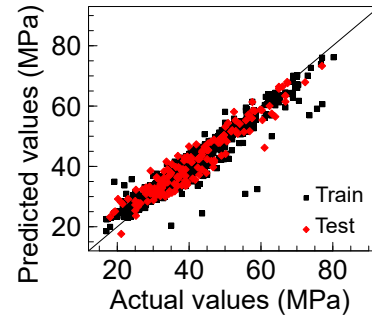


Figure 3. RF regression plot on both subsets (i.e., train and test).
Source: The authors

As can be appreciated in Fig. 3 and Table 2, results on train and test data subsets are similar, which points out the good performance of the model regarding overfitting [59,72].

3.2 Variable importance findings

Fig. 4 present the results of the Variable Importance (VI) in RF approach. The correlation between the input factors and the compressive strength of the RAC was examined in this instance in order to gain insight into their relationship. The study found that, in that order, silica fume (I2), RM (I4), and cement dosage (I1) had the most significant influence on the result. Silica fume is known to have significant pozzolanic reactivity due to its tiny particle size (about 150 nm) and high amorphous SiO₂ concentration. It forms a CSH gel when it reacts with the pore solution's Ca(OH)₂. The increase in CSH leads to the refining of the pore structure of

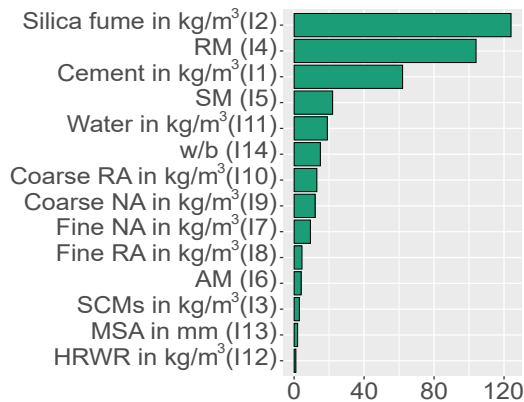


Figure 4. RF variable importance findings.

Source: The authors

the cementitious paste. This modification contributes to the enhancement of concrete's mechanical characteristics, particularly its CS [81]. RM is the second most influential parameter on the CS of concrete. Its reactivity is connected to the cement dosage, the most important contributor to this modulus. Moreover, certain SCMs with a high CaO concentration, such as blast furnace slag and type C fly ash, may create cementitious products, enhancing the mechanical properties of the cement paste and the concrete [82]. Researchers determined that adding cement or SCMs with high hydraulic reactivity [83] is a good strategy to mitigate the resistance losses caused by using recycled aggregates, hence validating the VI findings.

Regarding the cement content (I1), it is well known that cement is the principal source of hydration products that are responsible for the increased density and strength, even when RCAs are used [84].

As per [85], some other RAC features have a significant beneficial effect on the reaction of concrete to compressive stresses. These variables include silica modulus (I5), coarse NA content (I9), fine NA content (I8), SCMs excluding silica fume (I3), and superplasticizer dose (I12). Supplementary cementitious materials with high silicon and aluminum content, such as type F fly ash, recycled glass powder, rice husk ash, and metakaolin, possess pozzolanic properties. It has been demonstrated that in adequate proportions, they contribute to the increase in strength, particularly at advanced ages (e.g., after 56 days of curing), as they can react with the water and calcium hydroxide to produce calcium silicate hydrates (CSH) or calcium (CASH). Hydration products contribute to the cement matrix's densification and concrete's mechanical performance at advanced ages [17]. Certain SCMs have hydraulic characteristics that enable them to react with water to form cement-like hydration products [86]. The VI analysis demonstrates that these SCMs contribute to the RM index (I4). The research revealed, however, that the content of SCMs (I3) seems to be of minimal significance, indicating that it is not the dosage of SCMs that is significant but rather their nature. Hence, if these SCMs have hydraulic (recognized by the RM index) or pozzolanic (identified by

the SM index) capabilities on the siliceous side, the impact will be favorable. Nevertheless, it will be exposed later that the impact will be notably negative if the pozzolanic characteristics are on the aluminum side (as determined by the AM modulus).

Research [87,88] have indicated that the proportion of NAs replaced with RCAs reduces the compressive strength of concretes with comparable w/b ratios. This is mostly due to the higher water demand required to produce concrete workability and adequate hydration of cement paste and/or cementitious components. RCAs often have greater porosity than NAs and may retain residues of mortar and carbonated hydration products, resulting in lower effective bonding of cementitious elements in the new concrete and, as a result, fewer nucleation sites for freshly created CSH or CASH. The study's findings suggest that superplasticizers are essential for controlling the increasing demand for water in recycled aggregate concrete mixes. Hence, using superplasticizers favors the compressive strength (CS) of concrete, including RCAs, by decreasing the needed water content for such mixes, enhancing CS. When paired with the use of SCMs, its beneficial impact is supposed to compensate for the drop in CS caused by the use of RCAs [89-91]. However, the significance of the SCM appears to be limited in Fig. 4. Nevertheless, the impact of the superplasticizer (I12) on CS seems to be restricted and perhaps obscured by the impacts and interactions of the cement content (I1) and water (I11). It is important to note that superplasticizers are supposed to substantially affect the cement–water system [92]. The water content (I11), the w/b ratio (I14), and the coarse RA are among the most important input factors that negatively impact the CS of concrete containing RCAs [85]. Hence its importance, as observed in Fig. 4, where it can be seen that these factors occupy the fifth and sixth place in relevance. The negative impact of these factors on the compression response of RAC is consistent with the current literature, which demonstrates that water and the w/b ratio have a well-known detrimental effect on the mechanical resistance of concrete. In addition, several studies have shown that using RCAs reduces the CS of concrete proportionally to the replacement volume due to the great porosity, low resistance, and high-water absorption of these recycled aggregates. Hence, it is possible to deduce that recycled aggregates enhance the porosity of concrete, leading to a lower density and CS [88, 93-95].

Fine RA (I8), AM modulus of cementitious materials (I6), and MSA (I13) have a reduced effect on the CS of RAC concrete. Recent research has proved that these factors are harmful but not especially relevant for CS [85]. The impact of SCMs with a high aluminum content on RAC performance is particularly intriguing. Despite their high pozzolanic reactivity index, these components have a detrimental effect on the compressive strength of RAC concretes, according to the VI findings. Many mechanisms may explain this phenomenon, including the production of CASH-type gel compounds and the decrease in pH of the pore solution owing to the high aluminosilicate concentration. Even though this reaction initially enhances mechanical qualities, it is

detrimental in the long run [96]. In addition, several research [96,97] observed that the chemical interaction of reactive SiO_2 and Al_2O_3 concentration in SCMs with a high AM modulus increases the temperature during the cement's hydration process, resulting in decreased flowability, which could negatively affect the pouring process and the final mechanical performance of the concrete. In addition, several investigations have shown that more water or superplasticizer is necessary to obtain the appropriate workability when employing SCMs with a high alumina modulus [98-102]. Considering the unique situation of RCAs regarding porosity and water demand, the higher water needs of SCMs with high AM values may explain the findings reported in Fig. 4.

The CS of concrete made only with NAs is influenced by the maximum size of the aggregate (I13). Studies have shown that smaller aggregate sizes require larger amounts of cement paste to achieve a given resistance [59, 103]. Therefore, it can be concluded that a larger MSA should positively influence the CS of concrete. However, in the case of RAC, MSA (I13) has a noticeably negative impact on CS. The reason for this change in trend can be attributed to the fact that the thickness of the interstitial transition zone is directly proportional to the aggregate size [103], and in concrete with recycled aggregate, this zone is even more porous than in concrete made with only NAs, which impairs the CS of the concrete [104]. Hence, as the mixtures in the database combined NA and RCA, this factor appears to have a little significance as per Fig. 4.

4. Conclusions

To predict the CS of concrete with RCA and/or SCMs, this study analyzed the feasibility of using random forest regression. In light of the findings of this study, the following conclusions can be drawn:

1. The suggested RF approach with 563 CART models' data presents the lowest RSME on the test data subset. This justifies its selection.
2. Using different performance metrics, such as RMSE, MAE, NMSE, RSR, E, and R^2 , gave unbiased information that showed how well the proposed RF regression approach worked. Hence, can be concluded that the RF model is a good way to predict the compressive strength of concrete with RCAs and/or SCMs.
3. The results of the VI analysis show that the content of SCM does not have much of an effect on the compressive strength of RAC. It is more affected by the properties of the SCMs, such as whether they are hydraulic, pozzolanic on the silicon side, or pozzolanic on the aluminum side.
4. The findings of the VI analysis were consistent with many international research studies in the field, demonstrating the validity of the model from a scientific perspective.

The study's outcomes are expected to hasten the development of environmentally friendly concrete products,

addressing negative environmental impacts in the concrete industry.

In future research, exploring additional AI tools like Bootstrapping systems could be valuable. These systems offer sensitivity analysis through partial dependency graphs, providing insights into how different input variables impact the analyzed concrete's response, enhancing our understanding of its performance.

Also, future work should prioritize experimental validations of AI-derived results. This step will ensure the reliability and robustness of AI-based findings.

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Personnel selection system based on the selection algorithm

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Abstract

The evolution of personnel selection systems has been driven by technological advances and changes in the needs of organizations, referring to the set of processes and tools used by an organization to evaluate and select the most suitable applicants to fill a position within the company, in order to ensure that people with the skills, knowledge and competencies necessary to perform the responsibilities and functions associated with the position are hired. It is therefore proposed to implement a personnel selection system, which will help optimize the recruitment and selection process using the competency model and the selection algorithm to choose the best candidates according to the selection criteria established for each job position, resulting in the best candidates for the position with the qualities for which they were chosen.

Keywords: selection system; selection process; applicants; competency model; selection algorithm.

Sistema de selección de personal basado en el algoritmo de selección

Resumen

La evolución de los sistemas de selección de personal ha sido impulsada por los avances tecnológicos y los cambios en las necesidades y expectativas de las organizaciones y se refiere al conjunto de procesos y herramientas utilizados por una organización para identificar, evaluar y seleccionar a los postulantes más adecuados para ocupar una posición laboral dentro de la empresa, con el fin de garantizar que se contrate a personas que tengan las habilidades, conocimientos, competencias y características necesarias para desempeñar eficazmente las responsabilidades y funciones asociadas al puesto. Es por ello que se propone implementar un sistema de selección de personal, que ayudará a optimizar el proceso de reclutamiento y selección utilizando el modelo de competencias y el algoritmo de selección para así elegir a los mejores candidatos de acuerdo a los criterios de selección establecidos para cada puesto de trabajo, dando como resultado a dos de los mejores candidatos para el puesto con las cualidades por las cuales fueron elegidos.

Palabras clave: sistema de selección; proceso de selección; postulantes; modelo de competencias; algoritmo de selección.

1. Introduction

Personnel selection is an important issue for organizations because the success of their activities depends on it [1], which must be performed by suitable people, a good result in personnel selection not only directly affects the quality of work, but also indirectly influences competitiveness [2]. Personnel selection systems are an evolution of traditional selection methods [3], which use

technologies such as machine learning, natural language processing and data mining to evaluate and rank candidates more efficiently and objectively [4].

Personnel selection processes can be affected by the lack of complete information about candidates, which can make it difficult to assess their suitability for the position [3] furthermore they are carried out under time pressure, which can limit the ability of the selectors to properly evaluate the candidates [5].

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In this context, the implementation of a personnel selection system is proposed, which will allow transforming the input data sent to the company in order to choose the best candidates according to the selection criteria established for each job position, using the competency model, with which it will be possible to identify the key competencies based on two competencies which are specific and transversal, the applicants will be evaluated according to these competencies through specific tests and performance evaluations. Subsequently, the system will perform calculations with the input data stored in the database in order to perform the ranking of the best candidates by means of ranking scores using the selection algorithm.

Finally, by running the personnel selection system, it was possible to visualize the suitable candidates and clearly show the qualities for which they were chosen, which allows optimizing the recruitment process and ensuring that the best candidates were selected for the position.

The structure of this article is as follows: State of the art, proposed personnel selection system adequacy to the problem, execution, results, implementation of the system, conclusions, recommendations and references.

2. State of the Art

2.1 The problem of personnel selection

Personnel selection is a fundamental process for organizations, as it involves identifying, evaluating and choosing the most suitable candidates to fill jobs, this selection of candidates can present several problems and challenges that can hinder the proper recruitment process [4].

One of the most significant problems in personnel selection is the presence of bias and discrimination [6]. Recruiters may be influenced by biases based on age, gender, race, ethnicity, or other personal characteristics, which can lead to unfair and inequitable hiring decisions [7].

In addition, the tests and assessments used in the selection process may not be adequate to accurately measure the skills, competencies, and aptitudes required for the position [8]. This can lead to poor candidate selection and a mismatch between the skills of those selected and the needs of the position [9].

If proper selection is not performed, there may be a high rate of employee turnover or hiring errors [10]. This implies an additional cost to the organization in terms of time, resources, and productivity, and can negatively affect the overall performance of the company [11], as recruitment and selection processes can become lengthy and costly, especially when handling large volumes of candidates, which can lead to a delay in hiring and increase operational costs for the organization [12].

2.2 Personnel selection systems

Personnel selection is a fundamental process for organizations, as it involves identifying, evaluating, and

choosing the most suitable candidates to fill jobs. In recent years, the advancement of technology has significantly influenced this field, leading to more efficient and accurate personnel selection systems [13].

Personnel selection systems are decision support systems that generate a result showing a ranking for each potential employee, so that management decision makers can see the capability of each potential employee based on the ranking [5,6,14]. Generally speaking, it can be stated that personnel selection systems are among the most complex organizational and intellectual processes and of necessary precision [15,16]. There are organizations that already apply personnel selection systems in order to optimize this activity [9]; something that as a result of the pandemic contingency has forced other organizations to use and implement this type of systems [17], in this way the use of personnel selection systems is beginning to become widespread around the world.

There are several types of personnel selection systems used by organizations to identify and hire the most suitable candidates, such as filtering systems which can perform an initial filtering of candidates based on the criteria established by the company [6]. Analytics systems that can scan and analyze a large number of resumes quickly and automatically and virtual interviews using chatbots or virtual assistants [18], these systems can ask predefined questions and analyze candidate responses in real time, evaluating factors such as consistency, language used and communication skills [16,17].

Recruitment systems are taking advantage of advances in algorithms and machine learning techniques to improve the efficiency of their processes [11]. These algorithms can analyze large volumes of data and patterns to identify the most suitable candidates [19]. In addition, machine learning allows systems to improve over time as they are provided with more information [20].

There are several algorithms to build a personnel selection system, these are mathematical tools and models designed to assist in the selection and recruitment process [20], using predefined data and criteria to evaluate candidates and make decisions based on the information collected, some of them are the Decision Tree Algorithm, which creates a tree-like model [7], where each internal node represents a characteristic or attribute, each branch represents a decision based on that attribute, and each leaf represents the result or final decision [7,18], the Selection Algorithm, which establishes the criteria and requirements necessary for the vacant position, such as technical skills, competencies, work experience, educational level, in order to choose the most optimal applicant [12,21]. The Sentiment Analysis Algorithm, this algorithm evaluates and analyzes the comments and opinions of candidates, as well as interactions with the organization on digital platforms [22].

Recruitment systems are harnessing the power of data and predictive analytics to make more informed decisions [23]. By analyzing data from past candidates and their performance in the organization, these systems can identify patterns and success factors that help predict future candidate performance. This allows for more informed and objective decision making [21,24].

Table 1.
Input data.

Factors	Weight Factors	Dimension	Dimensional Weight	Definition	Abbreviation
Specific competencies	0.5	Behavioral	0.10	V1	CO
		Ability to learn			
		Adapting to change			
		Creativity			
		Innovation			
Transversal competencies	0.5	Teamwork	0.40	V2	IN
		Vision of the future			
		Instrumental			
		Analytical capacity			
		Synthesis capacity			
		Organizational capacity			
		Oral and written communication			
		Knowledge of a foreign language			
		Computer skills			
		Information management capability			
		Troubleshooting			
		Decision making			
		Personal			
		Working in an international context			
		Skills in interpersonal relationships			
		Recognition of diversity and multiculturalism			
		Critical reasoning			
		Ethical commitment			
		Systemic	0.40	V4	SI
		Autonomous learning			
		Leadership			
		Knowledge of other cultures and customs			
		Motivation for quality			
		Sensitivity to environmental issues			
		The ability to adapt to the company's philosophy			
		Customer orientation			
		Controlling emotions			
		Negotiation skills			

Source: Own elaboration.

3. Proposed personnel selection system

The proposal is to implement a personnel selection system, which will help to optimize the recruitment and selection process, saving time and resources, while ensuring the recruitment of the most suitable candidates for the vacancies.

For the construction of the personnel selection system the selection algorithm will be used where relevant data will be collected about the candidates, such as their work experience, skills, educational level, achievements. This data set and selected variables will be used to make the selection algorithm with similarity weights for each variable that organizes the decisions based on the characteristics of the candidates, resulting in the most optimal candidate for the position.

The input variables used to perform the recommendation of applicants are detailed in Table 1 where they are divided into factors, each factor has its corresponding dimensions, the factors and dimensions have their respective weights that are used to convert from qualitative to quantitative data these data will be taken using the competency-based method.

The weights only influence the rating of the factors or dimensions shown, and do not influence the recommendation of the personnel directly; furthermore, the values proposed

for the model are tentative, these can be modified or updated later for greater precision.

After having identified the input variables, we proceed to adapt the algorithm to the case study and develop the algorithm operating model. For the elaboration of the model it will be possible to make use of the input variables which are defined in Table 1 and the variables of the position in Table 2, in order to be able to calculate the similarity distance as shown in the following tables:

Based on the above, we use the selection algorithm, which calculates the distances between the knowledge data and the applicant's entry data, using the Euclidean distance,

Table 1.
Job variables.

Job variables			
CO	IN	PE	SI
CO1	IN1	PE1	SI1
CO2	IN2	PE2	SI2
CO3	IN3	PE3	SI3
...	...	...	...
CO _n	IN _n	PE _n	SI _n

Source: Own elaboration.

generating recommendations from the candidates who are closest to the published job.

```

Selection procedure(arr):
  n <- longitude(arr)
  For i from 0 until n-1 do:
    min_idx <- i
    For j from i+1 until n do:
      If arr[j] < arr[min_idx] then:
        min_idx <- j
    If min_idx != i then:
      exchange(arr[i], arr[min_idx])
  Here is the results that most closely match the requested
  preferences.
  for(i<k){
    print(arrayResult[i]);
    i++; }

```

In order to execute the solution, you must have the data that will be used for the selection calculation, which must be converted from qualitative to quantitative data, for this the values shown in Table 3 are used.

Table 2.
Quantitative data.

Factors	Dimension	Value
Specific competences	Behavioral	
	• Ability to learn	1
	• Adapting to change	2
	• Creativity	3
	• Innovation	4
	• Teamwork	5
	• Vision of the future	6
Transversal competences	Instrumental	
	• Analytical capacity	1
	• Synthesis capacity	2
	• Organizational capacity	3
	• Oral and written communication	4
	• Knowledge of a foreign language	5
	• Computer skills	6
	• Information management capability	7
	• Troubleshooting	8
	• Decision making	9
	Personal	
	• Working in an international context	1
	• Skills in interpersonal relationships	2
	• Recognition of diversity and multiculturalism	3
	• Critical reasoning	4
	• Ethical commitment	5
	Systemic	
	• Autonomous learning	1
	• Leadership	2
	• Knowledge of other cultures and customs	3
	• Motivation for quality	4
	• Sensitivity to environmental issues	5
	• The ability to adapt to the company's philosophy	6
	• Customer orientation	7
	• Controlling emotions	8
	• Negotiation skills	9

Source: Own elaboration.

Table 3.
Data entered by five users(applicants).

Factors	Variables	Candidate 1	Candidate 2	Candidate 3	Candidate 4	Candidate 5
Specific Competences	V1	1	1	2	4	1
	V2	3	2	1	3	3
	V3	4	3	2	1	1
	V4	5	4	3	3	1
	V5	2	4	5	1	4
	V6	3	2	1	3	5
Transversal Competences	V1	2	2	1	4	3
	V2	2	3	2	1	2
	V3	1	1	1	3	1
	V4	3	2	4	3	5
	V5	5	2	3	5	4
	V6	1	2	1	3	1
	V7	4	3	4	2	3

Source: Own elaboration.

The input data is obtained at the time of registration of the applicant when answering the questionnaire, these data will be used for the calculation of distances in the selection algorithm. Table 4 shows the data entered by 5 candidates for the position of administrator along with their numerical values.

After obtaining the data of both the knowledge, the applicant's entry data and the conversion of those data to quantitative values, the selection algorithm is executed. Next, the execution is done in 4 steps:

Step 1

Having the variables established, we proceed to store the input data in the variables V1, V2, V3, V4, V5, V6, V7. The entered variables transformed into quantitative data perform a procedure called selection that takes as input an arr array. The procedure implements the selection algorithm to sort the array in ascending order. A Para loop is used to iterate through the array indices, from 0 to n-1, where n is the length of the array.

Step 2

The loop is used to find the index of the smallest element in the unordered portion of the array. It starts with i+1 and compares each element with the element in min_idx. If a smaller item is found, it is updated min_idx.

```
array = [V1, V2, V3, V4, V5, V6, V7]
```

Iteration over the unordered portion of the array

```
for i in range(len(array)-1):
  min_idx = i
```

Index of the smallest element, we assume it is the current element.

Comparison of each element after the current one with the element in min_idx.

```
for j in range(i+1, len(array)):
    if array[j] < array[min_idx]:
        min_idx = j
```

We update min_idx if we find a smaller item.

Exchange of the current item with the smallest item found.

```
array[i], array[min_idx] = array[min_idx], array[i]

print(array)
```

Step 3

After the second loop is completed, it is checked if min_idx is different from the current index i. If so, the elements are exchanged at positions i and min_idx, ensuring that the smaller element is placed in the correct position.

At the end of the procedure, the array will be sorted in ascending order, as shown in the following pseudocode.

After obtaining the user's input data and converting that data to quantitative values, the selection algorithm is performed using the selection algorithm. Next, the execution is performed:

```
Function                                selectPersonal(Candidates,
competencesRequired):
    bestCandidates = []
    For each candidate in candidates:
        score = 0
        For each competition in competencesRequired:
            If candidate.hasCompetence(competence):
                score = score + 1
            If score == longitude(competencesRequired):
                bestCandidates.add(candidate)
    Return bestCandidates
End of function
```

After having executed the algorithm, the results obtained from this calculation are shown and the results are ordered in ascending order as follows:

```
arrayResult= [[idbestcandidates][1idcandidates],...,[^i][N]]
```

Step 4

The Table 5 shows the loop execution for each iteration:

Table 4.
Element array results.

N°	Variable	Formula	Candidate 1	Candidate2
1	V1	For j from i + 1 to n - 1: If array[j] < array[min_idx]	0.2	0.2
2	V2	For j from i + 1 to n - 1: If array[j] < array[min_idx]	0.03	0.01
3	V3	For j from i + 1 to n - 1: If array[j] < array[min_idx]	0.01	0.01
4	V4	For j from i + 1 to n - 1: If array[j] < array[min_idx]	0.2	0.1
5	V5	For j from i + 1 to n - 1: If array[j] < array[min_idx]	0.1	0.1
6	V6	For j from i + 1 to n - 1: If array[j] < array[min_idx]	0.3	0.2
7	V7	For j from i + 1 to n - 1: If array[j] < array[min_idx]	0.1	0.2
Score			0.98	0.82

Source: Own elaboration.

The Table 6 shows the results obtained from the top 3 candidates for the position:

Table 6
Results obtained and ordered from highest to lowest

Applicants	Compatibility with the position
1 Candidate 1	98%
2 Candidate 2	82%

Source: Own elaboration.

4 System Implementation

For the implementation of the prototypes of the selection system was developed with the PHP programming language together with the MySQL database manager, the Visual Code programming environment was used with the MVC software architecture (Model, view, controller). Among the functional requirements of the system, we have the registration of applicants, the registration and publication of jobs, the generation of personnel selection, and the generation of reports.

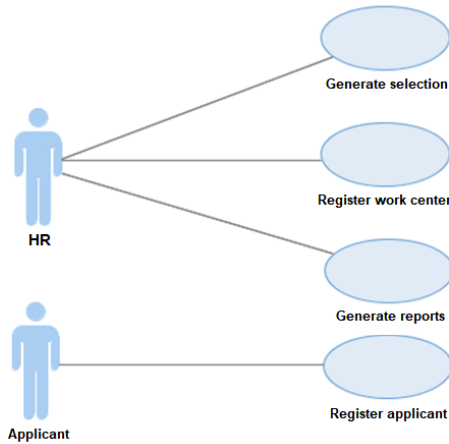


Figure 1. Basic system use cases.
Source: Own elaboration.

EVOL

PORTAL EMPLEO

REPORTE DE SOLICITUDES

LIMA - PERÚ

San Borja, Lima, Perú

Puesto de trabajo: Analista QA Funcional junior

Fecha Publicación:15/06/2023

Salario : 2500

Vacantes: 2

PUESTO	FECHA	N° IDENTIDAD	NOMBRE Y APELLIDOS	CORREO ELECTRONICO	TELEFONO	GENERO	PUNTAJE	ESTADO
01	15/06/2023	75355464	QUINTANILLA MEDINA MARIA DEL CARMEN VERONICA	201579@gmail.com	9452368746	F	600	Candidato
02	15/06/2023	08065019	CUZCANO LUYO VDA DE MEDINA ANTONIA	antonian@mail.com	942815159	F	300	Candidato
03	15/06/2023	08065759	MEDINA CUZCANO CECILIA ANTONIA	ceciliamedina@gmail.com	914567893	F	100	

Figure 2. Results generated by the algorithm.
Source: Own elaboration.

Fig. 1 shows the main system use cases that were established in the information collection phase, as well as the system actors and the iteration it will have with each use case.

The following Fig. 2 shows the applicants selected by the selection algorithm, these candidates are shown after having made the questionnaire of the work to be applied in this way the most optimal candidates are selected.

Fig. 3 shows the answers of the applicants with the percentage of their score, showing the most outstanding qualities of the applicants.

N°	pregunta	respuesta
1	¿Qué para ti es la current leader of the Catholic Church? Marque la respuesta correcta.	☐
2	¿Largo de tiempo que las pruebas automatizadas que realiza, de presentar un error ¿cuál sería la mejor acción?	☐
3	¿Qué tipo de pruebas automatizadas que realiza, de presentar un error ¿cuál sería la mejor acción?	☐
4	¿Qué tipo de pruebas automatizadas que realiza, de presentar un error ¿cuál sería la mejor acción?	☐

Figure 3. Applicants' answers with the percentage of their score.
Source: Own elaboration

5. Conclusions

The personnel selection system implemented with the selection algorithm has proven to be highly effective and efficient in the recruitment process. By using this algorithm, it was possible to significantly reduce the time required to review and evaluate resumes, as well as to conduct individual interviews. In addition, a substantial improvement in the quality of the selected candidates was observed, since the algorithm allowed to identify and prioritize the most relevant skills and competencies for each vacant position. This led to an increase in the success rate of hires, with highly qualified employees who better fit the requirements of the position and effectively contribute to the growth and development of the organization. In summary, the use of the selection algorithm in the personnel selection system has proven to be a valuable and powerful tool to optimize the hiring process and ensure the acquisition of suitable talent to achieve business objectives.

6. Recommendations

If the system is to be applied in a much larger area, it is recommended to increase the knowledge base considerably and condition the selection model so that it has an optimal functioning, infrastructure services must also be optimized and guaranteed.

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Smart sensors/actuators based in amorphous nanostructures, according to enhance robotic arms energy transmission

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Abstract

This article mainly analyzes the correlation between the carrier energy in robotic arms, according to enhance its performance. This task is achieved because of the sensors/actuators based on nanostructures properties: short response time and high robustness, which proportionated the possibility to execute intricate instructions by the control subsystem of the robotic arm. Therefore, the instructions executed by the controller are supported by a polynomial design, this algorithm helped to evaluate every response signal as a consequence of the main control system, which was consequently by the short response time from the main sensors “flow (carrier energy) and speed of the robotic arm”, moreover, the advantage of the proposed system is given by the extra time obtained also to verify the stability of the robotic arm based in Lyapunov models correlated with Lagrange, as well as every equations were solved and organized by neural network.

Keywords: sensors; actuators; nanostructures; robotic arms; modulating functions; Lagrange; Lyapunov; pneumatic; oleohidraulic.

Sensores/actuadores inteligentes basados en nanoestructuras amorfas, para mejorar la transferencia de energía en brazos robóticos

Resumen

Este artículo analiza principalmente la correlación entre la energía portadora en brazos robóticos, en función de mejorar su rendimiento. Esta tarea se logra gracias a los sensores/actuadores basados en propiedades de nanoestructuras: corto tiempo de respuesta y alta robustez, lo que proporcionó la posibilidad de ejecutar instrucciones complejas mediante el subsistema de control del brazo robótico. Por lo tanto, las instrucciones ejecutadas por el controlador están sustentadas en un diseño polinómico, este algoritmo ayudó a evaluar cada señal de respuesta como consecuencia del sistema de control principal, lo que fue gracias al corto tiempo de respuesta de los sensores principales “flujo (energía portadora) y velocidad del brazo robótico”, además, la ventaja del sistema propuesto está dada por el tiempo extra que se toma también para verificar la estabilidad del brazo robótico basado en modelos de Lyapunov correlacionados con Lagrange, así como todas las ecuaciones fueron resueltas y organizadas por red neuronal.

Palabras clave: sensores; actuadores; nanoestructuras; brazos robóticos; funciones moduladoras; Lagrange; Lyapunov; neumática; oleohidráulica.

1. Introduction

In Peru, such as in many Latin American countries, there are developed many tasks that need the support of robotic arms according to be a complement for economic activities, such as for example in mining, fishing, agriculture processing and mechanic metal manufacturing. Nevertheless, the reparation of robotic arms depends on good understanding of the physical laws, as well as its mathematical modelling that are the base for the control algorithms of the robotic arms, in this context, this research provides technical strategies for designers and users of robotic arms, based in sensors/actuators that were prepared by nanostructure samples. The mathematical analysis of the proposed research focuses the effects of the advanced sensors/actuators as part of the robotic arms in the energy balance correlated with the energy carrier “pneumatic or oleo hydraulic”.

The propose of this research is focused in the analysis, design and applications of smart sensors/actuators based in Anodic Aluminum Oxide amorphous nanostructures, according to be used by robotic arms, as well as to enhance their performance. The designed smart sensors/actuators are supported by the short response time and high robustness as characteristics of the transducers prepared by the amorphous nanostructures. Hence, the microcontroller of the designed smart sensors (as part of the studied robotic arms) can execute intricate algorithms as a consequence of the optimized time, due to by traditional electromechanical sensors/actuators it is not simple to execute advanced algorithms for robotic arm tasks in contrast to solve them in short time because of the high robustness and short response time are properties of the designed sensors based on nanostructures. For this reason, whether the designed sensors/actuators are working as part of robotic arms, they can execute more sophisticated algorithms to reproduce movement tasks that are needed by the robotic arm. In fact, in this proposed research, it is evaluated the performance by executing advanced mathematical models based in neural network to find solution of the differential equations designed for the dynamic description of the robotic arm evaluated, modulating functions, Lagrange and Lyapunov analysis, as well as the comparison results among the robotic arm using electromechanical sensors/actuators with the robotic arms using the designed smart sensors/actuators, besides there are explained some communication protocols used in the designed proposal that are based in wireless interchanging data between the sensors and actuators.

Furthermore, in this research is evaluated the enhancement of the robotic arms energy transmission as a consequence of the smart sensors/actuators integrated in them, for which, there were analyzed Lyapunov models according to get numerical results of the optimal energy transmission through the robotic arm (Lyapunov stability), as a result, it means an optimal energy transmission over the objective in which the robotic arm will execute a task.

In the following research is analyzed the energy transmission as well as the optimization according to

improve the performance of robotic systems. The main objective in this research is the analysis of the consequences to use sensors/actuators based on amorphous nanostructures owing to enhance the energy transmission/balance of robotic arms. Hence, in this article is detailed the mathematical model designed to achieve the proposed objective, then, as a consequence of the mathematical view, it was possible to design sophisticated algorithms for simulations and the prototype design.

It was necessary to focus the study of the energy carrier from which to get the movement consequence of the robotic system, therefore it was analyzed the energy carrier as part of a pneumatic or oleohydraulic system. By other side, the energy transmission can be improved by sensors and actuators with high robustness and short response time, these properties were obtained by the smart sensors/actuators designed by nanostructures as part of the robotic arm (robotic system studied in this research).

It is expected that this research could be a support for designers of robotic arms or for researchers who are trying to get optimal solutions (by optimal and adaptive algorithms) consequently to be used for the industrial and economical activities in the Latin-American market, because of the Latin-American countries have own reality by agriculture, mining and fishing with the high responsibility to care the environment conditions. In the following Fig. 1 is depicted a robotic arm, in which “A” represents the main energy transmission of the energy carrier over the block “B”, which coordinates the first degree of freedom for the robotic system, the second coordination of movement are given by “C” and “D” that get action over the holders of the subsystem “E”.

2. Theoretical analysis

The sensors and actuators of the robotic system were designed by amorphous nanostructures, from which the eq. 1 gives the information of the volume base “ V_b ” for a unit of nanostructures, in which “ l ” is the side base as well as “ L ” is the height [1-3,17].

$$V_b = \frac{6\sqrt{3}}{4} l^2 L \quad (1)$$

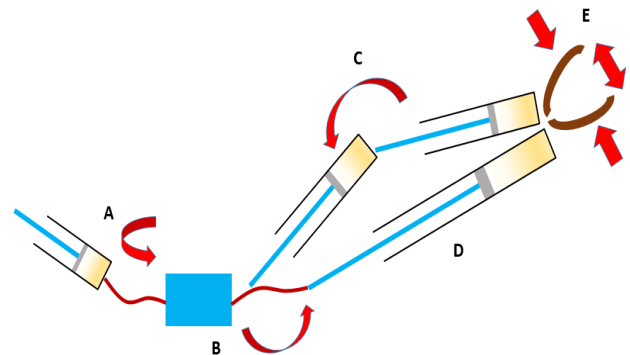


Figure 1. Representation of a robotic arm for the proposed research. Source: Own elaboration

The porous volume “ V_p ” is given by the eq. 2, which was obtained over the unit sample described by the previous eq. 1, furthermore, “ D_p ” is the diameter of the porous [1-3,17].

$$V_p = \frac{\pi}{4} D_p^2 L \quad (2)$$

Hence, the porosity “ P ” is achieved by the eq. 3 that is consequence to correlate eq. 1 and eq. 2 [1-3,17].

$$P = \frac{\frac{\pi}{4} D_p^2 L}{\frac{6\sqrt{3}}{4} l^2 L} \quad (3)$$

The Fig. 2 depicts the porous of Anodic Aluminum Oxide (AAO) prepared over the Aluminum sample due to anodization reactions that also can help for the controlling the porous diameter during the electrochemical reactions of their preparation, thus, the expansion of the porous (during the elaboration process) is depicted by the direction of every red arrow depicted on the Fig. 2. [1-3,17].

The following eq. 4 gives information regarding the first order transfer function of the flow sensor that was designed to analyze the optimal energy transmission on the studied robotic system. The flow sensor model also helped to get the implicit speed of the designed robotic system, in which the response time “ τ_1 ”, gain “ K_1 ” and delay “ L_1 ”; the flow variable (energy carrier) is the variable “ Y_1 ” and the input variable is given by “ X_1 ”. It must be understand that the eq. 4 (also the subsequent eq. 5) are given in Laplace “ S ” domain that were obtained by experiments, during the dynamic analysis of the system [6-12].

$$\frac{Y_1(S)}{X_1(S)} = \frac{K_1}{\tau_1 S + 1} e^{-L_1 S} \quad (4)$$

Moreover, the eq. 5 gives information concerning the displacement measured by infrared (IR), for which, the response time “ τ_2 ”, gain “ K_2 ” and delay “ L_2 ”; the displacement variable (of the robotic arm) is the variable “ Y_2 ” and the input variable is given by “ X_2 ” that is the IR signal over the displacement target of the robotic arm. [6-12].

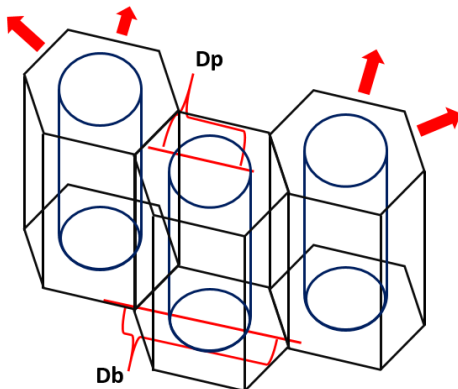


Figure 2. representation of AAO samples.
Source: Own elaboration

$$\frac{Y_2(S)}{X_2(S)} = \frac{K_2}{\tau_2 S + 1} e^{-L_2 S} \quad (5)$$

Therefore, it is possible to join both eqs. 4 and 5 by a differential matrix equation, as it is described by the eq. 6 on the time domain, as well as it was possible to evaluate the designed smart sensors on either hydraulic/pneumatic robotic system or electrical robotic system. [6-12].

$$\frac{d}{dt} \begin{pmatrix} y_1(t) \\ y_2(t) \end{pmatrix} = \begin{pmatrix} -\frac{1}{\tau_1} & 0 \\ 0 & -\frac{1}{\tau_2} \end{pmatrix} \begin{pmatrix} y_1(t) \\ y_2(t) \end{pmatrix} + \begin{pmatrix} \frac{K_1}{\tau_1} & 0 \\ 0 & \frac{K_2}{\tau_2} \end{pmatrix} \begin{pmatrix} x_1(t) \\ x_2(t) \end{pmatrix} \quad (6)$$

Thus, as a consequence, the solution is proposed by the following equation matrix eq. 7. [6-12].

$$y(t) = \begin{pmatrix} K_1 X_1(t) (1 - e^{-\frac{t}{\tau_1}}) \\ K_2 X_2(t) (1 - e^{-\frac{t}{\tau_2}}) \end{pmatrix} \quad (7)$$

For the both designed systems (hydraulic/pneumatic and electrical), the sensors are positioned near the articulations of the robotic arms according to measure the speed and position.

Since the eqs. 8 to 11 are the summary of the Lagrange analysis owing to validate the energy transmission through the robotic system. In which, “ L ” is the Lagrange function, “ T ” is the kinetic energy, “ U ” is the potential energy, and “ q ” is the coordinate axis, as well as “ Q ” is the external force, and “ i ”. [4,5,7].

$$\frac{d}{dt} \left(\frac{dL}{dq_i'} \right) - \frac{d}{dq_i} (L) = Q_i \quad (8)$$

$$\frac{d}{dt} \left(\frac{d(T - U)}{dq_i'} \right) - \frac{d}{dq_i} (T - U) = Q_i \quad (9)$$

$$\frac{d}{dt} \left(\frac{d(T)}{dq_i'} \right) - \frac{d}{dt} \left(\frac{d(U)}{dq_i'} \right) - \frac{d}{dq_i} (T) + \frac{d}{dq_i} (U) = Q_i \quad (10)$$

$$\frac{d}{dt} \left(\frac{d(T)}{dq_i'} \right) - \frac{d}{dq_i} (T) + \frac{d}{dq_i} (U) = Q_i \quad (11)$$

For the control analysis of the robotic arms, it was proposed a “Proportional, Integral, Derivative” PID controller, for which the eq. 12 is the characteristic equation of the robotic arm system [4,5,7].

$$\Delta_c(S) = 1 - M(S)C(S)P(S) \quad (12)$$

The transfer function of the designed sensors is given by the eq. 13, the transfer function of the designed sensor is one,

because of the measured displacement of the first degree of freedom. [4,5,7].

$$M(S) = \frac{K_S}{T_S S + 1} e^{-L_S S} \quad (13)$$

The PID controller in Laplace domain is given by the eq. 14, from which, the control parameters got dependences from the sensors/actuators based on nanostructures. [4,5,7].

$$C(S) = K_p + \frac{K_i}{S} + K_d S \quad (14)$$

As a response of step excitation signals over the robotic system, it was obtained first order transfer function for a robotic system, which is showed by the eq. 15. [4,5,7].

$$P(S) = \frac{K_Q}{T_Q S + 1} e^{-L_Q S} \quad (15)$$

Correlating all the described transfer functions, it was achieved the following eq. 16, in spite of it is not analyzed the adaptive equations yet. [4,5,7].

$$0 = 1 - \left(\frac{K_S}{T_S S + 1}\right) \left(K_p + \frac{K_i}{S} + K_d S\right) \left(\frac{K_Q}{T_Q S + 1}\right) \quad (16)$$

When the sensor response time " T_S " is null, and comparing the general second order model obtained was compared with the following second order system of the eq. 17. [4,5,7].

$$0 = S^2 + 2\varepsilon\omega S + \omega^2 \quad (17)$$

Hence, the second order model is given by the eq. 18. [4,5,7].

$$0 = S^2 + \left(\frac{1 + K_S K_Q K_p}{T_Q + K_S K_d K_Q}\right) S + \frac{K_S K_i K_Q}{T_Q + K_S K_d K_Q} \quad (18)$$

Comparing the eqs. 17 and 18, it was achieved the eq. 19, in order to find the control parameters. [4,5,7].

$$\frac{1 + K_S K_Q K_p}{T_Q + K_S K_d K_Q} = 2\varepsilon\omega \quad (19)$$

Therefore, the proportional controller is given by the eq. 20. [4,5,7].

$$K_p = \frac{2\varepsilon\omega(T_Q + K_S K_d K_Q) - 1}{K_S K_Q} \quad (20)$$

As well as, consequently to the comparison between the eqs 17 and 18, it is obtained the eq. 21. [4,5,7].

$$\frac{K_S K_i K_Q}{T_Q + K_S K_d K_Q} = \omega^2 \quad (21)$$

Furthermore, it was obtained the integral gain of the PID that is given by the eq. 22. [4,5,7].

$$K_i = \frac{\omega^2(T_Q + K_S K_d K_Q)}{K_S K_Q} \quad (22)$$

Notwithstanding, it must be analyzed the stability of the robotic system (robotic arm) that is composed by the designed smart sensors/actuators based on nanostructures, due to provide information of the control system can solve different movement tasks which can be asked to the robotic system, and as a consequence the robotic system needs to warrant good performance, it means the analysis of stability is quite important.

The eq. 23 gives information of the dynamic system for the robotic arm. [4,5,7,17].

$$\begin{aligned} \frac{d^2}{dt^2} y_1(t) + \frac{(T_{M_1} + T_{P_1})}{T_{M_1} T_{P_1}} \frac{d}{dt} y_1(t) + \frac{1}{T_{M_1} T_{P_1}} y_1(t) \\ = \frac{K_{P_1} K_{M_1}}{T_{M_1} T_{P_1}} X_1(t) \end{aligned} \quad (23)$$

From which, the eq. 24 is the speed of the robotic arm. [4,5,7,17].

$$v_1(t) = \frac{d}{dt} y_1(t) \quad (24)$$

Correlating the eq. 23 and the eq. 24, it was achieved the eq. 25. [4,5,7,17].

$$\begin{aligned} \frac{T_{M_1} T_{P_1}}{K_{P_1} K_{M_1}} \frac{d}{dt} v_1(t) + \frac{(T_{M_1} + T_{P_1})}{K_{P_1} K_{M_1}} v_1(t) \\ + \frac{1}{K_{P_1} K_{M_1}} y_1(t) = X_1(t) \end{aligned} \quad (25)$$

Moreover, it was proposed the eq. 26 as a Lyapunov function according to analyze the robotic arm stability, which also verifies the first Lyapunov stability condition, it means that is positive and bigger than zero. [4,5,7,17].

$$\frac{1}{2} \frac{T_{M_1} T_{P_1}}{K_{P_1} K_{M_1}} v_1^2(t) + \frac{1}{2} \frac{1}{K_{P_1} K_{M_1}} y_1^2(t) = E_1(t) \quad (26)$$

The eq. 27 looks for the verification of the second condition Lyapunov stability. [4,5,7,17].

$$\frac{d}{dt} E_1(t) = v_1(t) \left(\frac{T_{M_1} T_{P_1}}{K_{P_1} K_{M_1}} \frac{d}{dt} v_1(t) + \frac{1}{K_{P_1} K_{M_1}} y_1(t) \right) \quad (27)$$

The eq. 28 is obtained reducing the eq. 27 and using the eq. 26. [4,5,7,17].

$$\frac{d}{dt} E_1(t) = - \frac{(T_{M_1} + T_{P_1})}{K_{P_1} K_{M_1}} v_1^2(t) \quad (28)$$

In fact, the eq. 29 satisfies the second condition of Lyapunov stability because of it is negative while the response time parameters and the response gain parameters are positive, this effect is also a good consequence of the designed smart sensors/actuators based on nanostructures. [4,5,7,17].

$$\frac{d}{dt}E_1(t) = -\frac{(T_{M_1} + T_{P_1})}{K_{P_1}K_{M_1}}v_1^2(t) < 0 \quad (29)$$

In this research were analyzed the differential equation solutions by neural network, which were described by the eq. 30 [13], as a consequence of the multiple solutions from every studied model that comes from the transduction responses (every sensor response), the identification data based on the polynomial analysis results established on Lagrange (studied on paragraphs above), moreover the stability analysis from the dynamic of the system also in correlation with the optimal energy transmission through the robotic arm system. Thus, every differential equation was organized to achieve their solutions by neural network, in which the solution package is given by “ α ”, activation function is given by “ σ ” (this was generalized by consequences of Modulating Functions), every input variable “ x ” (for every differential equation from the full system), the weights matrix “ w ” according to find the adaptive solution for every subsystem of the robotic arm, every joined disturbance “ β ” that for some authors also this could be considered as kind of error signal, every variable indicated and fixed by the auxiliary variable “ i ”, counting the equations from 1 till “ n ”.

$$\begin{aligned} \alpha &= \sigma \left(\sum_{i=1}^n x_i w_i + \beta \right) \\ &= \sigma \left(\sum_{i=1}^n x_i w_i + \beta \right) \end{aligned} \quad (30)$$

It was necessary to improve the adaptive parameters of the eq. 30 (which were considered as weights matrix) in order to obtain the optimal solutions of every differential equation that describe the robotic arm, as well as its optimal energy transmission based on the stability and dynamic (Lyapunov and Laplace). Therefore, the recurrence of the eq. 31 [13] is also supported by every updated value in “ w ”, adjusted by “ η ” in the continuous decay of “ L ” because of its gradient in dependence on “ w_t ”.

$$w_{t+1} = w_t - \eta \nabla L(w_t) \quad (31)$$

Every component of the designed system has integration each to other wirelessly (some sensors, actuators, and the control system of the robotic arm). As it was explained in the previous chapters of this proposed article, the short response time in comparison with the traditional electromechanical sensors (in average that was around 0.5 to 0.8 seconds)

helped to execute intricate algorithms to achieve the main objective of the proposed article “Optimal energy transmission in the robotic arm to develop tasks”, moreover to get the correlation for the emitter/receptor of every measured data and control data without wires between each to other.

It means that it was necessary a protocol for the interchanging data communication (and control data), for this research, it was selected inferred (IR) signal according to be the electromagnetic wave (the medium) for the data communication/control of the robotic arm, and the standard protocol for the IR signal in communication systems is given by Infrared Data Association (IrDA) [14], the operation frequency for most of the data communication/control of the robotic arm are not inside of the range of work proportionated by IR, therefore, also it was one of the justification to work with IR signal in order to replace wires between every subsystem (such as a kind of embedded system).

Hence, it was decided to enhance the data communication between every subsystem of the robotic arm, for which, it was possible to interchange information from the main control system to the sensors and actuators by IrDA, it was a good advantage because of not using wires between the subsystem of the robotic arm. Notwithstanding, it was necessary to integrate a microcontroller for the designed sensors in order to support the dynamic responses of the robotic arm by the correlation between the consumed energy by the robotic arm with the dynamic parameters necessary to solve tasks.

3. Simulation analysis

After to organize the described equations and analysis from paragraphs above, it was prepared an adaptive algorithm in order to evaluate the optimal energy transmission of the studied robotic arms, and the following Fig. 3 shows a result of the simulated displacement on the axis X and Y. The scale was 10 cm for the displacement of the robotic arm over a plane surface “XY”.

The expected trajectory achieved by simulations and calculations was a result of the coordination from the energy transmission analysis. It means, from the interpretation results of the response time “ T_1 ” and “ T_2 ” (correlation between the dynamic effect over the robotic arm with its energy charger response), as well as the expected solutions for every dynamic model were soft curves based on the first order systems of their behavior. Furthermore, the dynamic interpretation achieved consequently from Lagrange analysis (because of the carrier energy effect) needed to be verified by Lyapunov, owing to the stability of the main system. Thus, every solution for every differential equation of the full system was organized through neural network analysis and supporting the simulations and experimental algorithms design. Hence, the Fig. 3 shows the representation of the robotic arm movement over the described XY plane.

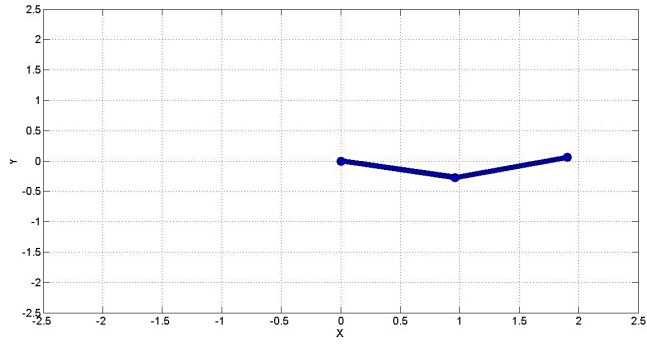


Figure 3: Simulation result of the robotic arm displacement.
Source: Own elaboration

4. Experimental analysis

The experiments to evaluate the performance of the designed robotic arm were made consequently to design the mathematical model that correlates the robotic arm dynamics with the optimal energy transmission given by the energy carrier (which was explained in chapters above).

Therefore, the optimal energy transmission through every subsystem of the robotic arm can achieve a successful result owing to the short response time of sensors/actuators designed for this research that was based on nanostructures prepared over AAO samples. In this context, the Fig. 4 shows holes with diameters around 1 μm or 1000 nm, over which were deposited atoms by “Sputtering process”, “physical vapor deposition”, or “electrochemical deposition”

There were prepared nanostructures by electrochemical depositions.

Nevertheless, the samples obtained were amorphous, in this context there were designed transducers (such as nano wires) based on titanium dioxide, silicon, ferric, cooper, gold and silver.

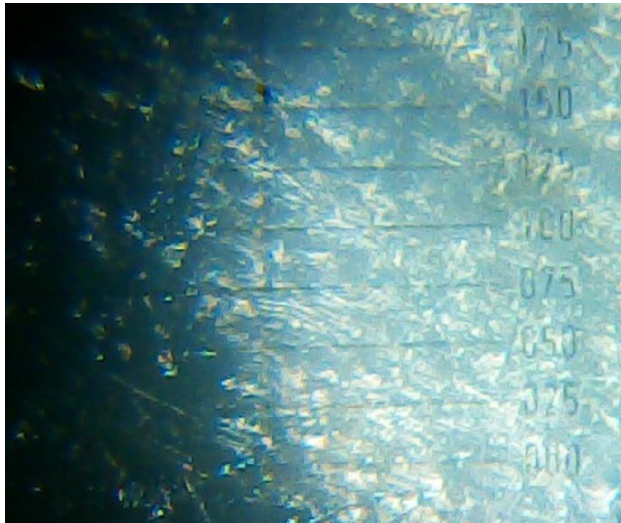


Figure 4: Sample of AAO analyzed by microscope Litz.
Source: Own elaboration



Figure 5: Setup for the experiments (some of them made in Oleo-hydraulic laboratory from the PUCP).
Source: Own elaboration

Even though, the samples are amorphous, it does not mean that cannot be useful [15,16], these samples are useful as clusters with good performance in the electromagnetic absorbance (for the wireless sensors designed in this task).

The Fig. 5 shows the setup for the experiments (in which the energy carrier was evaluated either as air or oil). The main robotic arm designed was under the procedure to test its performance between the dynamic parameters (response time and robustness) with the energy carrier parameters (fluid density and referential distance).

In the following Fig. 6 are showed the trajectories of the designed robotic arm, in the left upper subfigure and in the right upper subfigure, from which it was possible to verify the response of the robotic arm achieved by a classic electromechanical sensor (red color curves) in comparison with a theoretical analysis (blue color curves) of the robotic arm movement that was described in previous chapters.

In both cases, it is possible to see that the movement measured by the sensors based in nanostructures (green color curve) get more close correlation with the theoretical model (blue color curve).

As well as, for both lower subfigures of the following Fig. 5 are showed the trajectories of the designed robotic arm. Hence, also the measurement obtained by the sensors based in nanostructures has a better behavior than the electromechanical sensors, which is validated by their short response time and robustness under disturbances.

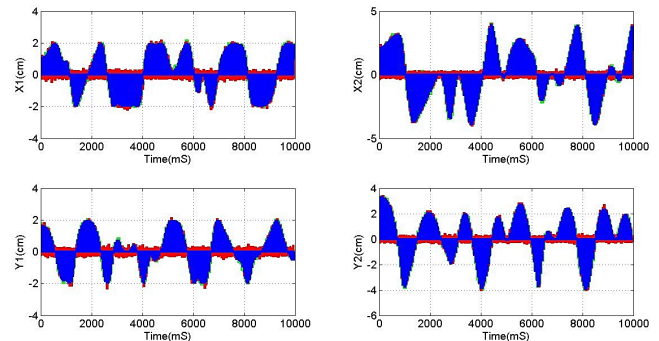


Figure 6: Responses and trajectories of the robotic arm.
Source: Own elaboration

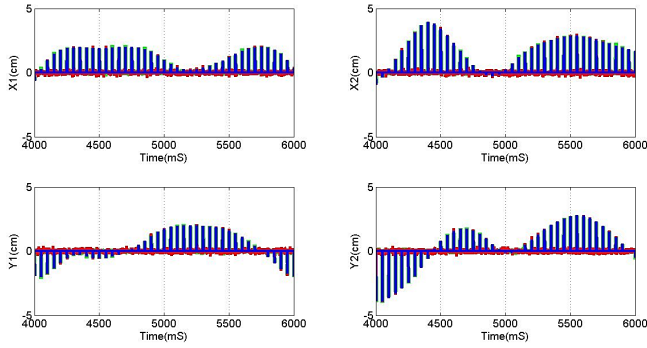


Figure 7: Responses and trajectories of the robotic arm (amplified view)
Source: Own elaboration

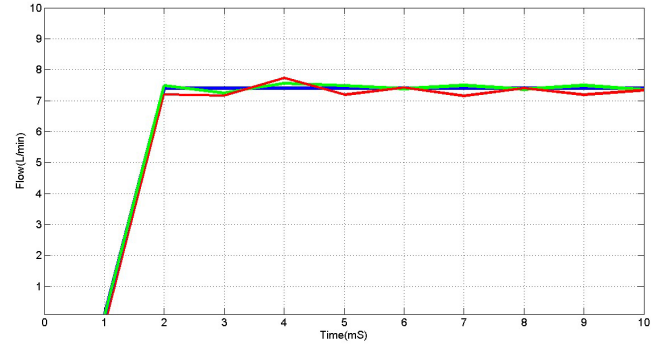


Figure 9: Dynamic response for the energy carrier of the robotic arm.
Source: Own elaboration

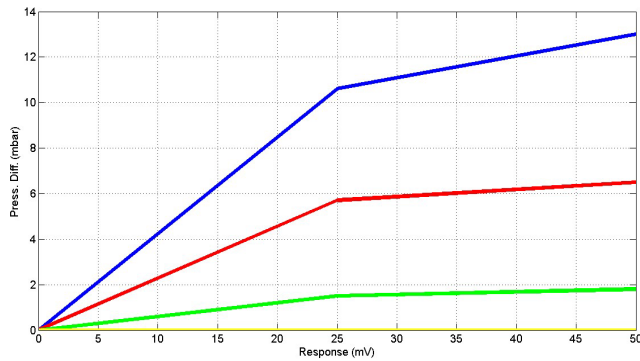


Figure 8: Static curves for the difference of pressure of the carrier energy on the designed sensor.
Source: Own elaboration

The following Fig. 7 is an amplification from the previous figure, in which is possible to verify that the designed smart sensors/actuators as part of the robotic arm can proportionate a better information of the movement task for the control system of the robotic arm, then it is a good support to keep its stability.

The green color curve for the 4 subfigures of the following figure is the data achieved by the designed smart sensors, the blue color curve is the theoretical trajectory analyzed by the previous mathematical models described in chapters above, as well as the red color curve is the data measured by the traditional electromechanical sensors.

Otherwise, it was analyzed the static responses of the carrier energy of the designed robotic arm, in which it was possible to identify the range of operation. In the Fig. 8, the blue color curve tends to give a wide operating range by linear response from 0 mbar to 11 mbar as difference of pressure.

The following Fig. 9 shows the dynamic response of the carrier energy for the designed robotic arm, which was air. Therefore, airflow was controlled as part of the control volume (carrier energy) to give the movement effect for the robotic system. The blue color curve is the theoretical model of the airflow as part of a step response over the robotic arm, the red color curve was the data measured by a traditional

electro mechanic sensor, and the green color curve is the airflow measured by the designed smart sensor.

Hence, the data measured by the designed sensor based in nanostructures provided high robustness and short response time over the proposed operating range.

5. Conclusions

It was designed and analyzed a general mathematical model for the study of the optimal transmission of the energy carrier in a robotic arm, according to research the effects to use sensors/actuators based on nanostructures.

It was designed an adaptive algorithm to simulate the movement effect of a robotic arm, as well as its energy carrier transmission. Even though, the algorithms designed were also used for the designed robotic arm.

It was correlated the displacement and speed of the robotic arm with the airflow as part of the energy carrier in order to get the stability analysis by Lyapunov.

It was verified the short response time and high robustness of the sensors/actuators based in nanostructures owing to enhance the energy transmission in a robotic arm that can be useful for researchers and designers.

6. Outlook

It is suggested to integrate the designed smart sensors/actuators and the robotic arm as part of a robotic system with autonomous movement, such as for example with independent dynamic and displacement.

It is suggested to analyze the enhancement of the designed robotic arm by autonomous support of saved energy and wireless communication inside its hardware, according to validate the importance to use sensors/actuators based in nanostructures.

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Influence of partial replacement of cement by biomass ashes on cement-wood composites properties

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Abstract

The aim of this work was to evaluate the physical and mechanical properties of cement-wood composites with the addition of biomass ashes at different levels (0, 5, 10, 15, 20, and 25%). The composites were produced using Portland cement CII, Eucalyptus grandis particles, and ashes from eucalyptus wood. The tests followed the NBR 7215 (2019) and ASTM E1876 (2022) standards, density, 24-hour thickness swelling, 24-hour water absorption, dynamic modulus of elasticity from non-destructive testing, static modulus of elasticity, and compressive strength at 28 days tests were carried out. After the tests, statistical analysis was performed to verify if there were statistically differences between the means at a 5% level of significance. The partial replacement of cement with ashes shows potential, especially with a 5% replacement, due to better physical and mechanical properties.

Keywords: cementitious composite; mechanical properties; physical properties; residues use.

Influencia de la sustitución parcial de cemento por cenizas de biomasa en las propiedades de compuestos de cemento y madera

Resumen

El objetivo del presente estudio fue evaluar las propiedades físico-mecánicas de compuestos cemento-madera con la incorporación de cenizas de biomasa en diferentes proporciones (0, 5, 10, 15, 20 y 25%). Estos compuestos se fabricaron utilizando cemento Portland CII, partículas de Eucalyptus grandis y cenizas procedentes de la combustión de madera de eucalipto, siguiendo las normativas NBR 7215 (2019) y ASTM E1876 (2022). Se realizaron pruebas de densidad, expansión en espesor a las 24 horas, absorción de agua a las 24 horas, módulo de elasticidad dinámico mediante ensayos no destructivos, módulo de elasticidad estático y resistencia a la compresión a los 28 días. Posteriormente, se efectuó un análisis estadístico para determinar si existían diferencias entre las medias con un nivel de significancia del 5%. La sustitución parcial del cemento por cenizas demostró tener potencial, destacándose especialmente el tratamiento con una sustitución del 5% debido a sus mejores propiedades físico-mecánicas.

Palabras clave: compuesto de cemento; propiedades mecánicas; propiedades físicas; aprovechamiento de residuos.

1. Introduction

Cement-wood composites are produced by combining wood particles with a mineral binder. The first cement-wood industries

emerged in the 1930s in Austria, with significant development occurring in the late 1940s. Large-scale production began in 1976 in Germany. Currently, cement-wood boards are widely used in the United States, Japan, Russia, and Mexico [1,2].

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Cement-wood composites are used as ceiling and wall coverings, as well as in structural applications such as floors and walls. In these composites, wood contributes to increased rupture resistance, while cement provides enhanced durability, fire resistance, and dimensional stability [3].

Some advantages of cement-wood composites include lower density, approximately 15% lower, compared to traditional cement boards, good thermal and acoustic properties, as well as resistance to weathering and wood-destroying agents, the possibility to use small-diameter trees or timber industry residues, reducing environmental impact, due to its renewable nature, and the good mechanical properties, such as high impact resistance, flexural strength, and hardness [4-6].

The construction industry is one of the most significant contributors to the economy. However, it also causes major environmental impacts, particularly in cement production, which is highly polluting due to limestone extraction and carbon dioxide emissions during its calcination [7,8]. An alternative to reducing cement usage is the partial substitution of cement with biomass ash in cement-wood composites.

Ashes are industrial solid waste originating from the incomplete combustion of biomass. Recycling and reusing ashes mitigate environmental impact and reduce transportation and landfill costs [9]. Currently, this waste is used for soil fertilization in agriculture and forestry [10-12]. However, other applications are being explored, including their use in cementitious composites.

The incorporation of ashes in cementitious products meets the construction industry's need for materials with high durability, strength, and cost-effectiveness [13]. The addition of ashes to cement mortar increased its normal compression and flexural strength [14]. In concrete, ash addition yielded favorable results in terms of water absorption and freeze-thaw resistance [15].

Therefore, the aim of this study was to assess the physical and mechanical properties of cement-wood composites with partial cement replacement by biomass ash at different proportions.

2. Methodology

For the production of the composites were used Portland cement type II, *Eucalyptus grandis* wood particles and biomass ash from the burning of eucalyptus wood. Table 1 presents the chemical composition of the ash used, based on three samples.

First, the wood pieces were processed using a drum chipper and a Wiley mill, followed by classification through a set of vibrating sieves with three different mesh sizes. The particles used were those that passed the 9-mesh sieve and were retained on the 16-mesh sieve. After the sieving, these particles were dried in an oven at $103 \pm 2^\circ \text{C}$ for 24 hours.

Table 1.

Ash chemical composition.

		Mean
Composition (%)	Nitrogen (N)	0,27
	Phosphorus pentoxide (P ₂ O ₅)	0,38
	Potassium oxide (K ₂ O)	0,88
	Calcium (Ca)	4,20
	Magnesium (Mg)	0,89
	Sulfur (S)	0,13
	Total organic carbon	1
Composition (mg * kg ⁻¹)	Sodium (Na)	3669
	Copper (Cu)	86
	Iron (Fe)	14602
	Manganese (Mn)	1005
	Zinc (Zn)	149
pH		12

Source: Adapted from Hansted et al., 2023 [16].

Table 2.

Evaluated treatments.

Treatment	Mixture ratio (Cement: Ash: Wood: Water)
CP II 0%	1,00 : 0,00 : 0,20 : 0,80
CP II 5%	0,95 : 0,05 : 0,20 : 0,80
CP II 10%	0,90 : 0,10 : 0,20 : 0,80
CP II 15%	0,85 : 0,15 : 0,20 : 0,80
CP II 20%	0,80 : 0,20 : 0,20 : 0,80
CP II 25%	0,75 : 0,25 : 0,20 : 0,80

Source: Authors.

Six different treatments were evaluated, varying the replacement of cement with biomass ash, as shown in Table 2. In studies using cementitious composites with ash and concrete with ash, the authors presented different levels as ideal for improving the properties of the material, varying between 5 and 25% [16-20]. In this way, treatments from 0 to 25% in cement-wood composites with partial ash replacement were evaluated. The mixture was used based on the mass of the materials, representing the amount of cement, ash, wood, and water, respectively.

The production of the composites followed the standard recommendations [21]. Mixing and compaction were done manually. For the mechanical and apparent density tests, cylindrical PVC molds with a diameter of 50 mm and a height of 100 mm were used. For thickness swelling and water absorption tests, prismatic wooden molds with a square cross-section of 50 mm and a height of 25 mm were used.

A thin layer of vegetable release agent was applied to the molds before adding the cement mixture, and a plastic sheet was placed in the prismatic molds to prevent adhesion. Six specimens of each model were produced for each treatment.

After compaction, the composites cured in an air-conditioned environment at 25°C for 28 days. Fig. 1 shows the production stages.

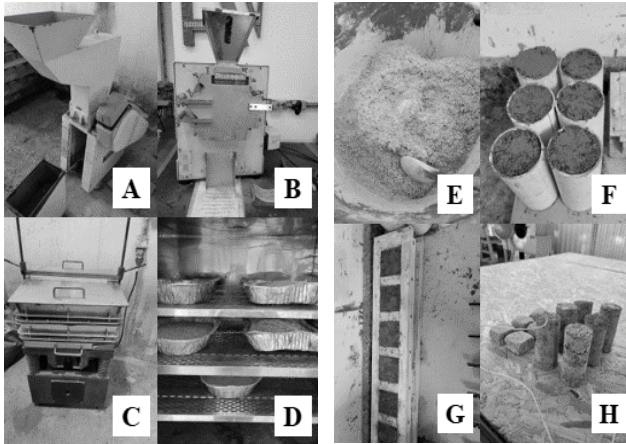


Figure 1. Production of composites, where (a) Drum chipper. (b) Wiley mill. (c) Set of vibrating sieves. (d) Oven drying. (e) Mixing of materials. (f) Molded cylindrical composites. (g) Molded prismatic composites. (h) Finished composites.
Source: Authors.

To determine the apparent density, the specimens were measured with a digital caliper with a resolution of 0.01 mm and then weighed on a semi-analytical balance with a resolution of 0.01 g. Density was calculated using the ratio of mass to volume.

To determine the swelling in thickness and water absorption, the prismatic specimens were measured caliper and weighed on a semi-analytical balance. They were then immersed in water for 24 hours and then weighed and measured again.

The thickness swelling was determined according to eq. (1).

$$TS = \frac{t_f - t_i}{t_i} * 100 \quad (1)$$

Where: TS is the thickness swelling 24h (%); t_i is the initial thickness of the specimen (mm) and t_f is the final thickness of the specimen (mm).

Water absorption was determined according to eq. (2).

$$WA = \frac{m - m_i}{m_i} * 100 \quad (2)$$

Where: WA is the water absorption 24h (%); m_i is the initial mass of the specimen (g) and m_f is the final mass of the specimen (g).

The dynamic modulus of elasticity was determined using the non-destructive method with the SONELASCTIC® system, following the standard recommendations [22]. For the test, the specimens were weighed on a semi-analytical balance and measured using a digital caliper.

Next, a non-destructive test conducted, where the specimens were placed in a horizontal position and impacted with a device, while a microphone was placed at the other end to capture the longitudinal resonance frequency. The dynamic modulus of elasticity was calculated using eq. (3).

$$Ec_d = 16 * m * fl^2 * \left(\frac{L}{\pi * d^2 * K} \right) * 10^{-6} \quad (3)$$

Where: Ec_d is the dynamic compression modulus of elasticity (MPa); fl is the mean of three consecutive measurements of the longitudinal resonance frequency (Hz); d is the mean diameter of the specimen (mm); L is the mean height of the specimen (mm); K is the correction factor calculated using eq. (4).

$$K = 1 - \left(\frac{\pi^2 * \mu^2 * d^2}{8 * L^2} \right) \quad (4)$$

Where: μ is Poisson's ratio, the value of 0.15 was used, referring to concrete [19].

The compression test was conducted to determine the static modulus of elasticity and strength [23]. The EMIC DL300 universal testing machine with a capacity of 300 kN was used, and the machine's loading speed was set at $0.25 \pm 0.05 \text{ MPa} * \text{s}^{-1}$. The test specimens were compressed until failure. Fig. 2 shows the tests procedure.

After the tests, statistical analysis was performed. First, the Shapiro-Wilk test was performed to verify data normality, and the Bartlett test was used to verify variance homogeneity. Subsequently, analysis of variance was performed to determine if there was a statistical difference among means at a significance level of 5%. In cases where necessary, the Tukey test was applied to identify which means differed. A regression analysis was also carried out to investigate the correlation between properties and the variation in cement replacement. All statistical tests were conducted using R software version 4.3.1.

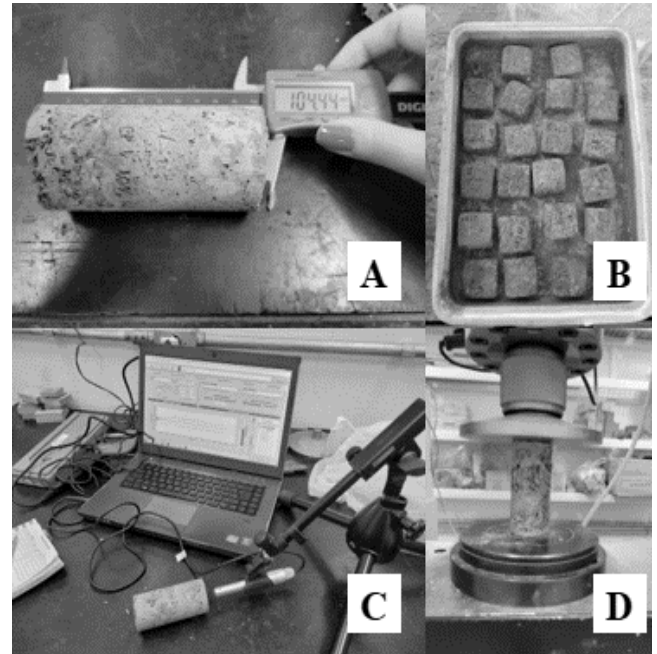


Figure 2. Physical-mechanical tests, where (a) Measurement of the test piece; (b) Test specimens immersed in water; (c) Non-destructive test; (d) Compression test.
Source: Authors.

3. Results and discussion

Table 3 presents the results of the physical tests containing the mean, standard deviation, in parentheses, and statistical analysis, where identical letters vertically do not differ at the 5% level of significance.

Table 3.
Results of the physical tests.

Treatment	Density (kg/m ³)	Thickness swelling (%)	Water absorption (%)
CP II 0%	1119 A (34)	2.28 A (1.68)	27.95 B (0.83)
CP II 5%	1075 A (18)	2.15 A (0.83)	27.94 B (1.72)
CP II 10%	1145 A (254)	1.70 A (0.60)	31.44 B (1.17)
CP II 15%	1034 A (20)	1.81 A (1.95)	31.56 B (3.34)
CP II 20%	1090 A (12)	1.64 A (1.46)	31.01 B (1.89)
CP II 25%	972 A (36)	2.61 A (1.52)	43.24 A (3.46)

Source: Authors.

Fig. 3 shows the physical property graphs for each treatment, containing the linear regression curve.

The linear function for the density property is indicated in eq. (5).

$$\rho = 1130,32 - 4,61 * AC \quad (5)$$

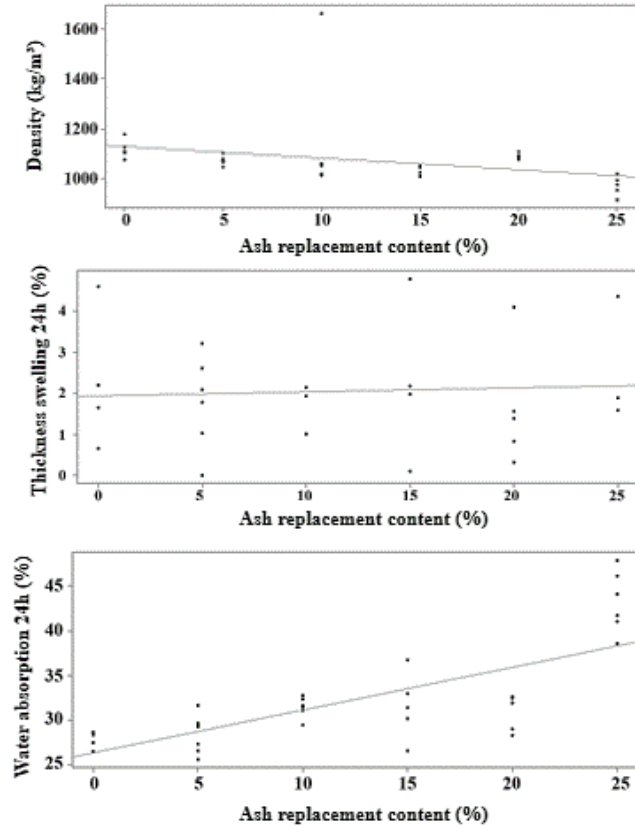


Figure 3. Chart of physical properties as a function of ash replacement content.

Source: Authors.

Where: ρ is the density (kg/m³) and AC is the ash content (%). The correlation between the density and the ash content is 34,99%

In the density test, there was no statistical difference among the means. However, a decreasing trend in the property is noticeable with the increase in the percentage of ash replacement, as observed in the linear function, whose angular coefficient is negative. This is because the density of ashes is slightly lower than that of the cement paste. This reduction has also been observed in concrete and mortar with partial cement replacement by wood ashes [14,24].

The linear function for the thickness swelling 24h property is indicated in eq. (6).

$$TS = 1,930 + 0,01 * AC \quad (6)$$

Where: TS is the thickness swelling 24h (%). The correlation between the TS and the ash content is 3,64%. The thickness swelling did not exhibit statistical variation due to the high standard deviation. However, it showed a trend of reduction with an increase in the amount of ashes.

This is a favorable factor and is justified by the smaller particle size of the ashes, which reduces the voids in the composite due to the increased surface area of the particles, resulting in better interaction between the materials [16].

The tendency towards reduced thickness swelling indicates that the C-S-H gel formed in the reaction of ash with calcium hydroxide contributes to the durability of the composites, even with a reduced amount of cement added [25].

The linear function for the water absorption 24h property is indicated in eq. (7).

$$TS = 26,29 + 0,48 * AC \quad (7)$$

Where: WA is the water absorption 24h (%). The correlation between the WA and the ash content is 74,62%.

Water absorption increased as the content of cement replaced by ash increased, presenting a high correlation index. The ash contains a significant amount of calcium, which is hydrophilic, and less silica, a hydrophobic element [26].

This occurs because, with the decrease in the amount of added cement, the hydration reaction is reduced, causing water to evaporate more quickly, leading to the formation of a greater number of pores in the composite, which in turn facilitates water penetration [27].

Table 4.
Results of the mechanical tests.

Treatment	Ec _d (MPa)	Ec (MPa)	fck (MPa)
CP II 0%	1798 A (524)	115 A (39)	2.39 AB (0.38)
CP II 5%	1573 A (108)	132 A (46)	2.373 A (0.53)
CP II 10%	1562 A (548)	100 A (42)	2.05 AB (0.35)
CP II 15%	1399 AB (166)	131 A (33)	2.01 AB (0.34)
CP II 20%	1637 A (71)	187 A (130)	2.27 AB (0.61)
CP II 25%	982 B (118)	89 A (39)	1.64 B (0.28)

Source: Authors.

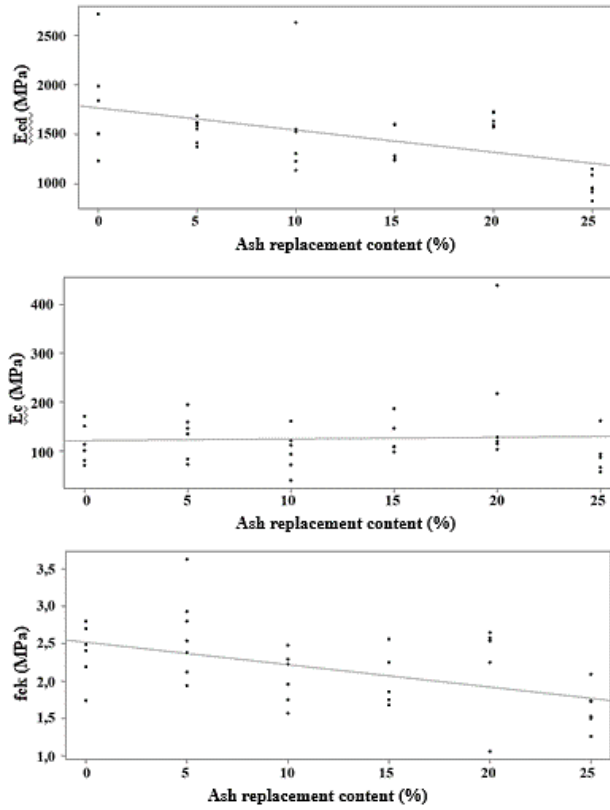


Figure 4. Chart of mechanical properties as a function of ash replacement content.

Source: Authors.

Table 4 presents the results of the mechanical tests containing the mean, standard deviation, in parentheses, and statistical analysis, where identical letters vertically do not differ at the 5% level of significance. Where E_{cd} is dynamic modulus of elasticity, E_c static modulus of elasticity and f_{ck} is compressive strength at 28 days.

Fig. 4 shows the mechanical property graphs for each treatment, containing the linear regression curve.

The linear function for the E_{cd} property is indicated in eq. (8).

$$E_{cd} = 1755,15 - 22,44 * AC \quad (8)$$

The correlation between the E_{cd} and the ash content is 49,31%. The linear function for the E_c property is indicated in eq. (9).

$$E_c = 121,62 + 0,33 * AC \quad (9)$$

The correlation between the E_c and the ash content is 4,24%.

The overall correlation between dynamic modulus of elasticity and static modulus of elasticity is 15.80%, while the correlation between dynamic modulus of elasticity and compressive strength is 57.08%. The properties showed weak and moderate correlation, respectively. A high correlation

represents the potential to predict the mechanical properties of composites without the need for rupture.

The linear function for the E_c property is indicated in eq. (10).

$$f_{ck} = 2,52 - 0,03 * AC \quad (10)$$

The correlation between the f_{ck} and the ash content is 46,52%.

The compressive strength at 28 days showed a tendency to reduce with the increase in the replacement of cement with wood ash. The same occurred in concrete and cementitious composites with fly ash [28-30].

The reduction in strength with the addition of ash occurs due to the higher number of pores and the formation of a microstructure with greater permeability [31]. In addition to the fact that the use of *in natura* ash compromises the mechanical strength of the material, it is recommended to carry out treatments such as grinding [32].

The CP II 5% treatment presented the highest compressive strength value. The same occurred in cement-wood composites with the addition of biomass ash and fly ash [8,33].

However, treatments with partial replacement of 10, 15 and 20% do not present a statistical difference with the treatment without adding ash, making it possible to replace larger amounts of ash without loss of physical-mechanical performance.

4. Conclusion

The partial replacement of cement by biomass ash in cement-wood composites has potential for use, due to its similar or superior properties to composites without ash, enabling the reuse of a waste product in a higher value-added product.

The density showed a tendency to reduce as the ash content decreased, as well as the dynamic modulus of elasticity and compressive strength at 28 days. On the other hand, 24-hour water absorption increased.

The properties of density, 24h thickness swelling and static modulus of elasticity did not exhibit significant variations with changes in the cement substitution content with ash in the composites.

The 5% replacement treatment exhibited superior overall physical-mechanical performance, but the treatments with 10%, 15%, and 20% replacement did not show a statistical difference compared to the control treatment. Thus, partial substitution of cement with ash is feasible without a reduction in physical-mechanical properties.

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Use of steel slag to improve the mechanical properties of subgrades in clayey soils

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Abstract

Large quantities of steel slag are generated annually throughout the world. Some slag from steel manufacturing is reused in the generation of other materials, such as hot mix asphalt aggregate, pipe filling, concrete, among others. The research aims to enrich the mechanical characteristics of soils and minimize road construction costs. The objective of this research is to find a material that increases the mechanical properties of the subgrade in clay soils with different plasticity indices using Electric Arc Furnace Slag (EAF) in percentages: 5%, 15% and 25% of the weight of the soil. From the tests carried out on the soil samples using parameters, it was possible to classify them by the Unified Soil Classification System (USCS) and also by the American Association of Highway Transportation (AASHTO) as low and high clays. plasticity. When testing the samples in their natural state and the samples with EAF, results were obtained that showed an improvement in the physical and mechanical properties of the clay soils with the addition of EAF, increasing the values of the Bearing Capacity Ratio (CBR) and the maximum dry density. of the clay soil as the percentage of HAE in the mixture increased. The optimal HAE addition content corresponds to 25% of the weight of the soil.

Keywords: clay soils; EAF slag; stabilization; maximum dry density; CBR.

Uso de escoria de acero para mejorar las propiedades mecánicas de las subrasantes en suelos arcillosos

Resumen

Grandes cantidades de escoria de acero se generan anualmente en todo el mundo. Parte de la escoria de la fabricación de acero se reutiliza en la generación de otros materiales, como agregado asfáltico en mezclas calientes, relleno de tuberías, hormigón, entre otros. La investigación se centra en enriquecer las características mecánicas de los suelos y minimizar los costos de construcción de carreteras. El objetivo de esta investigación es encontrar un material que aumente las propiedades mecánicas de la subsección en suelos arcillosos con diferentes índices de plasticidad utilizando Escoria de Horno de Arco Eléctrico (EAF) en porcentajes: 5%, 15% y 25% del peso del suelo. A partir de las pruebas realizadas en las muestras de suelo utilizando parámetros, fue posible clasificarlas según el Sistema de Clasificación de Suelos Unificado (USCS) y también según el estado natural de la Asociación Americana de Oficiales de Transporte de Carreteras (AASHTO) como arcillas de baja y alta plasticidad. Al probar las muestras en su estado natural y las muestras con EAF, se obtuvieron resultados que mostraron una mejora en las propiedades físicas y mecánicas de los suelos arcillosos con la adición de EAF, aumentando los valores del Índice de Capacidad de Soporte (CBR) y la densidad máxima seca del suelo arcilloso a medida que aumentaba el porcentaje de EAF en la mezcla. El contenido óptimo de adición de EAF corresponde al 25% del peso del suelo.

Palabras clave: suelos arcillosos; escoria de EAF; subrasante; estabilización; CBR; densidad máxima seca.

Notation

EAF	electric arc furnace slag
MDD	Maximum dry density
CBR	California Bearing Ratio
PI	Plasticity index
LL	Liquid limit
PL	plastic limit
C-1	Sample Calicata clay soil 1
C-2	Calicata sample clay soil 2
C-3	Calicata sample clay soil 3

1. Introduction

More than 1,951 million tons of crude steel have been produced globally in 2021 [28]. The manufacturing of this product generates a waste called “slag” that causes environmental problems [9], due to limitations in recycling [30].

In these last two decades there has been a growth in interest in the use of new materials in the construction industry (Rondon et al., 2018). Therefore, several studies have been carried out on the use of industrial waste in civil applications as an option for construction materials that can become less expensive and environmentally friendly and at the same time improve the physical and mechanical properties of the final result [21]. These residues can be used as replacement for soil and subgrade improvement of road pavement [21].

The subgrade is usually made up of natural soil, such as expansive clays. The clay material has characteristics that can be negative at the time of construction, such as: high potential for expansion and contraction, low load capacity and, finally, high compressibility; putting the age and performance of the pavement structure at great risk [24]. Therefore, it is important to make improvements to this type of soil, either with the incorporation of conventional or reusable materials (Shriful et al., 2022).

The stabilization of problematic soils with reusable byproducts is one of the most used procedures for the enrichment of their physical and mechanical characteristics [27]. This has increased the bearing capacity, increasing the mechanical resistance of the soil, the compressibility, durability and plasticity of the clay soil [22]. Many alternatives have been proposed as reusable industrial materials, from fly ash, silt, red mud [22]; including steel slag, the latter being the object of study for the stabilization of this investigation. The reuse of these slags would help in the elimination of these wastes and in reducing the excessive use of natural resources [9]. For Shalabi et al (2016), by using different percentages of added steel slag (0%, 15% and 30%), they demonstrate that, by increasing the steel content in clay soils, its CBR value increases and free swelling decreases. , this is why in this research a slag with different granulometry used in the research mentioned above and with different concentrations is used to determine if there is an improvement

This research is carried out with the objective of using steel slag in percentages of 5%, 15% and 25% depending on the weight of the soil, to improve the mechanical properties of subgrades in clay soils with different plasticity indices. For this, laboratory tests such as Modified Proctor and CBR will be carried out on three different samples of clay soils from the district of Chiclayo, Peru. Likewise, the maximum dry

density (MDD) and the bearing capacity (CBR) will be determined for the three types of soil in their natural state and then for the soil with the additions in different percentages.

2. Methodology

2.1. Phase 1. Characteristics of the EAF

For the investigation it was necessary to obtain samples of waste from the steel industry. The slag came from the steel company SIDERPERÚ. The type of material used was Electric Arc Furnace Slag (EAF) with an average particle size of 1/2” as shown in Fig. 1. Finally, four bags of this material were obtained, with a total of 30 kilos each bag.

- Chemical composition of EAF

The chemical components of slag are affected by various factors, such as the type of material (scrap) that is melted, handling processes, operating variables and cooling rate (Guevara, 2022). Table 1 shows the percentages of the different chemical components present in the SIDERPERU slag.

2.2. Phase 2. Collection of clay soil samples

Clay soil samples were extracted from the excavation of 3 wells. They are called "sample in its natural state." The excavation was carried out at a depth of 1.50 m. Three bags of soil of approximately 80 kilograms each were obtained from each test pit.



Figure 1. SIDERPERU steel slags.

Source: self-made

Table 1.

Chemical composition of steelmaking slag (SIDERPERÚ, 2019)

Type of slag	%Oxides	% Metals
Over , A, B, C	At ₂ or ₃	6.52
	CaO	21.58
	Ugly	30.40
	MnO	6.14
	MgO	10.62
	SiO ₂	15.81
Fine	At ₂ or ₃	6.04
	CaO	29.60
	Ugly	20.10
	MnO	4.53
	MgO	10.50
	SiO ₂	15.05

Source: SIDERPERU company, 2016

2.3. Phase 3. Characteristics of the laboratory samples

- Physical properties of the sample in its natural state.

Laboratory tests were carried out to determine the physical characteristics of the three samples in their natural state. These were carried out at the Santo Toribio University of Mogrovejo. Within this, the following was determined: granulometric analysis, moisture content, Atterberg limits; and with these data determine the plasticity index of the samples in their natural state. All found according to MTC E 109 of MTC Materials Manual Testing.

- First the water content was determined.
- Then a granulometric analysis was carried out, this would determine what type of soil would be used by the USCS and AASHTO.
- To calculate the liquid limit (LL), the sample was first mixed in a plastic container to properly homogenize it before carrying out the test. After this preparation, the resulting paste was placed in the Casa Grande glass, covering its entire surface. Using a groover, the sample was divided to begin the tapping process, following the guidelines established in the test method following the natural state given in ASTM D4318-05.
- To determine the plastic limit (LP), a small portion of the previously homogenized container was extracted where its humidity was ideal to be able to form small bars with the soil with an approximate diameter of 3.2 mm as shown in Fig. 2, that will be necessary to make the present essay. The guidelines and parameters indicated in the ASTM D4318-05 standard were followed.
- After finding the LL and PL values of each of the samples, the IP was calculated, using the following formula described by ASTM D4318-05.

$$IP = LL - LP$$

- Mechanical properties of the sample in its natural state.

To evaluate the mechanical properties of the samples, the Modified Proctor and CBR tests were carried out, which were carried out following the procedure described below:

- A total of 5000 grams of soil from each of the extracted samples (C-1, C-2, C-3) were weighed, the slag from the Electric Arc Furnace (EAF) was also weighed to add them in the percentages. of 5%, 15% and 25%, both

materials were placed together in an airtight bag to store them until the time of testing.

- Using the modified Proctor test, the MDD and the optimal moisture content of the 3 samples were determined without addition and with the addition of slag. The method used in this test was method A as indicated in the MTC Materials Testing Manual, because the material of each of the samples passed through the No. 4 sieve and there was no retention, using the mold with a diameter of 4 inches with a total of 25 strokes per layer.
- To carry out the CBR test and determine the resistant capacity of the soil as a subgrade, the following had to be carried out: the compaction of the clay sample in the CBR molds, the measurement of the expansion for a period of 4 days of each of the samples submerged in water. Subsequently, the penetration test was carried out on the samples in their natural state and with the addition of EAF.

3. Results

3.1. Clay soils in their natural state

The results of the physical characteristics of the three samples in their natural state were obtained he following results in Table 2.

Table 2.

Results of physical properties of samples in the natural state C-1, C-2 and C-3.

Samples	C-1	C-2	C-3
% water content	19.92	20.96	19.71
L.L.	43.72	51.28	45.13
LP	20.18	22.83	20.47
IP	23.54	28.45	24.66

Source: self-made

Table 3.

Soil type classification using the USCS and AASHTO Systems.

Sample	SUCS Classification		AASHTO Classification	
	Symbol	Composition	Group	Symbol
C-1	CL	Low plasticity clay of sand	A-7-6 (14)	Clay soil of oor quality
C-2	CH	High plasticity clay with sand	A-7-6 (18)	Clay soil of poor quality
C-3	CL	Low plasticity clay of sand	A-7-6 (15)	Clay soil of oor quality

Source: self-made

Table 4.

Summary of mechanical property tests of samples in their natural state.

Properties	C-1	C-2	C-3	You
MDD 95%	1,701	1,729	1,682	g/cm4
Optimum toilet content	17	16.4	18.65	%
CBR at 100%	5	4	3	%
MDD at 2.54 cm				
CBR at 95%				
MDD up to 2.54 cm	4	3	3	%

Source: self-made



Figure 2. 3.2 mm thick bars to determine the PL of C-3 clay soil samples.

Source: self-made

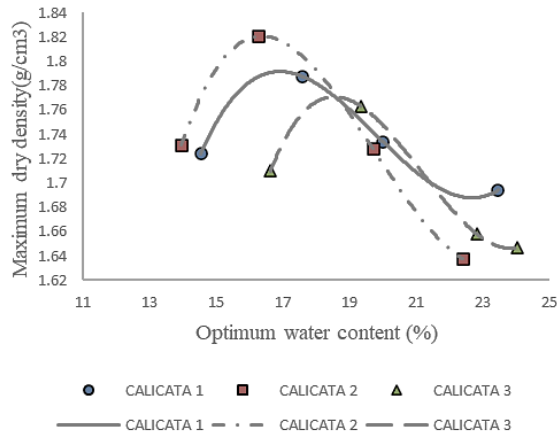


Figure 3. Modified Proctor plot of samples C-1, C-2 and C-3.
Source: self-made

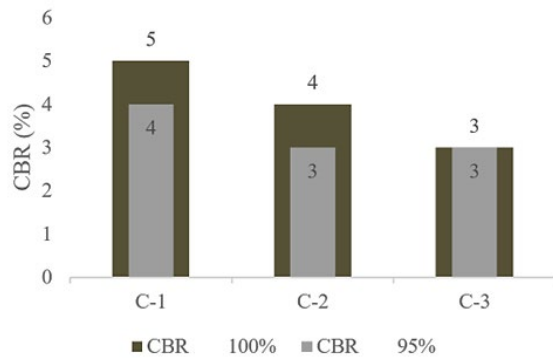


Figure 4. CBR at 1 inch (2.54 cm) penetration of raw samples C-1, C-2, and C-3.
Source: self-made

Table 5.
Maximum dry density and optimal moisture content of the experimental group of samples with addition.

Maximum dry density and optimum toilet content			
Samples	% Addition of EAF slag	Maximum dry density (g/cm ³)	Optimal Water Content (%)
C-1	5	1,792	14
	15	1,881	13.5
	25	1,921	13.2
C-2	5	1,84	15
	15	1,867	14.1
	25	1,859	14.6
C-3	5	1,786	17.6
	15	1,81	16.2
	25	1,921	13.5

Source: self-made

In addition, the soil samples were classified by the USCS and AASHTO System, as can be seen in Table 3.

In the tests to determine the mechanical properties, the maximum dry density, the optimal water content and its CBR were obtained, obtaining the following results in Table 4.

Fig. 3 shows the Modified Proctor curves of sample 3 in its natural state, relating the dry density to the optimal moisture content.

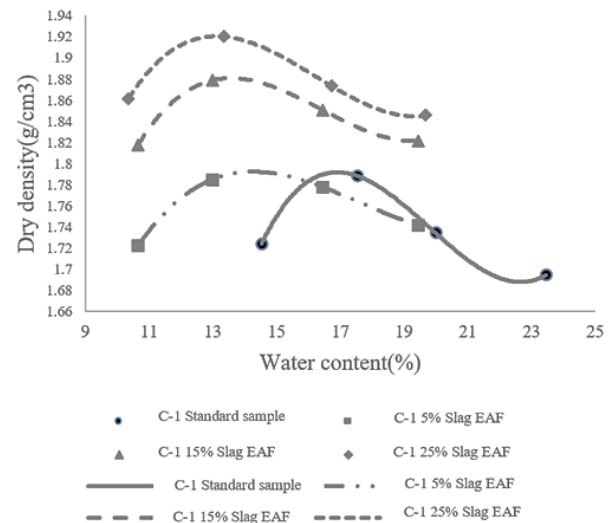


Figure 5. Modified Portfolio Graph of sample C-1 with addition of steel slag.
Source: self-made

For Fig. 4, the CBR results can be compared with the 95% and 100% of the three different natural state samples.

3.2. Clay soils with HAE

a) Maximum dry density

Below are the results to obtain the maximum dry density with the optimal moisture content for the experimental group by adding Electric Arc Furnace Slag in the doses of 5%, 15% and 25%.

Fig. 5 shows the Modified Proctor curves of C-1 with the addition of HAE slags in percentages of 5%, 15 and 25%, relating the dry density to the optimal moisture content, also showing the behavior of C-1. sample in natural state.

Fig. 6 shows the Modified Proctor curves of C-2 with the addition of HAE slags in percentages of 5%, 15 and 25%, relating the dry density to the optimal water content.

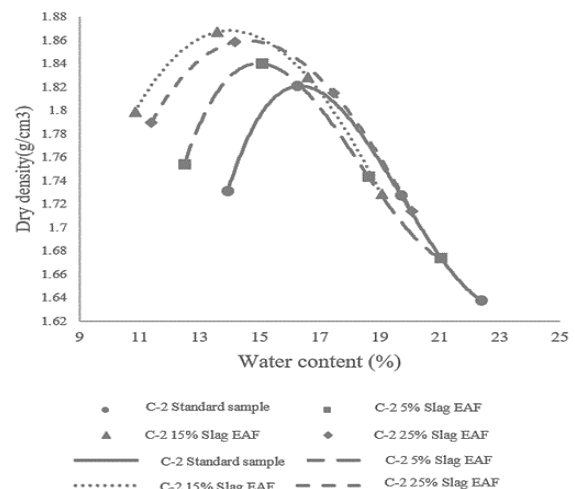


Figure 6. Modified Proctor plot of sample C-2 with addition of steel slag.
Source: self-made

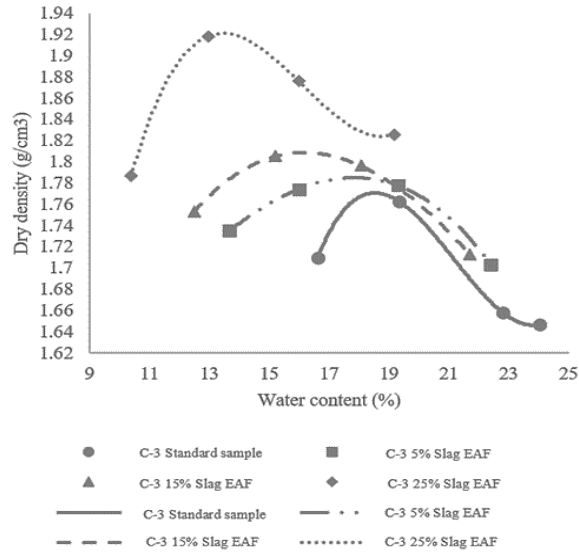


Figure 7. Modified Portfolio Graph of sample C-3 with addition of steel slag. Source: self-made

Table 6. Summary of mechanical property tests of the samples.

Properties	EAF	C-1	C-2	C-3	Und
MDD at 95%	5%	1702	1748	1687	g/cm ⁴
	15%	1787	1774	172	
	25%	1825	1766	1825	
Optimum water content	5%	14	15	176	%
	15%	135	141	162	
	25%	132	146	135	
CBR 100%	5%	6	6	7	%
MDD at 2.54 cm	15%	7	7	8	
	25%	9	9	9	
CBR 95%	5%	6	5	5	%
MDD at 2.54 cm	15%	6	6	6	
	25%	8	8	8	

Source: self-made

And, finally, in Fig. 7, the Modified Proctor curves of C-3 are observed with the addition of EAF Slags in percentages of 5%, 15 and 25%, relating the dry density to the optimal water content.

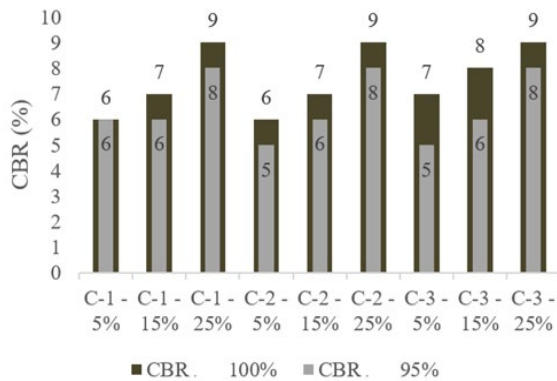


Figure 8. CBR at 1 inch (2.54 cm) penetration of C-1, C-2, and C-3 with EAF addition.

Source: self-made

a) Resistant capacity as subgrade by CBR

From the CBR test, the results are shown in Table 5 for the different clay soil samples with the addition of 5%, 15% and 25% HAE.

After the results, the CBR results can be compared with the 95% and 100% of the three samples with the different types of %EAF in Fig. 8.

4. Discussion

In the results, it was obtained that the moisture content of the samples in the natural state for C-1, C-2, C-3 was 19.92%, 20.96%, 19.71% respectively, as shown in Table 1. In addition, having found the LL and PL, the IP of all the samples was determined, with results of 23.54, 28.45 and 24.66, this characteristic is only shown by very clayey soils.

On the other hand, in the case of clay soils with the addition of electric arc furnace slag (EAF), the mixture with an addition of 25% of EAF achieved an DDM of 1,921 g/cm³ with an optimal moisture content of 13.2%, as shown in Table 6. If sample C-1 in natural state is compared to samples C-1 with FAE, an increase in MDD can be observed from 1.701 g/cm³ to 1.921 g/cm³ with 25% incorporation of EAF, which represents a notable improvement of 13%.

In the case of sample C-2, it is observed that with the 25% EAF mixture, a DDM of 1,859 g/cm³ was achieved with an optimal moisture content of 14.6%, as shown in Table 6. In comparison with for the sample in the natural state C-2, there is a variation in the maximum dry density from 1.729 g/cm³ to 1.867g/cm³, which represents a variation of 8%.

Table 6 also presents the results corresponding to sample C-3 with the sum of different percentages of FAE. With an addition of 25% HAE, a DMD of 1,921 g/cm³ was achieved with an optimal moisture content of 13.5%. It is interesting to note that the increase in MDD between sample C-1, C-2 and C-3 with the addition of 25% FAE has the best results.

The CBR of the samples in the natural state gave results, the C-1 for 2.54 cm (1 in.) of penetration had that the 100% CBR is 5%, while the 95% CBR is 4%. For C-2 for 2.54 cm (1 in.) of penetration the 100% CBR had to be 4%, while the 95% CBR was 3%. Finally, C-3 for 2.54 cm (1 in.) of penetration had the 100% CBR is 6%, while the 95% CBR is 3%. In the subgrade categories of [15], it is mentioned that, if the CBR is less than 3%, this subgrade will be considered inadequate and when it is between 3% and 6%, it will be insufficient. Therefore, the natural samples taken in the investigation are inadequate and insufficient to be used as subgrade.

The 95% and 100% CBR results for 1 inch of the raw samples and the EAF samples can be seen in Fig. 4 and Fig. 8. For sample C-1, when it has no addition of EAF, it presents 100% CBR. 5%, while 95% CBR is 4%; when %EAF is added, the one that shows best results is 25% EAF, with 100% CBR of 9%, while 95% CBR is 8%. This improvement persists in samples C-2 and C-3 with the addition of 25% EAF. For the MTC Testing Manual (2016), the CBR performed with the maximum addition of 25%, they are

between 6% and 10%, considered usable for regular subgrades. These results, being from clay soils, improve their conditions from inadequate and insufficient to adjustable to be worked.

For [30], in his research with residual steel slag added at 0%, 3%, 5%, 7% and 10%, in expansive soils, he indicated that the CBR increases with a higher % slag content, reaching 12 % CBR, with 10% steel slag added; satisfying the requirements as a road subbase according to the Chinese natural state. [22] carried out their study with 0%, 5%, 10%, 15%, 20%, 25% and 30% of slag additions as replacement for clay soils; showing you that as the slag content of steel increases, the CBR value increases.

The results obtained from the present investigation showed an improvement of up to 14% in the CBR of the clay soil with 25% EAF, making it the best mixture and making the soil suitable for subgrade.

5. Conclusions

An investigation was carried out into the potential of EAF slag, a by-product of the steel industry, for use in the modification of clay soils. The basic physical properties of the samples were evaluated in their natural state, including moisture percentage and plasticity index (PI). In addition to calculating the mechanical properties of the sample in the natural state and with the addition of EAF, such as the Maximum Dry Density (MDD), California Bearing Ratio (CBR and the optimal % of water), to understand the engineering behavior and the mechanism microstructural of the treated soils. The main results of this research are presented below.

1. The soil samples in their natural state (C-1, C-2 and C-3) were classified by USCS and AASHTO, demonstrating that they are considered low plasticity clay, sand and poor-quality clay soil, respectively. In addition, it was determined that the moisture content in the samples in the natural state for C-1, C-2 and C-3 was 19.92%, 20.96% and 19.71%, with a plasticity index of 23.54%, 28.45% and 24.66, respectively, resulting in a clay soil with high plasticity.
2. The Maximum Dry Density (MDD) of the samples in the natural state C-1, C-2 and C-3 had an increase of 7.26%, 2.14% and 8.53%, respectively, when adding 25% of EAF. Regarding the optimal moisture content, there was a decrease of 22.35%, 10.98%, 27.61%, respectively.
3. Sample C-1 with 25% EAF at 2.54 cm (1 in) of penetration, had a 100% CBR value of 9%, showing an 80% increase over its natural state sample C- 1, while sample C-1 95% is 8% with an increase of 100%.
4. Sample C-2 with 25% EAF at 2.54 cm (1 in) of penetration, had a 100% CBR value of 9%, showing a 125% increase over its natural sample C- 2, while sample C-2 with 95% is 8% with an increase of 167%.
5. Sample C-3 with 25% EAF at 2.54 cm (1 inch) penetration had a 100% CBR value of 6%, showing a 50% increase over its Sample C -3 in natural state, while sample C-3 at 95% is 8% with an increase of 167%.
6. According to the MTC Testing Manual (2016), the CBR obtained with the maximum addition of 25% are between 6% and 10%, considered usable for regular subgrades. These results, being clay soils, improve their conditions from inadequate and insufficient to adjustable to be worked.
7. Reusable materials can be used in the stabilization of clay soils, presenting improvements according to an optimal % of their addition to the normal soil used in subgrades.

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Structuring of an energy requirements guide for the feasibility study of private investment projects

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Abstract

The energy load requirements demanded to the network operator of the department of Huila are supplied according to corporate guidelines; but under the responsibility of the user, despite his technical-legal ignorance and the absence or inadequate technical advice, with the consequent irregularities in connections and, in fact, with economic and financial affectations. The analysis of this problem, with an exploratory scope, is approached with a quantitative and qualitative focus, which is deepened by means of the multiple case study strategy. In this way, an energy requirements guide and a tool, applicable during the phase prior to the load requisition, which allow to dynamize and improve the decision making process from the project management and the private investor.

Keywords: electrical load; network operator; electrical connection; decision making.

Estructuración de una guía de requerimientos energéticos para el estudio de viabilidad de proyectos de inversión privada

Resumen

Los requerimientos de carga energética demandados ante el operador de red del departamento del Huila son suministrados según las pautas corporativas; pero bajo la responsabilidad del usuario, pese a su desconocimiento técnico legal y la ausencia o inadecuada asesoría técnica, con las consecuentes irregularidades en conexiones y, de hecho, con afectaciones económicas y financieras. El análisis de esta problemática, con alcance exploratorio, se aborda con un enfoque cuantitativo y cualitativo, el cual se profundiza mediante la estrategia de estudio de caso múltiple. De este modo se estructura una guía de requerimientos energéticos aplicables durante la fase previa a la requisición de cargas, que permiten dinamizar y mejorar el proceso de toma de decisiones desde la gerencia de proyectos y del inversionista privado.

Palabras clave: carga eléctrica; operador de red; conexión eléctrica; toma de decisiones.

1. Introducción

El estudio tiene como objetivo, elaborar una guía para mejorar la toma de decisiones gerenciales relacionadas con el proceso de requisición de cargas eléctricas con destino a proyectos de inversión privada. En efecto, se precisa caracterizar demanda, determinar el proceso establecido por el operador de red, como también, identificar las diversas afectaciones por inadecuadas conexiones. De esta manera, se

hace énfasis en superar los vacíos de conocimiento de la norma técnico legal vigente en Colombia y la carencia o deficiente asesoría técnica, factores que constituyen importantes antecedentes de conexiones irregulares y de afectaciones de orden económico y financiero.

Para tal efecto, se toma como referente el operador de red del departamento del Huila, que se limita a suministrar las cargas requeridas bajo la responsabilidad del usuario, previo cumplimiento del protocolo corporativo establecido.

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De otra parte, se abordan los efectos políticos del ámbito internacional, nacional y departamental, debido a que se favorece el cumplimiento de normas técnicas y objetivos gubernamentales del sector eléctrico. Asimismo, se adiciona el impacto del orden académico.

1.1 Ámbito internacional

Contribuye a la difusión y aplicación del *National Electrical Code Handbook* (NEC), Código Eléctrico Estandarizado de los Estados Unidos (adoptado por diversos países, incluido Colombia) que suministra información técnica precisa para salvaguardar las personas y los bienes de los peligros derivados del uso de la electricidad. Además, reúne estándares, prácticas recomendadas y guías de la *National Fire Protection Association* (NFPA) que son normas de seguridad para el control de incendios [1].

1.2 Ámbito nacional

Aporta a la implementación de la Agenda de Desarrollo Sostenible, Industria, Innovación e Infraestructura, en su objetivo de: «Construir infraestructura resiliente, promover la industrialización inclusiva y sostenible y fomentar la innovación». De esta forma se tienen en cuenta las pequeñas y medianas empresas dedicadas al procesamiento industrial y la producción manufacturera que son las mayores generadoras de empleo. En el mundo, su participación en el mercado es mayor al 90% y en generación de empleo, entre el 50 y el 60% [2].

Igualmente, se coopera en el cumplimiento del Plan Estratégico de la Unidad de Planeación Minero Energética, UPME 2018-2022 en su objetivo de financiar, con recursos públicos y privados, el incremento de 180.000 usuarios nuevos del servicio, a través del diseño e implementación de un modelo para la ejecución de proyectos de acceso a energía eléctrica [3].

1.3 Ámbito departamental

Se apoya la propuesta del Plan de Desarrollo Departamental 2020-2023 «Huila crece» en su empeño de ejecutar obras eléctricas rurales y urbanas para mejorar la calidad de vida de la población que, en efecto, favorece el desarrollo de los diferentes sectores económicos [4].

De otra parte, se incentiva la formación de cultura ciudadana, en el sentido de buscar asesoría técnica idónea para evitar o minimizar riesgos, en su mayoría irreparables, que comprometen la vida y la salud humana, animal, vegetal y del medio ambiente; como también, la vida útil de los activos del proyecto y la supervivencia de las empresas.

1.4 Ámbito académico

Desde la perspectiva académica, se aplican conocimientos, métodos y experiencias compartidos en la Maestría en Gerencia Integral de Proyectos, entre otros, los relacionados con el proceso de toma de decisiones, el cual se

aborda como parte del modelo directivo asociado a la estructura organizacional y conlleva a la eficacia de la gestión gerencial.

A partir del contexto descrito y de las limitaciones de antecedentes de investigación y de los procesos desarrollados por operadores de red del orden nacional y multilatinos, que operan en el país. En este sentido, se evidencian, tres aspectos relevantes:

En primer lugar, el carácter técnico de las guías, como: el manual técnico europeo referenciado en las normas de la Comisión Electrotécnica Internacional (IEC) [5]; el *Electrical Pre-Construction Planning Process*, modelo de proceso de planificación eléctrica [6]; y el *Electrical Project Management Process, Implementation Manuals*, modelo de buenas prácticas de gestión de proyectos exitosos de la industria de la construcción eléctrica [7].

En segundo lugar, se tienen dos proyectos académicos orientados a procesos de proyectos energéticos para mejorar indicadores de gestión [8,9]

En tercer lugar, los procesos de requisición de cargas de las empresas que operan en el país son similares y se enmarcan en el cumplimiento de la normatividad técnico legal vigente.

En virtud de lo anterior, el presente estudio explora una alternativa de apoyo a la gestión gerencial, orientada a investigar: ¿Cómo facilitar el proceso de toma de decisiones gerenciales relacionadas con las requisiciones de cargas energéticas en proyectos de inversión privada, ante el operador de red del departamento del Huila?

2. Materiales y métodos

Con el fin de abordar esta problemática se aplicó un enfoque mixto, con alcance exploratorio, descriptivo y de orden aplicativo [10] que tiene como objetivo dar resolución a un problema del sector productivo a través de la aplicación de conocimientos [11]. Asimismo, se enmarca dentro de la estrategia de estudio de caso múltiple, que permite profundizar en el análisis de la situación problema [12].

Para tal efecto, se seleccionaron cinco casos de estudio que se identifican con experiencias de solicitud de cargas eléctricas por parte de inversionistas de proyectos privados, ubicados en la zona norte del Departamento (Tabla 1), dominio geográfico donde se encuentra más de la mitad del total de los usuarios.

Tabla 1.
Composición de usuarios por zonas, municipios, sedes y participación

Zona	Municipios	Sede	Usuarios	%
Norte	15	Neiva	219.438	52,16
Centro	8	Garzón	62.992	14,97
Oriente	5	La Plata	39.276	9,34
<u>Sur</u>	9	Pitalito	98.996	23,53
<u>Totales:</u>	37		420.702	100,00

Fuente: Elaboración propia con base en datos de ELECTROHUILA, 2021 [13].

Para obtener la información se accedió a fuentes primarias y secundarias, con apoyo en técnicas de recolección de información, como: la entrevista en profundidad y la observación no participante, complementada con la revisión documental de informes, guías y manuales técnicos de los operadores de red y del sector eléctrico, al igual que, la normatividad técnico legal vigente.

El análisis de los hallazgos se realizó mediante triangulación de la información. De este modo, se estableció un referente de necesidades y se diseñó un perfil de requerimientos de carga para proyectos privados, el cual es apto para aplicar en otros ámbitos geográficos.

Es necesario precisar que, el concepto básico de la investigación puede aplicarse a todos los operadores de red del país, teniendo en cuenta las tarifas propias de cada prestador del servicio y en forma exclusiva, dirigido a la categoría de monousuarios.

Como parte del manejo ético de la información suministrada por los inversionistas participantes en el estudio, se solicitó y aplicó un consentimiento informado, con el compromiso de que el uso de esta se hace con fines académicos.

3. Resultados

La elaboración de la guía propuesta supone el cumplimiento de tres fases, las cuales corresponden al desarrollo de los objetivos específicos.

3.1 Caracterización de la demanda por cargas

Del total de usuarios del operador de red, ELECTROHUILA, ubicados en el departamento del Huila, alrededor del 50% (Fig. 1) pertenecen a la zona norte.

Del total de usuarios ubicados en la zona norte del Departamento (Fig. 2), durante el periodo 2017-2021, un alto porcentaje (89-98%), demandan cargas con nivel de tensión de 13,8 kV y potencia entre 45-150 kVA.

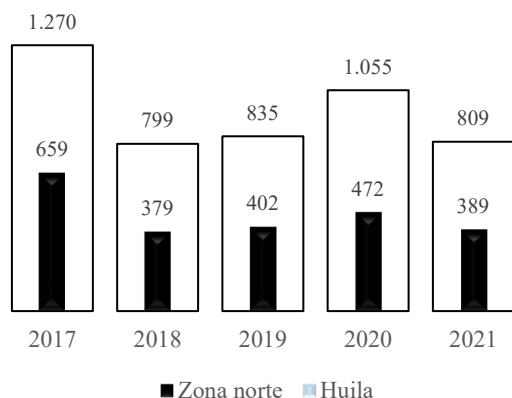


Figura 1. Composición de usuarios ELECTROHUILA.
Fuente: Elaboración propia con base en datos del Sistema Único de Información de Servicios Públicos Domiciliarios, 2023 [14].
Nota. Los datos de 2021 corresponden al primer semestre.

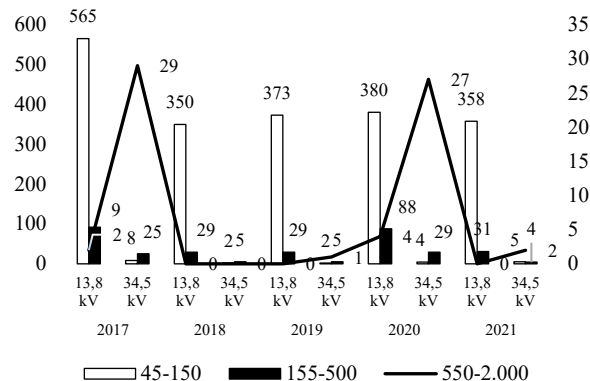


Figura 2. Composición de clientes zona norte por cargas y tensión.
Fuente: Elaboración propia con base en datos del Sistema Único de Información de Servicios Públicos Domiciliarios, 2023 [14].
Nota. Los datos de 2021 corresponden al primer semestre.

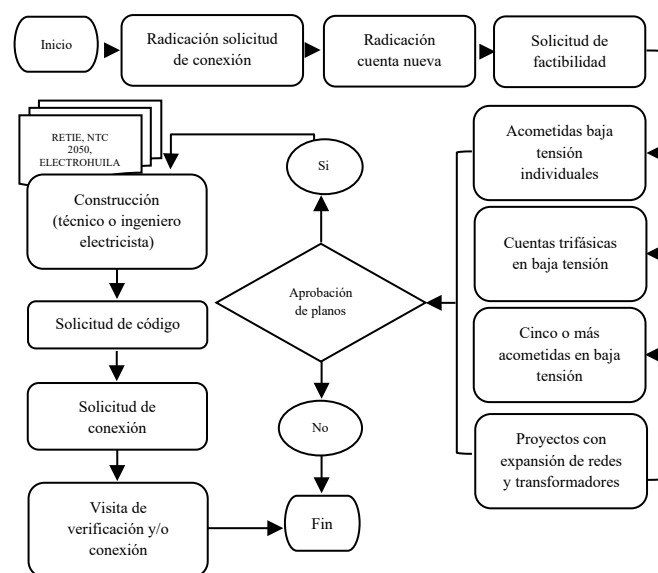


Figura 3. Flujograma proceso de requisiciones de cargas ELECTROHUILA.
Fuente: Elaboración propia con base en datos de ELECTROHUILA (s.f.) [15].

3.2 Proceso de solicitud de cargas ante ELECTROHUILA

Las actividades a realizar para el proceso de solicitud de cargas se estipulan en la Guía de conexión de cuentas nuevas y nuevos proyectos (Fig. 3), expuestas en la plataforma del operador de red.

3.3 Entrevistas a empresarios

Los cinco casos de estudio corresponden a empresas del sector agropecuario industrial, ubicadas en la zona norte del Departamento, según la distribución geográfica del operador de red, ELECTROHUILA.

3.3.1 Empresa piscícola

Empresa productora, procesadora y comercializadora de carne de pescado, ubicada en el municipio de Rivera y con nueve años de antigüedad.

La demanda de carga es de 13,8 kV y consumo mensual de carga es de 150.000 kWh y, acerca de la experiencia de requisición de cargas, dice que fue «patética... desastrosa» y añade: «lamentablemente es una empresa totalmente politizada»; duró seis meses haciendo el trámite para una nueva conexión mientras que otra, la realizó en 20 días. De hecho, esta demora le impidió incrementar la producción, y por lo tanto, aumentar sus ingresos. Alude que, el operador de red: «no presta ningún tipo de acompañamiento ni de asesoría ni hacia el tipo de canje que usted debe tener ni cómo debe hacer, ni bajo la forma como (...), nada, absolutamente nada». Asimismo, enfatiza que los empresarios desconocen las normas técnicas y que el trámite es insostenible: «porque hay un tema de cumplimientos de una cosa que se llama el RETIE que lo exigen (...) pero yo realmente no tengo problema con el RETIE, yo tuve problema (...) en la parte documental». De otra parte, recomienda: «...me parecería regio (...) que existiese ese tema de acompañamiento de la compañía, uno (...) y dos (...) sería muy bueno que uno pudiese tener la oportunidad de tener alternativas, pero lamentablemente no existen».

En cuanto a los incentivos por ser usuario regulado dice: «No, no, no, ni idea... y si los hubo nunca los vi». Sin embargo, sabe que tiene: «disminución en tarifa... puedo acceder al descuento de la contribución... a nivel local, el tema del alumbrado público es un impuesto municipal y eso yo lo puedo conseguir acá como minucia y acá lo hicimos».

3.3.2 Empresa piscícola

Esta empresa con sede en el municipio de Campoalegre y con nueve años de antigüedad, se dedica a la producción y comercialización de pescado con destino al mercado local y nacional.

La demanda de carga es de 13,8 kV y la potencia de 20 a 25 kWh y, pese a que tuvo asesoría para la requisición de la carga, dice: «los empresarios que están en la misma línea nuestra de piscicultores, no tienen conocimiento y el alcance que tiene es muy limitado para nosotros tomar las decisiones; no hay información realmente, ante todo, de beneficio». Sobre la información suministrada por el operador de red, afirma: «no, no fue clara, no fue claro porque después de cinco, seis años, supimos que había otras alternativas por pertenecer a un canal de riego y había otras bondades económicas que nos podía dar la red».

En cuanto a la parte técnica, es muy reiterativo: «no presta esa asistencia técnica; no hay manuales específicos que usted se oriente y que sea entendible a cualquier nivel de conocimiento y educación». «...lo ideal es que el ente distribuidor tenga alguien dedicado para que preste ese tipo de asesorías directamente y asistencia técnica en campo... cuantificando beneficios para ver qué tan viable o qué tanto le ayuda la viabilidad de su proyecto».

De los beneficios tributarios desconoce que tiene derecho a estos por tener un predio inferior a 50 hectáreas y por pertenecer a un distrito de riego. Además, paga la tasa del 20% de compensación para los negocios de distribución y tampoco

ha hecho efectivo el descuento tributario del 50% por la actividad económica que realiza.

3.3.3 Empresa molinera

La actividad agroindustrial de esta empresa, fundada hace tres años, es la producción de productos de molinería en la zona industrial de Neiva.

De su experiencia con el tema de conexión, refiere: «...no tiene uno como la noción de cuál es la necesidad técnica... no hay información... el único relacionamiento que tiene uno con, con el fluido eléctrico es que uno prende el switch en la casa y ahí prende el bombillo». También, reconoce su complejidad: «conversamos de vez en cuando con varios amigos empresarios y todos coincidimos en que, en cuanto a temas eléctricos todos los costos son de alto nivel y todos los tiempos y planes para un proyecto eléctrico pues son complejos...».

Respecto a la información requerida para conexiones eléctricas, afirma: «...el único contacto que uno tiene como usuario con el prestador del servicio de energía es la llegada del recibo mensual, de resto sé que hay canales de comunicación de servicio al cliente, pero no tengo conocimiento que haya canales especializados para asesoría técnica».

Del conocimiento de la norma técnico legal, destaca: «no, definitivamente no, siempre hay que contar con un ingeniero eléctrico experto... como empresarios no conocemos la norma técnica y necesariamente hay que asesorarse de alguien experto». Además, cree que el operador de red debería prestar asesoría integral al cliente, desde el diseño hasta la puesta en marcha del proyecto; no obstante, considera importante tenerla durante el desarrollo del mismo: «(...) somos una industria, yo puedo hacer un montaje para procesar x toneladas de materia prima, pero en algún momento puedo decir: esto es insuficiente, necesito ampliar o cambiar mi maquinaria... entonces, qué tengo que replantear de mi sistema eléctrico actual (...)».

Aunque es consciente de que su proyecto demanda permanente mantenimiento eléctrico, este empresario, al igual que los demás entrevistados, no recuerda cuál fue el monto de la inversión en esta fase, como tampoco, a cuánto ascendieron las pérdidas por un inconveniente relacionado con el suministro de energía reactiva.

Por último, niega conocer los incentivos tributarios de los que es beneficiario: «(...) no, absolutamente nada; (...) la única comunicación que yo tengo realmente con mi prestador de servicio, es el recibo (...) y es una comunicación en una sola dirección, es lo que ellos me comunican a mí por medio del recibo».

3.3.4 Trilladora de café

Esta empresa, perteneciente a la industria del café, tiene 28 años de tradición y está ubicada en la ciudad de Neiva; cuenta con tecnología para el beneficio, selección y clasificación del grano tipo supremo o excelso. Su capacidad

de producción es de 16.000 a 18.000 libras mensuales; además, es exportadora del grano, 100% huilense.

La demanda de carga eléctrica es de 13,8 kV y el contar con equipos ahorradores de energía, le permiten mantener estable el consumo y mitigar los altos costos del servicio. El inversionista heredero, cree importante contar con asesoría técnica para tomar decisiones relacionadas con los requerimientos de conexión eléctrica. Asegura que, si en su momento la hubiera tenido su padre, posiblemente estuvieran conectados a una carga de mayor tensión.

En cuanto al conocimiento de la norma técnica, dice que no es muy conocedor de esta. A quien vaya a hacer una inversión, le recomienda: «(...)que investigue muy bien (...), que conozca todas las opciones... desde energías renovables hasta los diferentes niveles de tensión; que tenga muy claro los pros y los contras (...) antes de tomar una decisión definitiva (...), planteándose una proyección (...)».

Para finalizar, resalta la importancia de disponer de asesoría técnica siempre, con el fin de tener un consumo eficiente y minimizar los costos de producción.

3.3.5 Empresa avícola

Esta empresa opera en la zona industrial de Neiva desde hace seis años; su actividad económica es la cría de aves de corral y de pollo de engorde.

Inicialmente, tuvo un transformador de 75 kVA, pero por innovación en la maquinaria requirió uno de 150kVA. Aunque tuvo asesoría técnica, de su experiencia al solicitar la conexión, recuerda: «...no, no es fácil, es bastante engorroso... no es ni siquiera desinformación, sino que le colocan muchas trabas, ...se bregó y es demorado...». Además, cree que los empresarios desconocen tanto de la norma técnica como de los requerimientos de conexión; en su caso, le hubiera gustado estar debidamente informado.

Asimismo, cree que el operador debería dar asesoría, incluso, hacer el montaje del sistema. A los nuevos emprendedores les recomienda: «llenarse de paz, llenarse de paciencia... intentar rodearse muy bien porque, se escucha

bastante de gente que, después termina con un problema porque no hicieron el RETIE bien; no cumplieron y ya uno ha pagado casi todo».

En cuanto a asesoría técnica, adicional a la del operador de red, cree oportuno una revisión anual: «para ajustar, para corregir ciertas cosas que puedan después resultar en un accidente... pues, un accidente puede generar un incendio bien tremendo y con un costo bien, bien bravo».

A pesar de sus experiencias estresantes y pérdidas no cuantificadas, al igual que los otros empresarios, no ha pensado en desistir de su actividad: «...todo es electrónico y muchos bajones...; ...quitan la energía, cuando la conectan, conectan en una línea diferente y los aparatos electrónicos no me trabajan... se me han quemado cosas y yo no puedo parar y nadie le responde».

Establece que, el acompañamiento técnico para la solicitud e instalación de la conexión es: «fundamental porque hay mucha burocracia en la electrificación... mejor dicho primero se lo come a uno el banco, antes que el proyecto salga adelante».

Para concluir, comenta que, si el mercado ofreciera más operadores de red, tendrían poder de negociar tasas competitivas y escoger la mejor opción de servicio.

3.3.6 Consolidación de la información

Pese a que, en un estudio de casos múltiple no se tiene el propósito de hacer generalizaciones estadísticas (enumerar frecuencias); sino hacer generalizaciones analíticas, en virtud de que cada caso es único y de interés para la investigación [12]; como parte del presente estudio, se consolidaron las características de las cinco empresas seleccionadas (Tabla 2), con el fin de tener una visión de conjunto del problema examinado ya que se trata de una población con atributos similares en lo relacionado con el nivel de tensión, tipo de proyecto, tipo de usuario, beneficios y subsidios según la normatividad legal vigente en Colombia. En este sentido, la excepción se encuentra en la Piscícola 2, por tratarse de un proyecto con categoría especial.

Tabla 2.
Caracterización empresas seleccionadas.

Empresas	Nivel de Tensión (kV)	Capacidad Instalada (KVA)	Tipo de Proyecto	Tipo de Usuario	Beneficios y subsidios	Normatividad
Piscícola 1	13,8	400	Industrial	No Regulado	50% descuento en la sobretasa y factor de comercialización	Artículo 211 del Estatuto Tributario, Resolución CREG 131 de 1998, artículo 1
Piscícola 2	13,8	45	Especial	Regulado	50% descuento costo de KW	Artículo 75. Modifíquese el artículo 80 de la Ley 633 de 2000
Molinera	13,8	500	Industrial	No Regulado	50% descuento en la sobretasa y factor de comercialización	Artículo 211 del Estatuto Tributario, Resolución CREG 131 de 1998, artículo 1
Trilladora de café	13,8	300	Industrial	No Regulado	50% descuento en la sobretasa y factor de comercialización	Artículo 211 del Estatuto Tributario, Resolución CREG 131 de 1998, artículo 1
Avícola	13,8	150	Industrial	No Regulado	50% descuento en la sobretasa y factor de comercialización	Artículo 211 del Estatuto Tributario, Resolución CREG 131 de 1998, artículo 1

Fuente: Elaboración propia.

3.4 Guía de requerimientos energéticos

Establecidas y analizadas las necesidades de información, se estructuró la guía de requerimientos energéticos para el estudio de viabilidad de proyectos de inversión privada, útil en la fase previa a la requisición de cargas ante el operador de red.

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Para dar mayor sustento a la toma de decisiones gerenciales, y a su vez, facilitar su operacionalización, se diseñó el flujograma del proceso (Fig. 4), el cual se nutre a partir de datos elementales y de interés para el análisis técnico y financiero del proyecto, de conformidad con los componentes que se relacionan a continuación:

- Nivel de tensión: 13,8 kV o 34,5 kV
- Carga proyectada según el transformador: desde 45kVA hasta 2.000 kVA
- Tipo de proyecto: industrial, comercial o especial
- Dominio geográfico del proyecto: urbano o rural
- Tipo de medición: directa, semidirecta e indirecta.

3.4.1 Análisis técnico económico y financiero

En este apartado se tuvieron en cuenta los costos relacionados con el tipo de conexión para monousuarios [32,33], los cuales incluyen:

- Costo por redes de conexión: compuesto por el costo por kilómetro de red más el costo del transformador, bajo un análisis de precios unitarios.
- Beneficios y subsidios: corresponde al 50% del valor de la sobretasa o contribución especial (del 20%), descontable del impuesto de renta.

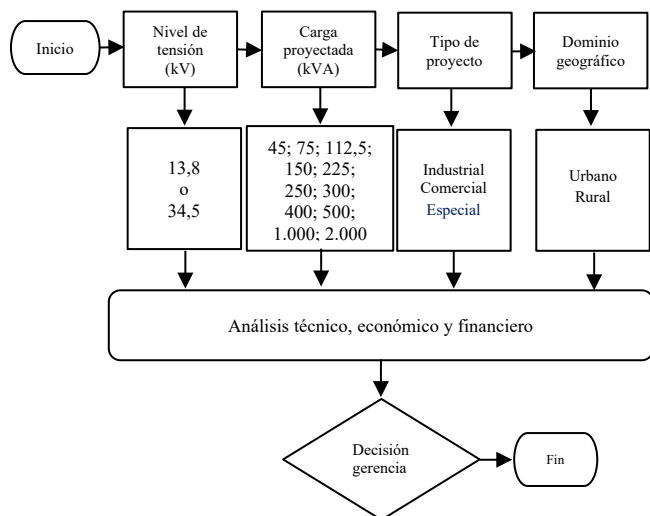


Figura 4. Flujograma fase previa a solicitud de cargas ante el operador de red. Fuente: Elaboración propia.

- Costos totales por redes de conexión: equivale a la sumatoria del costo del kilómetro de red más el costo del transformador, para cada una de las redes de media tensión trifásicas ofertadas por el operador de red.
- Consumo total de carga mensual: valor en KWH/mes, consumidos.
- Consolidado de costos por tipo de medición (directa, semidirecta e indirecta): incluye el costo mensual y anual de la carga, más los beneficios y subsidios.
- Comparativo de costos de inversión según el tipo de medición: incluye el costo anual del consumo, la diferencia del equipo de medida, el beneficio tributario y el subsidio que aplica solo para la categoría de usuario especial.
- Valor del retorno de la inversión en años y por tipo de medición semidirecta e indirecta (ofrecidas por el operador de red), con sus respectivos beneficios y subsidios.

De este modo, los diferentes aspectos analizados, constituyen un perfil para la toma decisiones gerenciales, dentro del proceso de solicitud de carga eléctrica ante el operador de red.

4. Discusión

Los cinco proyectos de estudio de casos pertenecen al sector agropecuario e industrial, con requerimientos de cargas eléctricas de 13,8 kV, atributo que los identifica en la categoría de usuarios no regulados y con derecho a ciertos beneficios tributarios:

- Estar exentos del pago por pérdidas de energía, debido a que se encuentran en el punto de conexión (frontera comercial); además pueden negociar la tarifa comercial por kW/hora [16].
- Descuento del 50% de la sobretasa o contribución especial, aplicada, entre otros, al sector eléctrico (20% del costo de prestación del servicio), por pertenecer, su actividad económica, al sector agropecuario e industrial [17].
- Subsidio del 50% en el costo de la energía por pertenecer a un distrito de riego y tener una propiedad inferior a 50 hectáreas [18].

Los empresarios, excepto la trilladora de café (el actual representante no experimentó este proceso), coinciden en que la solicitud de cargas ha sido muy difícil y demorada. Hay total desconocimiento de los requerimientos, no fueron informados adecuadamente, desconocen la norma técnica y los beneficios a que tienen derecho; dos de ellos dicen que hicieron efectivos los incentivos, no en su totalidad, después de seis y nueve años de funcionamiento.

Las afectaciones de carácter técnico, económico y financiero, por conexiones a cargas eléctricas inadecuadas, como también, las relacionadas con el alto costo del kilovatio/hora, les han generado serios inconvenientes, desde la etapa previa, la puesta en marcha y el desarrollo de las operaciones. Además, todos son conscientes del alto impacto

generado en los costos de producción. No obstante, ninguno ha cuantificado las pérdidas, pero sí las ha cualificado en: demoras en la puesta en marcha o en el incremento de la producción, los daños de los equipos y el consecuente incumplimiento de obligaciones económicas y financieras.

Finalmente, todos coinciden en la importancia de contar con asesoría técnica eléctrica para la requisición de conexión, desde la fase previa hasta la ejecución del proyecto, e incluso, creen que este servicio, en forma integral y sin costo adicional, debiera ser prestado por el operador de red a sus clientes.

Para estructurar la guía se tuvo en cuenta que este documento cumple diversos objetivos: orientar y establecer pautas para desarrollar una o más actividades de un proceso o procedimiento [19]; ser importante en el control de procesos y la optimización del tiempo de las tareas [20]; describir de manera sistemática las instrucciones, bases o procedimientos para realizar una actividad [21]; estar relacionado con la aplicación de técnicas de mejora continua [22]; también, servir de apoyo para coordinar, comunicar y transmitir instrucciones, lineamientos, conocimientos y experiencias para la ejecución de tareas [23, 24]; como también, hacer parte de la comunicación formal, debido a que consolida conocimientos de la empresa y documenta la formación del talento humano [25].

En tanto, la toma de decisiones es definida por todos los autores como un proceso que está presente desde el origen de un proyecto [26] y con un alto nivel de complejidad por el carácter global del entorno empresarial: la mala gestión de requisitos por decisiones deficientes es la segunda causa de fracaso en los proyectos después de la comunicación ineficaz [27]. Adicionalmente, para su conceptualización se rescata el modelo de la racionalidad limitada de Herbert Simon (Fig. 5), que es caracterizada con la insuficiente información, la complejidad de los problemas, el límite de la capacidad humana, el límite de tiempo y el conflicto de intereses [28]. Del modelo de Mintzberg, Raisinghani & Theoret se destaca la importancia del concepto técnico, previo a la elección administrativa [29]. No obstante, los esfuerzos investigativos, es imposible preconcebir normas, políticas y estrategias para alcanzar los objetivos, en virtud de los diversos modelos de decisión. En este sentido, lo más indicado es tener una referente de pasos a seguir y que pueda adaptarse a un caso particular, a partir de información y consultas a expertos, puesto que, el análisis cuantitativo nunca reemplazará al talento humano [30], pese a que implica emitir un juicio sobre la adopción de un riesgo [31].

En efecto, la guía aporte del presente ejercicio académico y antecedentes para futuros desarrollos, se construyó a partir de herramientas cualitativas orientadas por expertos y conocedores de la situación problema. No obstante, son susceptibles de valiosas mejoras, con el fin de posicionarlas como herramientas que apoyen el proceso de toma de decisiones, desde la gerencia de proyectos privados y públicos, teniendo en cuenta las dinámicas del mercado y las necesidades y exigencias del sector eléctrico.

De otra parte, esta investigación genera una oportunidad de mejoramiento y corrección de debilidades por parte del operador de red, en el sentido de evidenciar la necesidad de

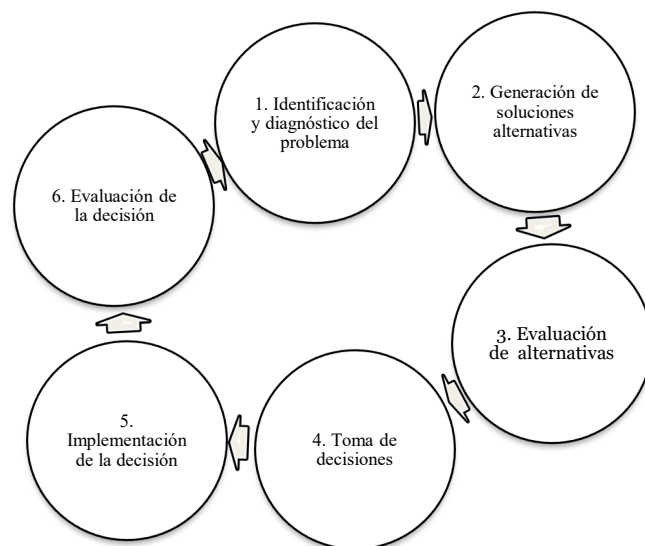


Figura 5. Etapas del proceso de toma de decisiones.

Fuente: Elaboración propia con base en datos de Bateman T & Snell S. [28].

establecer canales de comunicación con sus clientes, más allá de enviarles una factura bimestral, como lo expresó alguno de ellos. De igual manera, tener más apertura hacia los trabajos académicos, debido a que estos se realizan exclusivamente con tales fines y pueden producir significativos alcances para optimizar su desempeño corporativo.

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Comparative technical analysis of the current state of small-scale mining titles in California, Santander, Colombia

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Abstract

The mining activity developed in California, Santander municipality, has been mainly subsistence or small-scale, rooted in its ancestral heritage. According to the current regulations in the country, conducting mining activities requires obtaining a concession contract, a mining title, and the necessary licenses, such as the environmental license. The last one has caused setbacks in the mineral extraction process due to outgoing regulations, such as the delimitation of the Santurbán moorland and the prohibition of mercury use. This document aims to analyze the current state of certain mining operations in the area, provide recommendations, and establish a technical baseline for the addressed titles for future work.

Keywords: artisanal mining; mining title; moorland delimitation; metallurgical recovery; PTO.

Análisis técnico comparativo del estado actual de títulos mineros de minería a pequeña escala en California, Santander, Colombia

Resumen

La actividad minera que se realiza en el municipio de California, Santander, ha sido en mayor medida de subsistencia o a pequeña escala, partiendo de la ancestralidad de la misma. Con la normativa presente en el país, para llevar a cabo la actividad minera, es necesario contar con la obtención de un contrato de concesión, título minero y con ello, los debidos licenciamientos, como lo es la licencia ambiental. Esta última, ha generado contratiempos en el desarrollo de la extracción mineral debido a las normas salientes como la delimitación del páramo de Santurbán y la prohibición del uso del mercurio. El presente documento plantea analizar el estado en el que se encuentran algunas operaciones mineras de la zona, realizar recomendaciones y dejar una línea base técnica de los títulos abordados para futuros trabajos.

Palabras clave: pequeña minería; títulos mineros; delimitación de páramo; recuperación metalúrgica; PTO.

1. Introducción

El municipio de California se encuentra ubicado en la Cordillera Oriental de los Andes colombianos, en el departamento de Santander. Está situado a aproximadamente 51 km al este de la capital del departamento, Bucaramanga. Una de las principales actividades económicas en esta zona es la minería, una

práctica que se remonta a tiempos ancestrales. A lo largo de los años, la actividad minera se ha llevado a cabo a pequeña escala y con un enfoque principalmente de subsistencia [1].

Durante la década de los noventa, varias empresas ingresaron al país con el objetivo de explorar y explotar minerales, entre ellas Greystar Resources Ltda. Esta compañía tenía una ambiciosa idea de negocio que dividió la historia de la minería en el municipio en dos etapas. Su interés radicaba en

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llevar a cabo minería a gran escala [1]. Sin embargo, debido a problemas de seguridad en el año 2000, Greystar se vio obligada a abandonar sus instalaciones. No obstante, retomaron el proyecto en 2003 y continuaron hasta 2011, momento en el cual cambiaron su razón social a Eco Oro Minerals Corp. [2]. Sin embargo, debido a la falta de licenciamiento ambiental causada por la delimitación del páramo de Santurbán en 2014, establecida en la Resolución 2090 [3], la empresa decidió renunciar al contrato de concesión en 2019 y retirarse del país [4].

Para el año 2015, la Sociedad Minera de Santander (Minesa) empieza a hacer presencia en la zona, en área diferente abordada por Eco Oro, con la idea de realizar minería a gran escala en la Provincia de Soto Norte, donde la explotación minera estaría ubicada en el municipio de California y su proceso de beneficio se centraría en la zona de Surata. Minesa se ha esforzado por generar confianza en la comunidad con el apoyo a la formalización de mineros artesanales, para así tener el aval social para su operación [5]. En cuanto al licenciamiento ambiental, han estado atrasados en inicio de operación debido a la delimitación del páramo de Santurbán, aunque ellos han demostrado que sus operaciones estarían por debajo de los límites, operando a 2.640 msnm, les han negado el licenciamiento y para el 2022 el proyecto se encontraba en la categoría de “Proyectos en Evaluación” de la Agencia Nacional de Licencias Ambientales (ANLA) [6].

En la zona minera de California, hacen presencia tres agrupaciones mineras con diferentes características asociativas conformadas por mineros artesanales y de pequeña minería, sin contar con la participación de Minesa, estas asociaciones se distribuyen en: ASOMICAL, son aquellos mineros ancestrales que cuentan con título minero ante la Agencia Nacional de Minería (ANM) pero sin permiso de explotación para el 2023 por falta de licenciamiento ambiental, estos son 12 títulos asociados [7]. También está ASOPROMISOTO, asociación ubicada en 28 títulos, estos mineros son ancestrales al igual que la asociación anterior pero no cuentan con el título ante la ANM, se encuentran realizando actividades mineras por contar con la propiedad del terreno o por herencia familiar, además de otros que están dentro del título que fue anteriormente de Eco Oro y del título de Minesa. Por último, están aquellos mineros que no son del sector, mineros de subsistencia y los denominados galafardos, término adquirido en la zona para las personas que adelantan labores de extracción en los antiguos túneles de Eco Oro y extraen mineral para el sustento de sus familias, estos mineros no cuentan con la propiedad del terreno ni con el título minero, esta asociación es ECOOMINORO [8].

Con este panorama, el objetivo principal de este proyecto es realizar un diagnóstico de los títulos mineros que no cuentan con licenciamiento ambiental; ASOMICAL, para así avanzar por etapas y determinar algunas mejoras que se puedan realizar en sus operaciones. Para esto, se planeó la visita a cada uno de los títulos conjunto con sus operaciones que ahora se encuentran detenidas y obtener una perspectiva

inicial de lo que se encuentra en la zona y cuál es la forma en la que laboran, todo esto con el fin de obtener algunas muestras representativas que se puedan procesar para obtener indicadores que lleven a un primer panorama del material que están obteniendo y el mineral que extraen. Para complementar el trabajo realizado en campo, se hará una comparación de las actividades realizadas por los mineros con respecto a trabajos teóricos realizados previamente en zonas con potenciales similares para así finalmente dar algunas recomendaciones iniciales de lo que se evidenció en esta primera etapa.

2. Antecedentes y contexto general

Para tener conocimiento de la zona de influencia en la cual está centrado el presente trabajo, se debe tener en cuenta algunos aspectos que están estrechamente relacionados con la actividad minera y el desarrollo de la misma. Se determinó ahondar en factores sociales, ambientales, técnicos y legales. Todo esto con el fin de ampliar el contexto de la industria minera en la provincia de Soto Norte, con énfasis en el municipio de California.

2.1 Aspectos sociales

El municipio de interés se encuentra en la provincia de Soto Norte, la cual está conformada por los municipios de Surata, California, Vetás, Matanza, Charta y Tona, siendo Vetás y California los focos mineros principales de la zona que generan una influencia directa en Surata, debido a su ubicación geográfica y su orogenia plana, es considerado un municipio estratégico en la región [5]. El municipio de California cuenta con una población de 1.832 personas de las cuales 1.111 se encuentran en edad apta para laborar, siendo 52,7% hombres y 47,3% mujeres. El municipio de Vetás tiene una fuerza laboral muy similar, pues cuenta con 1.076 personas laboralmente aptas, de las cuales el 51,2% y el 48,85% corresponden a hombres y mujeres respectivamente. Por su parte, el municipio de Surata tiene una fuerza laboral mayor, con una población de 3.520 personas dentro de las cuales 2.003 se encuentran en edad apta para trabajar, correspondiendo el 51,9% a hombres y el 48,1% a mujeres, como lo muestra la gráfica 1 [9]. Estos datos indican que hay más disponibilidad de mano de obra masculina que femenina, dando como resultado un índice de masculinidad del 114% aproximadamente [9], demostrando así que los trabajos predominantes en la zona están relacionados con el sector primario: agricultura, ganadería y minería, siendo esta última, la actividad que predomina en la región. En la Fig. 1, mostrada a continuación, se observa la población en edad productiva de esta provincia.

El municipio de California fue duramente golpeado por el conflicto armado durante los años ochenta y noventa, dando como resultado desplazamiento forzoso, enfrentamientos en el casco urbano, homicidio y secuestro, acentuándose a mediados de los años noventa, que fue cuando iniciaron las operaciones de la compañía Greystar [10], llevando a la suspensión de las operaciones de la misma en el 2000 que se reanudaron en el 2003 [2,8].

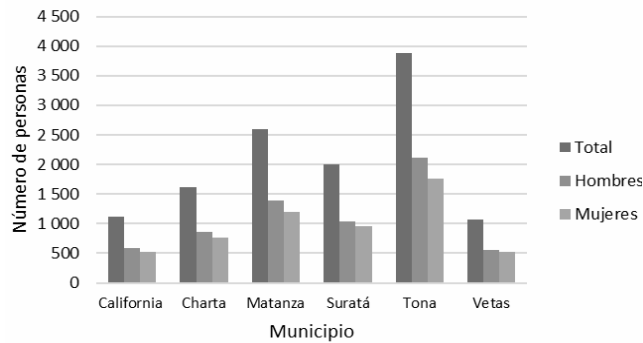


Figura 1. Población en edad productiva de la provincia de Soto Norte.
Fuente: [9]

Al final del siglo XX muchos mineros ancestrales vendieron sus tierras y sus títulos, dado que el valor de estas era desconocido. A día de hoy, estas familias están regresando al territorio con el fin de retomar la actividad y dado que no cuentan con los recursos para cumplir con los estándares técnicos y ambientales, se ven obligados a operar de manera ilegal, lo cual deja en evidencia la falta de promoción de la formalización y legalización [11]. A nivel histórico, la minería ha sido la principal actividad económica de la región, localizada en las proximidades de la quebrada La Baja, desempeñándose por más de cinco siglos de forma generacional [5]. Para el año 2011, con la promulgación de la Ley 1450, se aprobó el Plan Nacional de Desarrollo que prohibía las actividades extractivas en zonas de páramo [12]. Ésta ley fue ratificada en el 2018 por la Ley 1930 y por esto no se permite la extracción de minerales en la zona [13]. Dadas estas circunstancias, las personas que viven de la actividad minera en la región, han tratado de formalizar sus títulos por medio del plan de formalización minera establecido en la Ley 2250 del 2022 [14], pero debido a la alta incertidumbre gubernamental y a la delimitación de páramos, no ha sido posible, lo que ha conllevado a un trabajo colectivo entre los mineros locales para poder desempeñar sus labores [8].

2.2 Aspectos ambientales

Teniendo en cuenta la historia socio-ambiental que ha tenido la zona, es de vital importancia tener en cuenta dos factores en este apartado: la ley del manejo del mercurio en la minería de oro del país y la delimitación del páramo de Santurbán. Estos aspectos son importantes ya que han marcado de manera importante el desarrollo de la actividad en la zona de estudio.

2.2.1 Ley del mercurio

Reconociendo los efectos causados al medio ambiente y a la salud por exposición al mercurio, en el año 2013, en Colombia se estipuló la Ley 1658 por medio de la cual se establecen las disposiciones adecuadas para la comercialización y el uso del mercurio en diversas

industrias, haciendo énfasis en la actividad minera. Para esta última, se establece un plazo no mayor a 5 años, es decir, para el año 2018 el uso del mercurio dentro de los procesos mineros debería de estar erradicado, prohibiendo así, desde el año de promulgación de la ley, la creación de nuevas plantas de beneficio donde se utilizase este elemento para la concentración de oro, definiendo desde entonces que los establecimientos con beneficio mineral deban solicitar licencia ambiental, adoptando un plan de manejo ambiental, donde expongan el no uso del mercurio dentro de sus actividades, haciendo énfasis en la amalgamación. En cuanto a las plantas de beneficio antiguas que utilizan este modo de obtención de oro, deberán reubicar el establecimiento si estas se encuentran dentro de lugares delimitados por el Plan de Ordenamiento Territorial de cada zona, esto no debe suceder en más de 3 años después de anunciada la ley [15].

2.2.2 Delimitación de páramo de Santurbán

Según el Atlas de Páramos de Colombia, el páramo de Santurbán tiene jurisdicción en los departamentos de Santander y Norte de Santander. Tiene un área total de 82.664 ha, de las cuales 1.131 ha (1,37%) pertenecen a California y 7.339 ha (8,88%) a Vetás [16]. Para el año 2012, por parte del Instituto Humboldt se presenta un ajuste cartográfico el cual incrementa el área del páramo a 142.608 ha, disminuyendo notablemente el porcentaje que corresponde a los municipios de Vetás y California [17].

La Resolución 769 de 2002 del Ministerio de Medio Ambiente, establece que, en la cordillera oriental se denomina zona de páramo a la extensión de tierra que se encuentre sobre los 3.000 msnm. Dado que la zona de estudio se encuentra en el municipio de California, donde las altitudes oscilan entre 2.005 y los 4.000 msnm, la resolución ha generado consecuencias para la actividad minera local [18].

Para el 2011, con la Ley 1450 se aprueba el Plan Nacional de Desarrollo 2010-2014. En el artículo 22, capítulo 5, se prohíbe el desarrollo de actividades agropecuarias, exploración o explotación de hidrocarburos y minerales [12], posterior a esto, en el 2014 mediante la Resolución 2090 del Ministerio del Medio Ambiente y Desarrollo, se delimita la jurisdicción del Páramo de Santurbán, abarcando extensión territorial de más de 40 municipios entre Santander y Norte de Santander [3], donde Vetás y California son dos de los municipios involucrados en el caso de estudio que, para el 2022, entre estos dos municipios solo Vetás habría firmado este acuerdo de delimitación [19].

2.3 Aspectos geológicos

La provincia de Soto Norte se encuentra ubicada en la cordillera oriental. Esta cordillera alberga el macizo de Santander el cual está constituido principalmente por gneises y granitos peraluminosos, cuya edad varía desde el triásico superior hasta el jurásico temprano y se encuentra limitado por la Falla de Bucaramanga al oeste y por la Falla de Socota al este [20].

La geología presente se asocia a procesos de magmatismo y metamorfismo de contacto ubicadas en el centro de ambas fallas

[21]. La mineralización se encuentra asociada a sistemas de vetas de alta sulfuración, propias de procesos porfíricos, específicamente de molibdeno [22]. En la zona se evidencian tres yacimientos: La Bodega, La Mascota y Angosturas, siendo La Bodega y Angosturas las más ricas en recursos auríferos y la orientación de estas estructuras, son controladas por la falla La Baja, cuyo rumbo va en dirección NE. Las zonas de baja mineralización de oro se encuentran asociadas a la alteración sericitica (<1%), las cuales tienen contenido de bornita, covelina, calcopirita, hubnerita, enargita y pirita, todos estos se encuentran asociados a oro nativo y a telururos de oro y plata. Como consecuencia de la alteración supergénica, se pueden encontrar especies mineralógicas como hematita, goethita y algunas mezclas no determinadas de jarosita asociada a pirita y calcantita producto de la meteorización de sulfuros de cobre, como calcopirita [22].

La importancia de zonas de falla en el proceso de meteorización radica en su capacidad para facilitar el flujo de aguas superficiales hacia capas más profundas, lo cual contribuye a la oxidación de rocas y vetas. Es común observar una completa oxidación de los sulfuros presentes en las vetas y de los minerales de hierro en la roca hasta una profundidad de aproximadamente 10 metros por debajo de la superficie [22].

2.4 Aspectos técnicos y legales

La producción de oro en Colombia, específicamente en la provincia de Soto Norte, se ha llevado a cabo principalmente a través de la minería artesanal y en pequeña escala [23], la cual se caracteriza por la poca tecnificación de sus operaciones; haciendo uso de máquinas simples y herramientas portátiles y rudimentarias, intensificando el uso de mano de obra no calificada y generando bajos márgenes de producción por yacimiento [24,25].

Estas características son producto de limitaciones económicas y sociales que se ven reflejadas en el escaso acceso a tecnologías que permitan un adecuado proceso de extracción y beneficio del oro y en la formación básica, técnica y tecnológica de los mineros, las cuales, en muchos de los casos, es transmitida por generaciones, lo que lleva a bajos rendimientos en los procesos extractivos, que conducen, en algunos casos, a una recuperación de menos del 60%, y en la mayoría de unidades productivas, a costos de operación y producción elevados asociado a baja rentabilidad, generando de esta manera, una dinámica económica que tiende a estancar y a pauperizar las condiciones de las pequeñas operaciones, generando riesgos relacionados a la salud y seguridad de los mineros, así como al agua, aire y medio ambiente [26].

La contaminación por uso de mercurio en el proceso de beneficio del oro, es una de las afectaciones más importantes asociadas a la degradación de las condiciones de estas operaciones, aun cuando su uso es ilegal. De acuerdo a la Corporación Geoambiental Terrae, en el año 2018 se realizó un estudio de la calidad del agua superficial

relacionada a la actividad minera en la cuenca alta de la quebrada Páez y cuenca baja y media de la quebrada La Baja en el municipio de California, en el cual se encontró presencia de Hg (II) en todos los puntos de muestreo, aguas abajo. En aquellos puntos situados después de vertimientos procedentes de pequeñas unidades mineras, los valores se incrementaron más de 18 veces, el valor más alto que se encontró fue de 788,9 µg Hg/kg [27]. El aumento en la concentración de esta especie de mercurio a lo largo de la quebrada puede indicar una relación con la actividad minera, especialmente cuando se detectaron valores de más de 480 µg Hg (II)/kg. Además de esto, estas pequeñas operaciones mineras enfrentan una serie de situaciones que dificultan y amenazan la actividad, como la desconfianza y zozobra frente al estado colombiano, la falta de seguridad jurídica de cara al sector minero y la falta de articulación entre los distintos sectores. Estas situaciones, generan además, problemas relacionados a la falta de acceso a crédito y beneficios tributarios favorables y a la ausencia de acceso a suministros químicos y explosivos debido a restricciones impuestas desde el gobierno y el ejército colombiano [26].

Desde gobiernos anteriores, se han adelantado esfuerzos encaminados a mejorar este tipo de condiciones técnicas y económicas que rodean esta actividad. En agosto de 2001 se promulga el actual Código de Minas a través de la Ley 685. En esta ley, en el artículo 84 se introduce el Plan de Trabajos y Obras (PTO), el cual es el instrumento legal que viabiliza un proyecto minero. Este documento suministra la base técnica, logística, económica y comercial para tomar la decisión de invertir y desarrollar un proyecto minero [28] y debe ser anexado como exigencia contemplada dentro de las obligaciones técnicas.

Este documento debe contener la siguiente información, siguiendo como referencia las guías minero ambientales expedidas por la ANM, en concordancia con el actual código minero [29]:

1. Delimitación definitiva del área de explotación.
2. Mapa topográfico de dicha área.
3. Detallada información cartográfica del área y, si se tratase de minería marina, especificaciones batimétricas.
4. Ubicación, cálculo y características de las reservas que habrán de ser explotadas en desarrollo del proyecto.
5. Descripción y localización de las instalaciones y obras de minería, depósito de minerales, beneficio y transporte y, si es el caso, de transformación.
6. Plan Minero de Explotación, que incluirá la indicación de las guías técnicas que serán utilizadas.
7. Plan de obras de recuperación geomorfológica, paisajística y forestal del sistema alterado.
8. Escala y duración de la producción esperada.
9. Características físicas y químicas de los minerales por explotar.
10. Descripción y localización de las obras e instalaciones necesarias para el ejercicio de las servidumbres inherentes a las operaciones mineras.
11. Plan de cierre de la explotación y abandono de los montajes y de la infraestructura

Según este código, los requerimientos aquí exigidos no hacen distinción alguna entre los distintos tipos de minería [28].

En el 2014, bajo el Decreto 480, se reglamentan las condiciones y requisitos para la celebración y ejecución de los subcontratos de formalización minera. Dentro de este decreto, se introducen los Planes de Trabajos y Obras Complementarias (PTOC) para la fiscalización diferencial [30].

Posteriormente, en el año 2022 el gobierno promulga la Ley 2250, la cual, además de introducir la definición de minería tradicional, establece un marco jurídico especial en materia de legalización y formalización minera y normas especiales en materia ambiental para este tipo de minería [14]. Dentro de este marco, el gobierno implementa los Planes de Trabajos y Obras Diferencial (PTOD) ya dispuestos en la Resolución 614 de 2020, la cual instaura los criterios para evaluar las condiciones económicas de un proyecto minero, con el fin de adoptar los términos de referencia para la presentación del documento como anexo a la propuesta de concesión [31].

3. Metodología

El presente estudio se realiza con base a la comparación cualitativa y cuantitativa de los parámetros técnicos consignados y observados de cinco de las operaciones mineras, de once títulos de interés. Esta comparación nos permitirá establecer un diagnóstico técnico de las unidades mineras que se encuentran en el área de influencia.

Las discusiones planteadas, resultados y recomendaciones se construyeron a partir de la información facilitada por los titulares mineros mediante los PTOs, la información recolectada y las muestras tomadas en campo que fueron procesadas en un laboratorio ubicado en el municipio de Medellín, Antioquia.

Las muestras fueron tomadas de operaciones mineras ubicadas en la zona de estudio. Corresponden a muestras de material de cabeza (M1), veta (M2) y material de colas (M3), a las cuales se les realizó un análisis de liberación y dos ensayos al fuego de oro y análisis químico de plata respectivamente. Aunque se obtuvieron resultados de los muestreos, estos arrojaron pocos niveles de recuperación debido a los incorrectos procesos desarrollados en las operaciones, razón por la cual no se profundizó en este aspecto.

Inicialmente, se realizó una revisión de los PTOs de dichos títulos con el fin de establecer el estado técnico del mismo y así poder determinar, si están o no presentes en dicho documento los requerimientos técnicos consignados en los términos de referencia expedidos por la autoridad minera, en este caso la ANM. Posteriormente, con los componentes técnicos registrados en cada uno de los documentos de acuerdo a los términos de referencia, fueron identificadas aquellas componentes comunes a todos los PTOs, con el fin de contrastar con la realidad de las operaciones.

Con cada uno de estos elementos, y de acuerdo a la evidencia encontrada y registrada en campo, se comparan los registros de campo con lo expedido en cada uno de los documentos, estableciendo el nivel de adherencia y grado de concreción de cada título a su respectivo PTO.

Adicionalmente, se incluyen datos puntuales de carácter técnico y económico de interés, y los resultados entregados de los análisis de las muestras reportados por el laboratorio, los cuales permitirán un análisis detallado de los resultados y una mejor interpretación de los mismos.

3.1 Descripción de títulos (PTO)

Para el estudio, se solicitan los PTOs de los títulos localizados en la zona de interés, los cuales, por fines de confidencialidad, se van a nombrar de la siguiente forma: T1, T2, T3, T4, T5. La información más relevante para este ejercicio, extraída de los PTO de dichos títulos, se encuentra condensada en la Tabla 1 a continuación:

Tabla 1.
Resumen de PTOs

Variable	T1	T2	T3	T4	T5
Vida del proyecto [años]	30	20	20	32	30
Tenor de oro [g/t]	1,4	8,95	4	7	3,25
Producción anual [t/año]	2.711	6.728,5	7.762.6	21.000	2.420
Precio g oro [\$ COP/ g]	\$73.000	\$235.699	\$87.000	\$118.733	\$47.472
Variación del Valor oro [%]	2,50%	11,90%	N/I	6,50%	10%
VPN [M COP]	\$271	\$3.181	\$687	\$5.724	\$4.804
TIR [%]	21%	17%	28%	106%	18, %
Recuperación metalúrgica [%]	80%	80%	60%	55%	80%
Área [ha]	94	10,46261	1	10,088	38
Densidad [t/m ³]	2,8	2,7	2,7	2,65	2,8
Capacidad de planta [t/h]	20 - 40	2,5	0,8	1,5	20 - 100
Cut off [g/t]	9,2	3,68	N/I	N/I	N/I
Trabajadores	12	7	11	8	34
Recursos medidos	N/I	N/I	N/I	90.559,560 [ton]	4'328.800 [m ³]
Recursos indicados	N/I	N/I	N/I	N/I	N/I
Recursos inferidos	N/I	N/I	N/I	N/I	N/I
Reservas probadas	N/I	N/I	4.992	N/I	N/I
Reservas probables	N/I	38.851	N/I	11.211	4.805
Dilución [%]	10	N/I	N/I	N/I	N/I
Tenor de plata [g/t]	5	N/I	N/I	N/I	N/I
Ley de plata [ppm]	39,5	N/I	N/I	N/I	N/I
Metros perforados [m]	3.600	10.932,14	N/I	N/I	N/I

N/I: No hay información en el PTO.

Fuente: Los autores.

3.2 Verificación y comparación

En esta etapa, se busca identificar el estado de cumplimiento de cada uno de los documentos, de acuerdo a los términos de referencia expedidos por la autoridad minera, la ANM.

A continuación, en la Tabla 2, se presentan los resultados de dicha identificación de las componentes presentes y ausentes en cada uno de los PTOs, denotando por SI aquella componente presente y por NO aquella componente ausente en el documento.

A partir de los datos consignados en las Tablas 1 y 2, fueron identificados aquellos componentes comunes en todos los documentos. A éstos, fueron añadidos otros parámetros que aunque no eran comunes en todos los documentos, se consideran destacables para este ejercicio analítico.

Con los factores identificados, se realiza la comparación entre lo consignado en los documentos con lo observado en campo, significando SI, aquella componente presente ya sea en el documento o en la realidad y para aquellas donde se determina NO, significa que no se evidencia ni en el PTO o en la realidad. A continuación, en la Tablas 3 y 4 se presentan las tablas obtenidas de esta identificación y de su posterior comparación.

Tabla 2.
Verificación de términos de referencia en PTOs.

Componente	T1	T2	T3	T4	T5
Descripción y localización del proyecto	SÍ	SÍ	SÍ	SÍ	SÍ
Delimitación definitiva del área de explotación	SÍ	SÍ	SÍ	SÍ	SÍ
Mapa topográfico del área	SÍ	SÍ	SÍ	SÍ	NO
Análisis de precios	SÍ	SÍ	SÍ	SÍ	NO
Análisis de oferta	SÍ	NO	NO	SÍ	NO
Análisis de demanda	SÍ	SÍ	NO	NO	NO
Pronóstico de venta	SÍ	SÍ	NO	SÍ	NO
Proyecciones futuras nacionales	SÍ	NO	NO	NO	NO
Proyecciones futuras internacionales	SÍ	NO	SÍ	NO	NO
Análisis de alternativas de explotación	NO	NO	SÍ	NO	SÍ
Selección de método de minado	SÍ	SÍ	SÍ	SÍ	SÍ
Estimativos de producción	SÍ	SÍ	SÍ	SÍ	SÍ
Mano de obra requerida	SÍ	SÍ	SÍ	SÍ	SÍ
Infraestructura requerida	SÍ	SÍ	NO	SÍ	SÍ
Modelo geológico	SÍ	SÍ	NO	NO	NO
Perforaciones	SÍ	SÍ	NO	NO	NO
Características físicas y químicas del mineral	SÍ	SÍ	SÍ	SÍ	NO
Selección de equipos	SÍ	SÍ	SÍ	SÍ	SÍ
Diseño de mina	SÍ	SÍ	SÍ	SÍ	NO
Plan de ventilación	SÍ	NO	SÍ	SÍ	SÍ
Diseño de planta de beneficio	SÍ	SÍ	NO	SÍ	NO
Estabilidad de taludes, túneles y manejo de aguas	SÍ	SÍ	SÍ	SÍ	SÍ
Mantenimiento y suministro	SÍ	SÍ	SÍ	SÍ	SÍ
Seguridad minera	SÍ	SÍ	SÍ	SÍ	SÍ
Escala y duración del proyecto	SÍ	SÍ	SÍ	SÍ	SÍ
Análisis de flujo de caja	SÍ	SÍ	SÍ	SÍ	SÍ
Evaluación económica	SÍ	SÍ	SÍ	SÍ	SÍ
Evaluación financiera	SÍ	SÍ	SÍ	SÍ	SÍ
Plan de obras de recuperación geomorfológica, paisajística y forestal	SÍ	SÍ	SÍ	SÍ	SÍ
Plan de cierre	SÍ	SÍ	NO	SÍ	SÍ

Fuente: Los autores

Tabla 3.

Comparación de PTO vs visto en campo.

Componente	T1	Real	T2	Real
Descripción y localización del proyecto	SÍ	SÍ	SÍ	SÍ
Delimitación definitiva del área de explotación	SÍ	SÍ	SÍ	SÍ
Selección de método de minado	SÍ	SÍ	SÍ	SÍ
Ley	SÍ	NO	SÍ	SÍ
Estimativos de producción	SÍ	NO	SÍ	NO
Mano de obra requerida	SÍ	NO	SÍ	SÍ
Infraestructura requerida	SÍ	SÍ	SÍ	SÍ
Perforaciones	SÍ	NO	SÍ	NO
Selección de equipos	SÍ	SÍ	SÍ	SÍ
Diseño de mina	SÍ	NO	SÍ	SÍ
Plan de ventilación	SÍ	NO	NO	SÍ
Diseño de planta de beneficio	SÍ	SÍ	SÍ	SÍ
Estabilidad de taludes, túneles y manejo de aguas	SÍ	NO	SÍ	SÍ
Plan de obras de recuperación geomorfológica, paisajística y forestal	SÍ	NO	SÍ	NO
Seguridad minera	SÍ	NO	SÍ	SÍ

Fuente: Los autores.

Tabla 4.

Comparación de PTO vs visto en campo (continuación).

Componente	T3	Real	T4	Real	T5	Real
Descripción y localización del proyecto	SÍ	SÍ	SÍ	SÍ	SÍ	SÍ
Delimitación definitiva del área de explotación	SÍ	SÍ	SÍ	SÍ	SÍ	NO
Selección de método de minado	SÍ	SÍ	SÍ	NO	SÍ	NO
Ley	SÍ	NO	SÍ	NO	NO	NO
Estimativos de producción	SÍ	SÍ	SÍ	NO	NO	NO
Mano de obra requerida	SÍ	SÍ	SÍ	SÍ	SÍ	NO
Infraestructura requerida	SÍ	SÍ	SÍ	NO	SÍ	NO
Perforaciones	NO	NO	NO	NO	NO	NO
Selección de equipos	SÍ	SÍ	SÍ	NO	SÍ	NO
Diseño de mina	SÍ	SÍ	SÍ	SÍ	NO	NO
Plan de ventilación	SÍ	SÍ	SÍ	SÍ	SÍ	NO
Diseño de planta de beneficio	SÍ	SÍ	SÍ	NO	NO	NO
Estabilidad de taludes, túneles y manejo de aguas	NO	SÍ	SÍ	SÍ	SÍ	NO
Seguridad minera	SÍ	SÍ	SÍ	NO	SÍ	NO
Plan de obras de recuperación geomorfológica, paisajística y forestal	SÍ	NO	SÍ	NO	SÍ	NO

Fuente: Los autores.

4. Análisis, resultados y discusión

A continuación, se presentan los análisis realizados con la información levantada en campo y proporcionada por el laboratorio. Dentro de las discusiones planteadas en el marco del proyecto, se sugieren algunas mejoras cuyo sustento se encuentra dentro del análisis estadístico realizado.

4.1 Análisis estadístico

A partir del estudio realizado a los títulos mineros por medio de la comparación de los PTOs de los mismos, se calcula el porcentaje de títulos que cumplen con los términos de referencia allí mencionados, dando como resultado lo que se muestra en la Tabla 5.

Tabla 5.
Porcentaje de cumplimiento.

Componente	Cumplimiento
Descripción y localización del proyecto	100%
Delimitación definitiva del área de explotación	100%
Mapa topográfico del área	80%
Análisis de precios	80%
Análisis de oferta	40%
Análisis de demanda	40%
Pronóstico de venta	60%
Proyecciones futuras nacionales	20%
Proyecciones futuras internacionales	20%
Análisis de alternativas de explotación	40%
Selección de método de minado	100%
Estimativos de producción	100%
Mano de obra requerida	100%
Infraestructura requerida	100%
Modelo geológico	40%
Perforaciones	40%
Características físicas y químicas del mineral	60%
Selección de equipos	100%
Diseño de mina	80%
Plan de ventilación	80%
Diseño de planta de beneficio	80%
Estabilidad de taludes, túneles y manejo de aguas	80%
Mantenimiento y suministro	100%
Seguridad minera	100%
Escala y duración del proyecto	100%
Análisis de flujo de caja	100%
Evaluación económica	80%
Evaluación financiera	100%
Plan de obras de recuperación geomorfológica, paisajística y forestal	100%
Plan de cierre	80%

Fuente: Los autores

De acuerdo a la Tabla 5, el mayor cumplimiento se da en las componentes relacionadas a la descripción del proyecto, su delimitación; en algunos aspectos técnicos propios de la operación como mano de obra, selección de método de minado y algunos aspectos económicos como análisis económico. Esto contrasta con el déficit de cumplimiento en aspectos relacionados a los precios y proyecciones futuras nacionales e internacionales y en la falta de un estudio de mayor rigor al respecto. Esto puede verse reflejado en los precios del oro que cada proyecto estima, y en las variaciones que presentan. Es importante tener en cuenta que los aspectos económicos son importantes para la viabilidad del proyecto.

Además, los componentes de mayor cumplimiento son aquellos que, a priori, no necesitan inversiones para estimarse. Lo cual deja en evidencia, la poca inversión en cada uno de los proyectos, a la hora de disminuir la incertidumbre dentro del mismo. Lo anterior se ve reflejado no solo en el bajo nivel de detalle de exploración que exhibe cada proyecto, sino en la ausencia de definición de recursos y reservas en cada uno, dejando en entredicho cualquier análisis económico o financiero.

Para complementar la información, se evalúa el porcentaje de adherencia que tienen los PTOs con respecto a lo evidenciado en la visita técnica, para determinar qué tanto se acoge el PTO a la realidad, como se muestra a continuación en la Tabla 6.

Tabla 6.
Porcentaje de adherencia.

Componente	Adherencia
Descripción y localización del proyecto	100%
Delimitación definitiva del área de explotación	80%
Selección de método de minado	60%
Ley	20%
Estimativos de producción	20%
Mano de obra requerida	60%
Infraestructura requerida	60%
Perforaciones	0%
Selección de equipos	60%
Diseño de mina	60%
Plan de ventilación	40%
Diseño de planta de beneficio	60%
Estabilidad de taludes, túneles y manejo de aguas	40%
Seguridad minera	40%
Plan de obras de recuperación geomorfológica, paisajística y forestal	0%

Fuente: Los autores

Tabla 7.
Porcentaje de cumplimiento y adherencia de títulos a PTO.

	T1	T2	T3	T4	T5
Porcentaje de Cumplimiento	96%	83%	67%	80%	57%
Porcentaje de Adherencia	40%	86%	92%	43%	10%

Fuente: Los autores

El componente que mayor adherencia presenta es la descripción y localización del proyecto, siendo este, nuevamente, uno de los componentes que menos inversión requiere. En contraste a esto, los componentes que menos adherencia exhiben son los de perforación y de plan de obras de recuperación geomorfológica, paisajística y forestal, siendo estos los de mayor inversión. Es importante resaltar el contexto ambiental presente en esta zona y las problemáticas asociadas a la minería, por lo que se hace imperante la necesidad de acoger un plan que contemple la recuperación geomorfológica y paisajística de la zona, a fin de viabilizar y armonizar la actividad minera en la región. Los porcentajes de adherencia y cumplimiento se muestran en la Tabla 7.

Con respecto al grado de adherencia que tienen los documentos a la realidad, se puede observar, de acuerdo a la Tabla 8, que así como hay títulos donde este valor es muy elevado, aproximadamente del 92%, hay otros títulos donde apenas alcanza el 10%, siendo el promedio de 54%. Si se asume que los cinco títulos tienen una representatividad del 80% de los títulos de California, con una desviación de más o menos el 30%, podría significar que todos los títulos del municipio presentan adherencias entre el 24% y el 84%, con media de 54%.

4.2 Resultados de laboratorio

De acuerdo al análisis de liberación realizado a la muestra M2 en el laboratorio, se puede observar el 73,34% del oro libre se retiene entre las mallas 50 y 80, el cual es posible recuperar mediante procesos gravimétricos, posterior a una molienda que

Tabla 8.
Resultados del ensayo de liberación.

Malla	Tamaño [μm]	Masa retenida [g]	Au libre [%]	Au asociado [%]
-50/+80	300	10,38	24,58	37,93
-80/+100	180	11,15	48,76	13,40
-100/+140	150	13,53	5,06	11,82
-140/+200	106	13,35	5,61	10,69
-200/+270	75	11,71	8,12	9,87
-270	53	39,88	7,87	16,29

Fuente: Laboratorio

lleve el material a tamaño de 53 μm y previo a una etapa de cianuración. Se puede observar que el oro asociado se puede recuperar a este tamaño, haciendo innecesario, remoler a tamaños más pequeños. En la Tabla 8 mostrada a continuación, se observan los resultados del ensayo de liberación.

Con respecto a los ensayos al fuego para oro y análisis químico de plata en las muestras M1 y M3, en la Tabla 9, es posible deducir que el índice de recuperación asociado a procesos gravimétricos es de aproximadamente el 45%, produciendo un mineral de colas muy rico en plata y una cantidad considerable de oro atrapado. Es importante considerar los tenores de plata aquí encontrados como subproductos con valor económico. De acuerdo con los componentes analizados, solo el 20% de los documentos (1 título), incluye la plata en los análisis de ley y ninguno lo incluye como subproducto en los análisis económicos.

Tabla 9.
Resultados de ensayo al fuego y ensayo químico de plata.

Muestras	Tenor Ag [g/t]	Tenor Au [g/t]
M1	144,45	75,81
M2	159,53	565,77
M3	1563,79	34,21

Fuente: Laboratorio

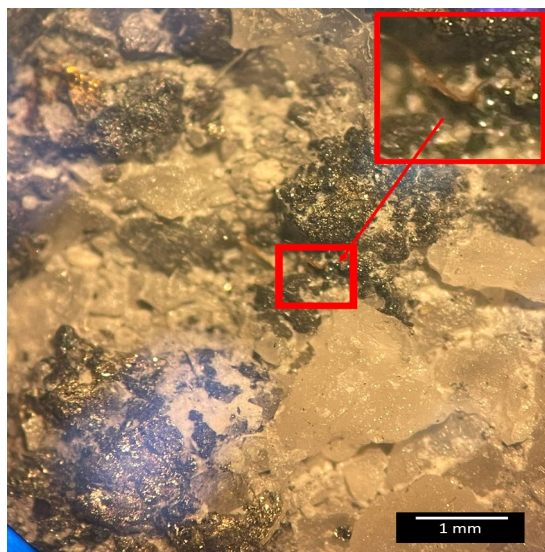


Figura 2. Vista en estereoscopio de muestra M2 donde se visualiza oro en su estado nativo.

Fuente: Los autores.

Esto implica una pérdida directa por costo de oportunidad. Sumado a esto, se tiene que solo el 40% de los PTOs reportan ley de corte, solo el 20% reporta reservas probadas y el 60% reporta reservas probables.

Es importante tener en cuenta que las leyes reportadas en los ensayos de laboratorio, especialmente aquellas tomadas sobre la veta, son significativamente más altas que las reportadas en los documentos, posiblemente debido al sesgo del muestreo y efecto pepita asociado. En la Fig. 2 se observa la vista en estereoscopio de la muestra M2.

5. Conclusiones y recomendaciones

Teniendo en cuenta que, en los documentos suministrados por cinco de los once títulos de interés, se resalta que el precio del mineral corresponde al de los años en los que se realizaron los PTOs (en 2007, el más antiguo y del 2020 el más reciente) y no se tuvo en cuenta la fluctuación del mismo, perdiendo el costo de oportunidad que se presenta para la actualidad, sabiendo que para el 1 de junio del 2023, el precio del oro se sitúa en \$ 232.517,27 COP/g [35].

Se evidencia que la adherencia que tienen los PTOs con respecto a la realidad de las operaciones, en el 60% de los títulos el índice es inferior al 50%, por esto se recomienda a los titulares no solo refinar el instrumento legal, sino ahondar esfuerzos en implementarlo.

Con respecto al cumplimiento de los lineamientos expedidos por la autoridad minera, se observa que solo uno de los documentos presenta un cumplimiento de más de 90%. Es importante tener en cuenta que para la sostenibilidad de la actividad económica generada por la minería y especialmente; bajo el escenario socio-ambiental en el que se encuentran inmersas estas operaciones, se debe trabajar en pro del carácter legal de las mismas, manteniendo en todo momento el pleno cumplimiento de los lineamientos expedidos por la autoridad.

A partir de los resultados obtenidos del laboratorio, se encuentra que en la zona de California hay mineral auroargentífero de alto tenor cuya recuperación es ineficiente, por lo tanto, se recomienda proponer para fases futuras, abordar de manera rigurosa el reporte del tenor de mineral en los títulos, proporcionando información que puede ser útil para los titulares de la zona.

Para trabajos futuros, se recomienda actualizar cada uno de los documentos asociados a los distintos títulos, ya que algunos de estos son incluso, anteriores al 2013 previo a la expedición de la ley del mercurio, en los cuales aún se reportan técnicas de beneficio que incluyen uso del elemento.

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Performance of an unpaved roads reinforced with geogrid: construction of a physical model in laboratory and numerical validation

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Abstract

This study evaluated the mechanical behavior of a physical laboratory model of an unpaved route reinforced with a BG biaxial geogrid. To this end, 0.15 m of improvement material and 0.20 m of subgrade were compacted in a square box of 0.35 m. Tests were carried out with and without reinforcement, by applying 10000 dynamic load cycles on a universal machine. A frequency of 2.5 Hz and pressure of 560 kPa was used by a circular plate of 0.10 m in diameter, simulating the circulation of a tire of a simple wheel axis. The numerical validation for the Finite Elements Methods (MEF) defined parameters using the Hardening Soil model. As a great conclusion, it could be evidenced that reinforcement with a geogrid reduces approximately 45% the magnitude of the rutting, depending on the model, because the geogrid reduces the concentration of cutting stresses (relative τ) decreasing plastic deformation.

Keywords: geosynthetics; unpaved; reinforcement.

Desempeño de una vía no pavimentada reforzada con geomalla: construcción de un modelo físico en laboratorio y validación numérica

Resumen

Este estudio evaluó el comportamiento mecánico de un modelo físico laboratorial de una vía no pavimentada reforzada con una geomalla biaxial GB. Para tal fin, se compactaron 0.15 m de material de mejoramiento y 0.20 m de subrasante en una caja cuadrada de 0.35 m. Se realizaron ensayos con y sin refuerzo, mediante la aplicación de 10000 ciclos de carga dinámica en una maquina universal. Se utilizó una frecuencia de 2.5 Hz y presión de 560 kPa mediante una placa circular de 0.10 m de diámetro, simulando la circulación de una llanta de un eje rueda simple. La validación numérica vía Métodos de los Elementos Finitos (MEF) definió parámetros usando el modelo Hardening Soil. Como gran conclusión, se pudo evidenciar que el refuerzo con una geomalla reduce aproximadamente 45% la magnitud del ahuellamiento, según el modelo, debido a que la geomalla reduce la concentración de esfuerzos cortantes (τ relativo) disminuyendo la deformación plástica.

Palabras clave: geosintéticos; vía no pavimentada; refuerzo.

1. Introducción

En Colombia, la red vial está conformada aproximadamente por 205000 km, de las cuales el 70% corresponde a vías de bajo volumen de tránsito [1]. Esas vías se encuentran ubicadas principalmente en zonas rurales. Según datos del Instituto Nacional de Vías (INVIAS), las

vías no pavimentadas presentan condiciones buenas, regulares y malas, en 12%, 38% y 50%, respectivamente [2]. Ante este panorama se busca estudiar nuevos materiales y tecnologías que contribuyan al fortalecimiento de las vías rurales, con el fin de mejorar las condiciones de circulación de vehículos para proporcionar mayor integración y crecimiento económico.

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Actualmente, existen técnicas para la construcción o mejoramiento de vías de bajos volúmenes de tránsito [3, 4]. Las cuales buscan mejorar o estabilizar la subrasante o el tratamiento de materiales granulares. Algunas técnicas consisten en: utilización de geosintéticos [5–7], uso de materiales convencionales (p.e. cemento, cal, asfálticos) [8], uso de materiales no convencionales (p.e. sulfatos, silicatos, resinas, aceites sulfonatos, entre otros) [9–11] técnicas de electroósmosis, [12–14] uso de materiales alternativos (p.e. asfaltos naturales) [15–16], construcción de estructuras en placa huella [17], losas cortas [18–19], entre otras. La selección de una técnica depende de los requerimientos técnicos de los proyectos, disponibilidad de materiales, condiciones ambientales, costos de construcción, entre otros.

Los geosintéticos son materiales poliméricos sintéticos que se utilizan en obras geotécnicas. Existen diferentes tipos que se clasifican en: geotextiles, geomallas, geomembranas, geoceldas, geocompuestos, geonets, productos para control de erosión, entre otros [20]. El uso de geosintéticos proporciona beneficios en las características mecánicas e hidráulicas. Se caracterizan por incrementar la rigidez, resistencia a la tracción, lo cual proporciona mayor capacidad estructural [21]. Asimismo, son utilizados para la separación de capas, barreras, control de filtración, protección y como elementos de drenaje [22–25]. Se emplean ampliamente en la ingeniería de carreteras por su fácil aplicación durante la construcción [20,26]. Sus principales aplicaciones son: mejoramiento de subrasantes y materiales granulares, refuerzo de mezclas asfálticas, obras de drenaje, entre otros [27]. Adicionalmente, son amigables con el medio ambiente por reducir las cantidades de materiales naturales e impactos ambientales [21].

Los principales geosintéticos empleados en vías pavimentadas y no pavimentadas para mejoramiento de subrasante corresponden a: geomallas, geoceldas y geotextiles. Se caracterizan por proporcionar confinamiento lateral, incrementar la capacidad estructural, reducir el efecto de tensión de membrana y separación de capas. A nivel internacional, diversos estudios se han realizado a gran escala para evaluar el desempeño en pavimentos [28–31], a fin cuantificar variables y factores tales como: tránsito, clima, subrasante, materiales (p.e. materiales granulares, mezclas asfálticas), espesores, geometría, rigidez, profundidad/posición, entre otros [21]. A pesar de ser ampliamente estudiados a nivel internacional, mayores estudios se requieren para evaluar y cuantificar los efectos físico-mecánicos a nivel local.

Por lo anterior, el principal objetivo de este estudio consistió en realizar un modelo físico de una vía no pavimentada reforzada con una geomalla biaxial. Asimismo, se realizaron simulaciones numéricas con el fin de analizar la influencia de la respuesta mecánica de los suelos en presencia de una geomalla. La validación numérica incluyó la caracterización de los parámetros del modelo constitutivo Hardening Soil usando valores preestablecidos de ensayo de Índice de Soporte California, por sus siglas en inglés California Bearing Ratio (CBR). A partir de los resultados encontrados, se pretende realizar estudios adicionales

contemplando otros tipos de geosintéticos y materiales, que permitan validar metodologías mecánico empírico para el cálculo de espesores para vías pavimentadas y no pavimentadas.

2. Estado del arte

Diversos estudios se han realizado con el objetivo de analizar los beneficios de los geosintéticos vías pavimentadas y no pavimentadas [24,32,33]. Dicha eficiencia se determina mediante la relación de beneficio de tráfico por sus siglas en inglés TBR Traffic Benefit Ratio. El TBR es definida como la relación del número de ciclos de carga para el mismo ahuellamiento en una carretera reforzada sobre la no reforzada. Los valores típicos reportados en estudios indican que el TBR varían entre 2 y 16, dependiendo del tipo de suelo, características del geosintético, entre otros, [29,34]. Asimismo, Alimohammadi et al., [21] proponen un factor de equivalencia granular entre capas de pavimentos flexibles con y sin geomallas (GE). Lo anterior, basado en estudios experimentales con geomallas y la metodología de diseño AASHTO 1993, que reporta valores entre 1.78 y 10.56.

De forma general, mayores valores de TBR y GE indican mayor capacidad estructural del pavimento por influencia del geosintético, este parámetro indica mayor rigidez, resistencia a la deformabilidad (ahuellamiento) y mayor durabilidad, lo cual se puede traducir a menores espesores de materiales y consecuentemente menores costos de construcción.

En vías no pavimentadas, Leng and Gabr [28] construyeron un modelo físico compuesto por suelo de subrasante (85% arena y 15% caolín) y base granular a fin de ser sometido a carga cíclica. Se utilizaron 2 tipos de geomallas biaxiales de igual geometría y diferente rigidez. Se analizaron espesores de base de 15 cm - 25 cm y de subrasante de 90 cm - 75 cm, respectivamente. El modelo físico se construyó en una caja metálica de 1.50 m x 1.50 m de base y 1.35 m de altura. Los ensayos se realizaron aplicando 8000 ciclos de carga a una frecuencia de 0.67 Hz, empleando una carga de 40kN, presión de inflado de 550 kPa a través de una placa circular de diámetro 0.30 m. Los resultados indican que las geomallas contribuyen a reducir significativamente la deformación permanente. Mediciones de esfuerzos en la base granular con geomallas reportan menores valores en referencia al modelo no reforzado. Asimismo, las bases granulares reforzadas exhibieron menor degradación del módulo con la aplicación de ciclos de carga.

Palmeira & Antunes [29] analizaron el desempeño de una geomalla biaxial y un geotextil como refuerzo en vías no pavimentadas. Construyeron un modelo físico en una caja metálica de base cuadrada y altura de 1.6 m y 1.2 m, respectivamente. Fueron compactadas dos capas de 20 cm y 80 cm de base y subrasante, respectivamente. Se aplicó carga dinámica con presión de 556 kPa a frecuencia de 1 Hz en una placa circular de 0.30 m de diámetro. Se instrumentó la subrasante con celdas de carga y medidores de desplazamiento a profundidades de 0 m, 0.20 m y 0.40 m. En una primera etapa se aplicaron ciclos de carga hasta generar

ahuellamiento de 25 mm. En una segunda y tercera etapa se realizaron reparaciones y se aplicó nuevamente ciclos de carga para conseguir el mismo ahuellamiento. Los resultados indicaron que el modelo con geomalla soporto mayores ciclos de carga en las tres etapas en referencia al geotextil. Los valores de TBR para las tres etapas se encontraron en los rangos de 7.4 a 9.2 para la geomalla y 2.3 a 2.8 para el geotextil. Asimismo, se evidenció una reducción significativa de los esfuerzos verticales. Finalmente, análisis económicos indican que vías no pavimentadas con geomallas requieren menores costos de mantenimientos en referencia a las vías reforzadas con geosintéticos.

Qian et al., [25] estudiaron el desempeño en vías no pavimentadas reforzadas con geomallas triaxiales. Las geomallas triaxiales se caracterizan por distribuir esfuerzos de manera más uniforme. Para tal fin se construyó un modelo físico a gran escala en una caja metálica de base de 2.0 m y 2.2 m de ancho y largo, respectivamente. Se emplearon espesores de 15 cm, 23 cm y 30 cm de base granular, apoyados sobre un espesor de subrasante de 1.0 m. Fueron aplicados ciclos de carga empleando una placa circular de 0.3 m, carga de 40 kN, frecuencia de 0.77 Hz y presión de 550 kPa. Se instrumentó con medidores de desplazamiento en la superficie a 0, 25, 50 y 75 cm desde el punto de aplicación de carga. Los resultados evidencian mayor desempeño de los modelos con geomallas triaxiales en referencia al no reforzado. Los rangos de valores de TBR oscilan entre 1.0 a 13 para ahuellamientos de 25 y 75 mm, dependiendo de la relación modular entre capas (subrasante/base). La interacción entre las partículas de agregados con la geomalla triaxial reduce el efecto de tensión de membrana, lo cual incrementa la rigidez.

Palmeira & Gongora [35,36], analizaron la influencia de las características físicas de geomallas y geotextiles en vías no pavimentada. Fueron analizadas diferentes geomallas considerando diferentes aberturas, resistencia a la tracción, rigidez, entre otras. Para tal fin, construyeron un modelo físico circular (1.20 m de diámetro) compuesto de una capa de subrasante y material granular de 30 cm y 22.50 cm, respectivamente. Se realizó la aplicación de carga dinámica empleando una presión de 560 MPa a través un actuador a frecuencia de 1 Hz por medio de una placa circular de 0.2 m diámetro. Los resultados indicaron un incremento del TBR oscilando entre 1 y 121, dependiendo del tipo de geotextil. Los resultados determinaron correlaciones entre algunas características físicas de los geotextiles y el comportamiento mecánico. Sin embargo, la eficiencia del geosintético no depende directamente de su resistencia a la tracción, abertura y rigidez. Empleando el mismo modelo físico, Gongora & Palmeira [31] usaron agregados reciclados provenientes de residuos de construcción y demolición como material granular. Los resultados evidenciaron un alto potencial en el aprovechamiento de materiales reciclados para vías no pavimentadas reforzadas con geotextiles.

A partir de la literatura consultada, diversos investigadores realizaron la construcción de modelos físicos para simular vías no pavimentadas con diferentes geosintéticos, tipos de suelos, materiales granulares, espesores, entre otros. Algunos emplearon cajas (cuadradas o rectángulos) o tanques

circulares para conformar diferentes estructuras. En todos los casos, se aplicaron condiciones similares de carga simulando el paso de eje estándar de diseño de 80 kN, presión de inflado, magnitud y tamaño del área de aplicación de carga, entre otros. De igual forma, se instrumentaron los modelos físicos con el objetivo de cuantificar esfuerzos y desplazamientos superficiales. De forma general, los resultados indicaron que existe un beneficio por la presencia de los geosintéticos. Sin embargo, no existe un consenso en valores de la eficiencia de los geotextiles, dado que los rangos de TBR son amplios. Así, mayores estudios son requeridos con el fin de proporcionar adecuadamente los criterios de selección de geosintéticos, basado en su eficiencia, características físicas y mecánicas de suelos, materiales granulares, tránsito, clima, entre otras.

3. Materiales y métodos

3.1 Materiales

3.1.1 Geomalla biaxial

La geomalla biaxial utilizada para el refuerzo de la vía no pavimentada fue suministrada por la empresa Pavco Wavin y es de común uso en obras de infraestructura de la ciudad de Bogotá (Ver Fig. 1). En la Tabla 1 se presentan los principales ensayos de caracterización de la geomalla.

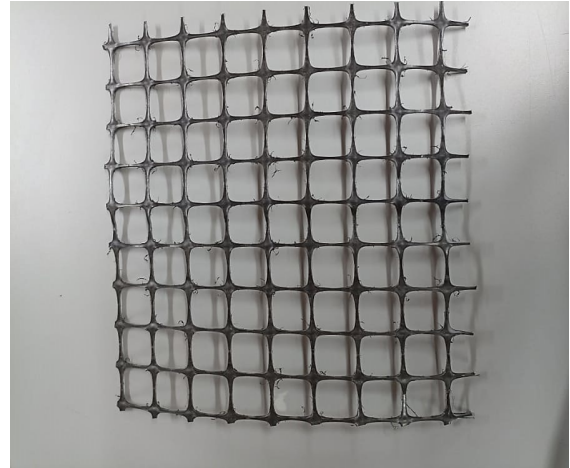


Figura 1. Geomalla biaxial.
Fuente: Autores.

Tabla 1.
Características de la geomalla biaxial 20X20.

Características	Procedimiento de medición	Resultado
Abertura (mm)	Manual	20
Espesor de costilla (mm)	Manual	2.3 a 3.1
Rigidez radial (kN/m)	ISO 10319	380
Rigidez ultima a la tensión (kN/m)	ASTM D6637	20
Rigidez flexural (mg.cm)	ASTM D7748	700000
Rigidez torsional J (cm.kg/deg)	GRI GG9	3.3
Resistencia a la degradación UV (%)	ASTM D4355/D6637	90
Resistencia a los daños químicos (%)	EPA 9090A	100

Fuente: Autores.

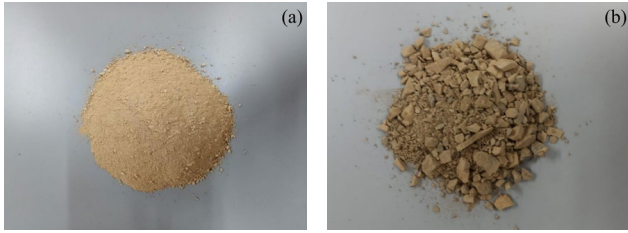


Figura 2. Materiales para pavimentos: a) Suelo de subrasante, b) material granular.

Fuente: Autores.

Tabla 2.

Características físicas del suelo de subrasante y material de mejoramiento.

Parámetros	Suelo de subrasante	Material de mejoramiento
D ₁₀ (mm)	0.15	1.2
D ₃₀ (mm)	0.36	4.7
D ₆₀ (mm)	1.1	19
Coefficiente de uniformidad	7.3	15.8
Coefficiente de curvatura	0.8	1.0
Contenidos Finos (%)	8.3	5.6
Límite Líquido (%)	86	26.9
Límite Plástico (%)	10.2	12.2
Índice de Plasticidad (%)	75.8	14.7
Índice de Grupo	0	0
Clasificación AASTHO	A-2-5	A-2-6
Clasificación SUCS	SW-SC	GW-CL
Contenido de humedad óptima (%)	14.5	8.5
Peso Unitario Máximo seco (kN/m ³)	18.3	20.6
PDC (mm/golpe)	30.8	14.98
California Bearing Ratio CBR (%)	7.6	14.4

Fuente: Autores.

3.1.2 Suelo de subrasante y material de mejoramiento

La subrasante del pavimento corresponde a un suelo de la ciudad de Bogotá (ver Fig. 2a). Para la capa de mejoramiento un material granular (ver Fig. 2b). Fueron realizados ensayos de caracterización física, tales como: determinación del tamaño de las partículas INV-E 123 2013, límite líquido (LL) INV-E 125 2013, límite Plástico (LP) relación de humedad-peso unitario seco (ensayo de compactación energía normal) INV-E 142 2013 e Índice de Soporte California (CBR) INV-E 148 2013. Los resultados de los ensayos para el suelo y el material granular se presentan en las Tablas 2 y 3, respectivamente. A partir de los resultados, el suelo y el material granular se clasifican en los grupos A-2-5 y A-2-6 según el sistema de la AASTHO, respectivamente.

3.2 Construcción del modelo físico

La construcción del modelo físico se realizó con el objetivo de simular una estructura de pavimento unicapa. Esa estructura se compone de una capa de subrasante y una capa de material de mejoramiento. En la interfaz entre las capas se consideró la presencia y ausencia de la geomalla biaxial como material de refuerzo. Para construcción de las capas, se procedió a construir una caja metálica abierta cuadrada de 0.35 m por cada lado. Dicha caja se realizó con acero

inoxidable calibre 12, el cual corresponde a un espesor aproximado de 2.75 mm. En la Fig. 3 se presentan el modelo físico y el equipo para la aplicación de la carga dinámica cíclica.

En la construcción del modelo físico se utilizaron los resultados de los ensayos de compactación. A partir de la máxima densidad húmeda obtenida en el Proctor, se calculó la masa húmeda para completar el volumen de cada material (Ecu. 1). Donde $M_{húmeda}$ y $\gamma_{húmeda}$ corresponden a la masa en kg y densidad húmeda en kg/m³ de cada material, respectivamente; V es el volumen geométrico en m³. Fueron adoptados espesores de 20 cm y 15 cm para la subrasante y subbase granular.

$$M_{húmeda} = \gamma_{húmeda} \cdot V \quad (1)$$

El número de capas y de golpes para la compactación de los materiales fueron determinados a partir de la energía de compactación Proctor, conforme a (Ecu. 2). Donde E corresponde a la energía de compactación en kN-m/m³; n y N equivale a los números de capas y de golpes/capa, respectivamente; W y H al peso y altura de caída del martillo en kN y m, respectivamente y V equivale al volumen del cilindro o modelo físico en m³.

$$E = \frac{n \cdot N \cdot W \cdot H}{V} \quad (2)$$

En la compactación del modelo físico, se subdividió en 4 y 6 subcapas la subrasante y el material de mejoramiento. Se utilizaron los mismos martillos empleados en los ensayos de compactación Proctor.



Figura 3. Modelo físico de laboratorio.

Fuente: Autores.

Tabla 3.
Variables para la energía de compactación.

Material	Suelo de subrasante		Material de mejoramiento	
Tipo de energía	Normal		Modificada	
Compactación	Ensayo	Modelo físico	Ensayo	Modelo físico
Número de golpes/capa	25	331	56	270
Número de capas	3	4	5	6
Altura de caída (m)	0.30	0.45	0.30	0.45
Peso del martillo (kN)	0.02	0.02	0.04	0.04
Volumen (m ³)	0.00093	0.025	0.00212	0.018
Energía (KN-m/m ³)	595	595	1764	1764

Fuente: Autores.



Figura 4. Construcción del modelo físico: a) protección de la caja metálica; b) colocación la subrasante; c) compactación de la primera capa de subrasante; d) compactación subrasante; e) colocación de la geomalla; f) colocación del material de mejoramiento.

Fuente: Autores.

En la Tabla 3 se presentan los valores de energía de compactación para cada modelo físico.

Para garantizar la humedad óptima de compactación, los materiales fueron secados en un horno a temperatura de 60°C durante 24 horas. Posteriormente, se adicionó la cantidad de agua suficiente para alcanzar la humedad óptima de compactación. Estudios previos indican que el secado de los materiales a temperaturas mayores de 60°C puede originar cambios significativos en la estructura, composición química y mineralógica. Adicionalmente, en la interfaz entre la caja metálica con los materiales se colocó papel vinipel para reducir la fricción entre materiales según recomendaciones de [35,36]. En la Fig. 4 se presenta la metodología en laboratorio para la construcción del modelo físico. Es decir, la compactación de la subrasante, colocación de la geomalla y compactación de la capa de mejoramiento.

Luego de construir los modelos físicos (con y sin geomalla), se colocó en una Máquina Universal de Ensayo (UTM) para la realización del ensayo. Se aplicó una carga dinámica de manera cíclica a través de una placa metálica circular de 0.1 m de diámetro. Se aplicó una presión de contacto de 560 kPa y una carga de 4.4 kN. La frecuencia de carga correspondió a 2.5 Hz, lo cual equivale a que, durante 1 ciclo de carga, el periodo de carga corresponde al 40% y el periodo de descarga al 60%. Dicha frecuencia representa la velocidad real de un vehículo a una velocidad entre 30 a 40 km/hora, lo cual es común en las vías terciarias. Fueron aplicados 10000 ciclos de carga con el objetivo de analizar el ahuellamiento en el tiempo.

La eficiencia de la geomalla como refuerzo en una vía sin pavimento se puede cuantificar mediante la *TBR*, definido en (Ecu. 3), donde N_r y N_u corresponden al número de ciclos de carga para el mismo ahuellamiento en una carretera reforzada y no reforzada, respectivamente. Para este estudio, *TBR* se determinó para 10 mm.

$$TBR = \frac{N_r}{N_u} \quad (3)$$

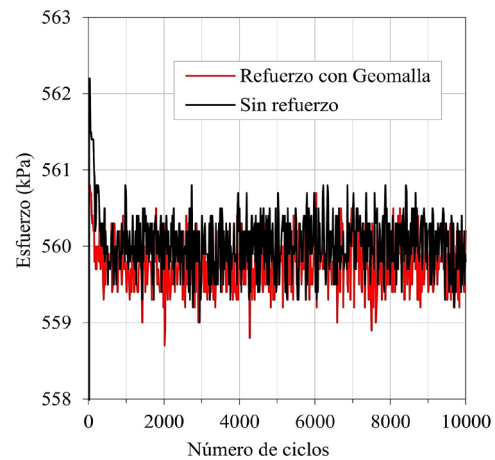


Figure 5. Variación del esfuerzo aplicado con el número de ciclos.
Fuente: Autores.

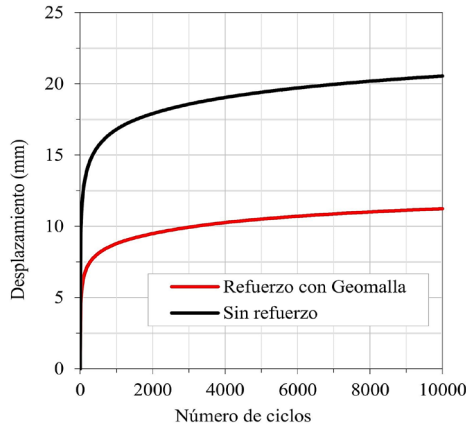


Figure 6. Variación del desplazamiento con el número de ciclos.
Fuente: Autores.

4. Resultados experimento físico

Resultados del esfuerzo aplicado y el desplazamiento con el número de ciclos para los dos modelos físicos se presentan en las Figs. 5 y 6, respectivamente.

El esfuerzo promedio para los dos modelos corresponde a 560 kPa. Sin embargo, la diferencia entre el mayor y menor esfuerzo corresponde a 2.0 kPa y 3.2 kPa para el modelo reforzado y no reforzado, respectivamente. Lo anterior, puede indicar que el modelo reforzado presenta mayor acomodo de partículas en referencia al modelo sin refuerzo, dado que se presenta menor variabilidad en el esfuerzo aplicado. Por otro lado, el modelo con geomalla presentó mayor resistencia al ahuellamiento en referencia al modelo no reforzado. Ese comportamiento fue evidenciado para todos los ciclos de carga aplicados. Los incrementos de la resistencia al ahuellamiento para 1000, 2000, 3000, 5000 y 10000 ciclos de carga corresponden al 47.7%, 47.0%, 46.5%, 45.9% y 45.3%, respectivamente. En términos del ahuellamiento, los desplazamientos finales para los modelos con y sin refuerzo corresponden a 11.2 y 20.5 mm, respectivamente. Lo anterior evidencia que la geomalla aporta rigidez y capacidad estructural. Según [21], ese comportamiento es proporcionado por el incremento del confinamiento lateral producto de la interacción materiales-geosintético. Finalmente, los resultados indican que para producir un ahuellamiento de 10 mm se requiere de aproximadamente 33 y 3185 repeticiones de carga para el modelo sin y con geomalla, respectivamente. Lo que lleva a obtener un valor de 138 para el TRB. Valores típicos de TBR para diseño de pavimentos oscilan entre 2 y 16, dependiendo del tipo de suelo, geosintéticos, entre otros. Aunque [25] señala que los TBR resultantes de ensayos experimentales en el laboratorio no debe usarse directamente para el diseño de pavimentos. Por lo anterior, mayores estudios se deben realizar para establecer valores de diseño, basados en calibraciones locales para Colombia. Dichos estudios deberán incluir modelaciones numéricas que validen la caracterización de parámetros mecánicos de los suelos.

5. Simulación matemática con Método de Elementos Finitos (FEM)

El modelado numérico del ensayo físico abarca tres etapas metodológicas. La primera etapa correspondió a la selección del modelo constitutivo y determinación de los parámetros mecánicos de cada elemento. La segunda etapa corresponde a la definición de la geometría y de la secuenciación de la simulación. Finalmente, la tercera etapa corresponde a la interpretación de los resultados numéricos la luz del análisis del ahuellamiento en el experimento a escala.

Caracterización mecánica: Se escogió el modelo Hardening Soil (HS) para los suelos granulares [37], y elástico lineal para las paredes de la caja y la geomalla. Así, los parámetros mecánicos del modelo HS de los suelos se realizó implementando los siguientes criterios propuestos (Ecu 4 a 6), donde E_{50} , E_{edo} , E_{ur} corresponden al módulo elástico obtenido con el 50% de carga de ruptura, modulo edometrico y módulo de descarga en MPa, respectivamente. Asimismo, M_r , corresponde al Modulo resiliente en MPa.

$$E_{50} = 0.66M_r \quad (4)$$

$$E_{edo} = 1.15E_{50} \quad (5)$$

$$E_{ur} = 2E_{50} \quad (6)$$

El módulo resiliente de cada suelo fue obtenido a partir de la siguiente correlación con el CBR (Ecu 7), la cual aplica para materiales densificados-remodelados en laboratorio [38], donde PDC corresponde a la pendiente de la curva del ensayo del penetrómetro dinámico de cono según INVIAS 172 de 2013.

$$CBR = 10^{2.182 - 0.872 \log(PDC)} \quad (7)$$

A partir de la caracterización física e implementación de las Ecuaciones 4 a 7 fueron calculados los parámetros del modelo, los cuales se presentan en la Tabla 4.

Tabla 4.

Parámetros Hardening Soil Model para los suelos

Parámetros	Suelo de subrasante	Material de mejoramiento
Modelo Constitutivo	Hardening Soil	Hardening Soil
PDC (mm/golpe)	30.8	14.9
CBR (%)	7.6	14.4
M_r (MPa)	79.2	149.2
E_{50} (MPa)	52.3	98.4
E_{edo} (MPa)	60.1	113.2
E_{ur} (MPa)	104.5	196.9
Exponente m	0.5	0.5
Poisson (v)	0.33	0.33
Angulo de fricción ϕ (°)	30	45
Dilatancia $\Delta\phi$ (°)	0.0	0.0
Cohesión c' (kPa)	7.3	0.0
Relación de sobreconsolidación Over Consolidation Ratio OCR	5.0	3.0

Fuente: Autores.

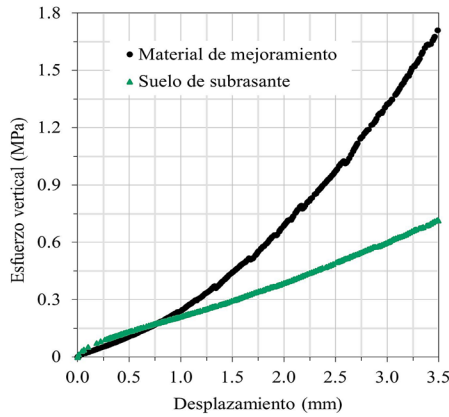


Figure 7. Simulación ensayo CBR parámetros Hardening Soil Model
Fuente: Autores.

Tabla 5.
Parámetros numéricos materiales adicionales

Parámetros	Paredes de la caja	Área de aplicación de carga	Geomalla
Tipo de elemento	plates	plates	geogrids
Modelo constitutivo	Elástico lineal	Elástico lineal	Elástico Lineal
Módulo Axial EA (N/mm)	3.0×10^7	7.0×10^8	20.0
Módulo a flexión EI (N mm ² /mm)	6.3×10^7	5.83×10^9	--
Poisson v	0.33	0.33	--

Fuente: Autores.

Se realizó una validación de los parámetros adoptados mediante la implementación de un ensayo numérico de CBR bajo condiciones drenadas [39], [40]. El resultado se presenta en la Fig. 7. A partir de la simulación, se obtuvo un CBR a 2.54 mm de 14.53% y de 7.27% para el material de mejoramiento y la subrasante, respectivamente.

Los parámetros mecánicos para las paredes de la caja, la placa circular para la aplicación de carga y geomalla se presentan en la Tabla 5.

Creación del modelo numérico: Se implementó un modelo numérico FEM usando el programa PLAXIS 2D en condiciones axi-simétricas. La geometría correspondió a un cilindro con dimensiones 175 mm de radio y 350 mm de altura. En el borde lateral e inferior externo se contempló un elemento de borde (paredes de la caja). La carga fue aplicada sobre un elemento circular para la aplicación de carga de 0.10 m, en una porción inicial de 15 mm con magnitud 6.2 MPa, simulando el pistón del equipo. La geomalla se alejó 10 mm de la pared para evitar interferencia con la interfaz parde caja-materiales. De esta manera se garantiza la aplicación al mejoramiento de la presión de 560 kPa. El enmallado consistió en 4511 elementos triangulares de 15 nodos con tamaño promedio de 5.4 mm. No se implementó la interfaz del geotextil con el material de mejoramiento, dado que se considera que la trabazón de los granulares alejan la superficie de falla por fuera de la geomalla [41]. La geometría del modelo numérico del modelo físico se presenta en la Fig.

8. El modelado del experimento del ahuellamiento consistió en una fase inicial tipo gravedad incremental para considerar una distribución de esfuerzos relacionada con la pared vertical de acrílico, la cual es una superficie libre. Seguida la fase inicial, siguieron dos ciclos de carga-descarga en condiciones monotónicas-estáticas drenadas.

Resultados del modelo numérico: En la Fig. 9 se presenta la curva esfuerzo desplazamiento de los dos ciclos de carga para el modelo físico con y sin geomalla. Considerando que el primer ciclo de carga es una etapa de establecimiento elastoplástico, en este estudio se considera que el segundo ciclo de carga-descarga consiste de un comportamiento resiliente. Para el caso del según ciclo de carga, el aporte en la deformación permanente es de 5.58×10^{-2} mm/ciclo y 3.47×10^{-2} mm/ciclo, para los casos sin refuerzo y con refuerzo respectivamente. Estas velocidades de ahuellamiento son coherentes con cien ciclos de carga en el experimento físico en el laboratorio. Lo que implica una reducción del 38% en la velocidad del ahuellamiento con la inclusión de la geomalla. Este incremento es coherente con el experimento físico en donde la mediana de la reducción de la rata del ahuellamiento es de 36.4%.

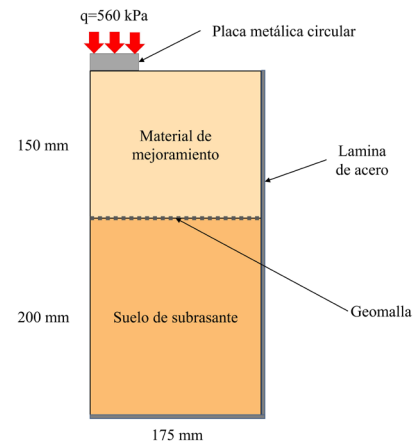


Figura 8. Geometría del modelo numérico FEM de la caja experimental
Fuente: Autores.

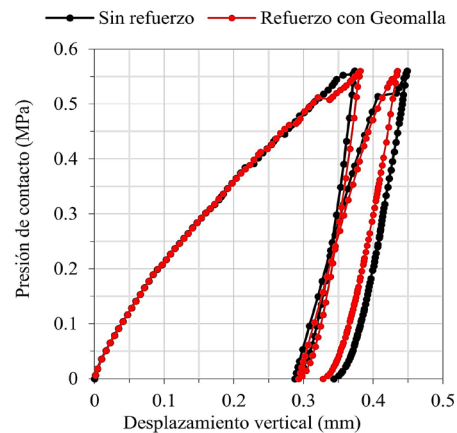


Figura 9. Resultados modelado numérico dos ciclos de carga
Fuente: Autores.

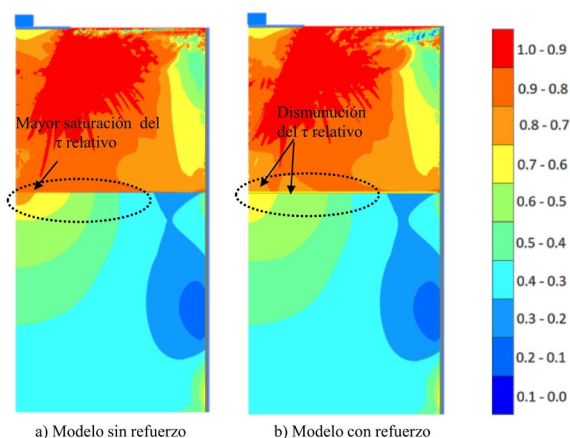


Figura 10. Distribución del τ relativo modelado FEM
Fuente: Autores.

El aumento en la resistencia a la deformación permanente debido a la inclusión de la geomalla puede ser entendido a partir de la distribución del τ relativo. El cual se define como relación entre el esfuerzo cortante movilizado con respecto a la resistencia disponible. La Fig. 10 presenta la distribución de los resultados de las modelaciones sin refuerzo y con la geomalla. Se puede verificar visualmente que la mayor concentración del τ relativo corresponde al caso no reforzado. En este caso, se presenta un τ relativo hasta el 80% en la subrasante debajo de la carga, justo en el contacto con el material de mejoramiento. Mientras que el modelo reforzado, el τ relativo no supera el 70%.

Por otro lado, la presencia del geotextil también disminuye la magnitud del τ relativo en el material de mejoramiento: hacia la base del estrato gravoso, el τ relativo pasa de 80-90% sin refuerzo a 70-80% con refuerzo. La concentración de esfuerzos cortantes es uno de los parámetros que controla la predicción del ahuellamiento en materiales granulares [42 - 43].

6. Conclusiones

Este estudio evaluó el comportamiento mecánico de un modelo físico en laboratorio de una vía no pavimentada compuesto por una capa de material granular apoyada en una subrasante reforzada con una geomalla biaxial GB. La cual fue sometida a la aplicación de 10000 ciclos de carga dinámica en una máquina universal. A partir de los resultados obtenidos, es posible concluir:

La geomalla como material de refuerzo aumenta considerablemente la resistencia a la deformación permanente y reduce consecuentemente el ahuellamiento en aproximadamente 45% comparado al modelo sin refuerzo. Lo cual evidencia una alta eficiencia del geosintético. Según la literatura, lo anterior es atribuido al incremento del confinamiento lateral, lo cual proporciona mayor capacidad estructural y reduce el efecto de tensión membrana.

La validación numérica permitió la verificación de los efectos que tiene la geomalla en el modelo físico. El análisis por elementos finitos incluye criterios para la determinación de los parámetros Hardening Soil. El modelado numérico permite encontrar la distribución del tau relativo (τ relativo), siendo menor para el caso reforzado. A menor τ relativo se presenta menor deformación plástica acumulada en cada ciclo. Este efecto redunda en una disminución del ahuellamiento.

Los resultados presentados en este estudio son válidos únicamente para el tipo de geomalla, de suelo, de material granular y las condiciones de carga empleadas. Nuevos estudios se recomiendan con el objetivo de establecer correlaciones entre las características físicas de diferentes geomallas y geotextiles con los parámetros geotécnicos de los suelos y los materiales. Así como analizar diferentes materiales granulares convencionales y alternativos (p.e. Residuos de demolición y construcción, material asfáltico reciclado (Reclaimed Asphalt Pavement RAP), residuos industriales, entre otros).

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Development of an IoT architecture for environmental monitoring: integrating open source technologies with application projection in the mining sector

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Abstract

This work describes the design and implementation of an Internet of Things architecture that focuses on monitoring temperature and humidity. The system is based on the strategic selection of technologies, including Arduino, LoRa modules, DHT11 sensors, and ESP32 microcontrollers. Python Flask was used to develop a user interface for the web application, ensuring an easy and accessible user experience. Moreover, to enhance the scalability and security of the system, it is recommended to implement modular algorithms and authentication measures. The article concludes by emphasising the advantages and effectiveness of open source technology in data acquisition, processing, and monitoring across various application scenarios. Suggestions for future improvements are provided, with particular attention to expanding data visualisation and environmental monitoring. The limitations and advantages of the system are addressed, highlighting its potential application in remote or resource-limited areas. The results obtained in this work can be scaled to the different stages of a mining project in which environmental parameters must be monitored.

Keywords: Internet of Things (IoT); environmental parameters; open source.

Desarrollo de una Arquitectura IoT para monitoreo ambiental: integración de tecnologías de código abierto con proyección de aplicación en el sector minero

Resumen

Este trabajo detalla el diseño y la implementación de una arquitectura de Internet de las Cosas centrada en el monitoreo de temperatura y humedad. La selección estratégica de tecnologías, como Arduino, módulos LoRa, sensor DHT11 y el microcontrolador ESP32, constituye la base del sistema. Se destaca el empleo de Python Flask para desarrollar una interfaz de usuario en la aplicación web, asegurando así una experiencia de usuario fácil y accesible. Además, se enfatiza la implementación de algoritmos modulares y medidas de autenticación para mejorar la escalabilidad y seguridad del sistema. El artículo concluye resaltando los beneficios y la eficacia de la tecnología de código abierto en la adquisición, procesamiento y monitoreo de datos en diferentes escenarios de aplicación. Se proporcionan sugerencias para futuras mejoras, con especial atención a la expansión de la visualización de datos y la monitorización ambiental. Se abordan las limitaciones y ventajas del sistema, destacando su potencial aplicación en áreas remotas o con recursos limitados. Se espera que los resultados obtenidos en este trabajo puedan ser escalados a las diferentes etapas de un proyecto minero de pequeña y mediana escala en los que se requiere monitorear parámetros ambientales que oriente la toma de decisiones, como una metodología de trabajo que esté al alcance de pequeñas agremiaciones y explotación de recursos naturales de manera sostenible.

Palabras clave: Internet de las cosas (IoT); parámetros ambientales; código abierto.

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1. Introducción

El paradigma del Internet de las Cosas (IoT) ha experimentado una difusión significativa, extendiéndose en aplicaciones que abarcan desde la atención médica inteligente hasta ciudades inteligentes, industria, transporte y agricultura, entre otros dominios. Las plataformas de IoT han emergido como herramientas fundamentales al proporcionar información supervisada y soluciones prácticas para abordar desafíos del mundo real [1]. La interconexión de sensores, dispositivos y sistemas inteligentes ha optimizado la toma de decisiones fundamentadas en datos, impulsando la comprensión, gestión y eficiencia en diversos sectores [2].

Los sistemas basados en IoT se caracterizan por una arquitectura con tres niveles fundamentales. En el nivel más bajo, el de dispositivos, se encuentran sensores y objetos conectados encargados de la recopilación de datos. El nivel intermedio, de red, facilita el transporte de datos mediante tecnologías de comunicación. El nivel más alto, de aplicaciones, se encarga del procesamiento de datos y ofrece servicios a los usuarios [3]. La estructura en capas de IoT permite separar las diferentes funciones de un sistema IoT en tres niveles distintos, facilitando el diseño, la implementación y la gestión.

Además, la implementación de redes de sensores inalámbricas (WSNs) [4] desempeña un papel esencial al respaldar diversas operaciones en conjunto con los dispositivos IoT, contribuyendo así a la funcionalidad integral del sistema. Las WSNs posibilitan la comunicación entre dispositivos en el sistema de IoT, facilitando el intercambio de información y la coordinación entre diferentes componentes [3]. Esto habilita la recopilación de datos provenientes de un amplio número de sensores, los cuales, a su vez, pueden emplearse para supervisar y controlar distintos aspectos.

La conexión a la red de múltiples dispositivos permite realizar un monitoreo en tiempo real de los objetos, lo que aumenta la eficiencia en la gestión de recursos y operaciones a través de un control remoto [5]. Estos dispositivos recopilan datos sobre el estado de los objetos, como temperatura, humedad y ubicación, que se utilizan para monitorear su funcionamiento y detectar problemas, así como para controlarlos de forma remota. Este proceso contribuye a la detección temprana de fallos en equipos y al control del consumo de energía. En última instancia, este avance ha revolucionado la recopilación de datos, generando nuevas oportunidades de investigación en diversas áreas, incluyendo las ciencias de la tierra [1].

La implementación de IoT proporciona la capacidad para supervisar diferentes aspectos del entorno, mejorando la adquisición de datos y el monitoreo [6]. En el ámbito de las ciencias de la tierra, se han desarrollado diversas aproximaciones con estos propósitos, destacándose principalmente el monitoreo de la calidad del aire, la calidad del agua, el análisis de la salud estructural y la agricultura de precisión.

En relación con el monitoreo de la calidad del aire, se

hace énfasis en la necesidad de sistemas de monitoreo continuo de contaminantes, debido a la amenaza que la contaminación del aire representa para la salud y el medio ambiente. Los sistemas basados en IoT han demostrado reducir costos, consumo de energía y mejorar la red de detección, facilitando la construcción de modelos de contaminación [7]. Balarengadurai et al. [8] han introducido un sistema autónomo de control de la calidad del aire mediante sensores de bajo costo, como Arduino Uno, Raspberry Pi y el protocolo de comunicación MQTT. Este sistema ha demostrado su eficacia al recopilar datos en tiempo real de temperatura, humedad, partículas PM 2.5, monóxido de carbono y dióxido de carbono, contribuyendo así al monitoreo ambiental. Además, la investigación sobre la aplicación de la tecnología LoRa de largo alcance para sistemas de monitoreo ambiental busca extender la vida útil de la batería y reducir los costos totales del sistema, abarcando parámetros como partículas PM 2.5, partículas PM 10, dióxido de carbono, temperatura y humedad [9].

En cuanto al monitoreo de la calidad del agua, esencial en diversas aplicaciones para la gestión de cuerpos de agua y el control de contaminantes, se han desarrollado sistemas efectivos de bajo costo para monitorear fuentes hídricas [10]. Un ejemplo es el sistema presentado por Mendez et al. [11], que utiliza un sensor capacitivo interdirigido de bajo costo para medir la conductividad del agua, junto con una red IoT de comunicación de campo cercano (NFC). Este sistema permite la interacción entre un microcontrolador, un dispositivo móvil y una interfaz en línea, facilitando el monitoreo de fuentes hídricas. Además, en [12] se propuso una arquitectura basada en IoT de código abierto que emplea Arduino. Esta plataforma ofrece características como bajo consumo de energía, lectura casi en tiempo real y sensores de luz, temperatura y presión para aplicaciones en entornos acuáticos.

Por otro lado, el seguimiento y evaluación del estado estructural, crucial para prevenir incidentes relacionados con colapsos, ha llevado a la implementación de sistemas basados en IoT, como el propuesto por [13] para el monitoreo de puentes. Este sistema, que comprende varios módulos, utiliza sensores de desplazamiento, microcontroladores y un protocolo de comunicación NB-IoT para almacenar y visualizar datos en la nube. Los resultados validaron su efectividad, especialmente en entornos de construcción.

Adicionalmente, en la agricultura, los sistemas basados en IoT han demostrado ser valiosos para la optimización de prácticas de cultivo. Estos sistemas permiten la recolección de datos climáticos, seguimiento del ganado, detección temprana de problemas en cultivos, gestión de residuos, monitoreo de calidad del suelo y crecimiento de las siembras, entre otros parámetros [14]–[15]. Por ejemplo, [16] propusieron un sistema de agricultura inteligente con nodos que emplean tecnologías de comunicación Wifi, ZigBee y LoRaWAN para la transmisión de datos en diversas condiciones ambientales. En este se concluyó que LoRaWAN es la tecnología óptima para sistemas de monitoreo agrícola cuando se prioriza el consumo de energía y la vida útil de la red.

En este contexto, el objetivo central de la presente

investigación radica en diseñar e implementar una metodología para un esquema de registro y visualización de parámetros en línea de bajo costo, como una tecnología de fácil acceso que apoye la transformación digital de las pequeñas y medianas empresas, y aporte al cuidado del medio ambiente. Este sistema pretende posibilitar la monitorización en tiempo real y el control de variables en diversas áreas de la ciencia de la tierra, con la finalidad de optimizar la recopilación de datos, mejorar la eficiencia en el uso de recursos y proporcionar información precisa para la toma de decisiones en los respectivos campos de estudio. Por ejemplo, en el sector minero, podrá ser empleado para el monitoreo de la calidad de los parámetros ambientales en todo el ciclo de vida de un proyecto minero de pequeña y mediana escala de producción.

2. Materiales y métodos

La metodología adoptada en este estudio se enfocó en la implementación de una arquitectura IoT eficaz destinada al monitoreo y control en diversos contextos dentro del ámbito de las ciencias de la tierra. La contribución principal reside en la optimización de recursos, la detección temprana de problemas y la toma de decisiones fundamentadas. A continuación, se detallan los pasos involucrados en el desarrollo de la metodología.

2.1 Identificación de parámetros a monitorear

Esta etapa implicó un análisis destinado a determinar los parámetros y variables específicos que serían objeto de monitoreo. Este proceso incluyó la consideración de factores en diversas áreas, evaluando criterios tales como relevancia, impacto en el contexto de monitoreo y posibilidad de control. La definición precisa de estos parámetros se fundamentó en una revisión bibliográfica exhaustiva y la evaluación de los requisitos específicos del entorno.

2.2 Selección de componentes de la arquitectura

Durante esta etapa, se procedió con la selección de sensores, considerando su adaptabilidad a los parámetros previamente identificados. Posteriormente, se llevó a cabo la elección de dispositivos de adquisición de datos, incluyendo microcontroladores, mediante un análisis comparativo según las especificaciones del fabricante, que evaluó sus capacidades en eficiencia energética y compatibilidad con los sensores seleccionados. En la fase final de esta etapa, se realizó la elección del protocolo de comunicación entre los dispositivos para garantizar una integración eficiente en la arquitectura general del sistema.

2.3 Diseño, implementación y validación de la arquitectura IoT

Tras la selección de componentes, se procedió con la planificación detallada de las interacciones en el sistema, considerando la disposición espacial de los sensores, la configuración de los protocolos de comunicación y la

definición de estrategias para el almacenamiento y procesamiento de datos. La conectividad con la plataforma IoT se abordó con un enfoque centrado en la eficacia del monitoreo remoto, asegurando una integración fluida entre las diversas capas del sistema. La implementación progresiva incluyó la configuración de sensores y dispositivos, seguida de una validación iterativa mediante pruebas de funcionamiento y confiabilidad de los datos, con ajustes continuos para optimizar el rendimiento del sistema.

2.4 Desarrollo de la interfaz de visualización

La fase de desarrollo de la interfaz de visualización se concentró en la creación de paneles con gráficos dinámicos. Esta etapa se basó en la identificación de los usuarios finales y sus necesidades específicas de visualización. La interfaz resultante pretende representar claramente los datos recopilados, permitiendo una interpretación efectiva de los parámetros monitoreados en tiempo real.

3. Resultados y discusión

3.1 Identificación de parámetros a monitorear

Se eligieron los parámetros de temperatura y humedad, con base en la relevancia de estas variables en contextos específicos, como la agricultura de precisión, la calidad del aire y el agua, y el seguimiento estructural como un factor de seguridad. En Colombia, estos parámetros muestran variaciones notables a lo largo del año, afectando la productividad, la salud humana. En la agricultura, monitorear la temperatura y la humedad es esencial para prever la producción de cultivos y mejorar las prácticas agrícolas, mientras que el seguimiento de la calidad del aire y el agua es crucial para evaluar la contaminación y la salud pública, como parte de las buenas prácticas hacia una producción sostenible de sectores económicos como el sector minero energético.

3.2 Selección de componentes de la arquitectura

Sensor DHT11 (Temperatura y Humedad): Este sensor fue elegido por su versatilidad y bajo costo. Es capaz de medir tanto la temperatura como la humedad, lo que lo hace adecuado para el monitoreo ambiental en diferentes contextos. Su amplia utilización y bajo costo facilitan su implementación a gran escala, siendo esencial para recopilar datos precisos sobre los parámetros seleccionados.

Arduino Nano (Nodo Sensor): Este microcontrolador se seleccionó debido a su versatilidad y facilidad de programación. Permite la adaptación de cada nodo sensor a las necesidades específicas de recopilación de datos en entornos remotos. Su tamaño reducido y bajo costo lo hacen ideal para implementaciones distribuidas, como la propuesta en la arquitectura IoT.

Módulos LoRa Ra-02 (Comunicación de Larga Distancia): Estos módulos se eligieron por su eficiencia

energética y capacidad para transmitir datos a largas distancias. La tecnología LoRa es esencial para una arquitectura IoT distribuida, asegurando una comunicación robusta entre los nodos sensores y la plataforma de monitoreo y control.

ESP32 (Gateway): Se seleccionó este dispositivo por su conectividad Wi-Fi y Bluetooth. Funciona como una puerta de enlace que recopila datos de los nodos sensores y los transmite a la plataforma de monitoreo y control en línea. Su capacidad para gestionar eficientemente grandes cantidades de datos y su versatilidad en términos de conectividad lo hacen un componente clave en la arquitectura.

Python Flask (Interfaz de Usuario): Se eligió Flask para el desarrollo de la interfaz de usuario en la aplicación web. Su facilidad de desarrollo permite la creación de una interfaz amigable y accesible para la visualización de datos recopilados. Flask proporciona la capacidad de presentar la información de manera clara y eficiente para los usuarios finales

3.3 Diseño, implementación y validación de la arquitectura IoT

La implementación de la arquitectura comprendió la integración de componentes interconectados para asegurar el funcionamiento integral del sistema, dividiéndose en tres capas esenciales.

3.3.1 Capa de Dispositivos

En esta capa se alojan los dispositivos físicos utilizados, que incluyen sensores, actuadores y cualquier otro hardware encargado de recopilar datos o ejecutar acciones.

Arduino Nano: Estos dispositivos compactos y autónomos operan como nodos sensores, encargados de recopilar datos de temperatura y humedad. Son desplegables en ubicaciones remotas, contribuyendo a la adquisición de información relevante.

Módulo LoRa Ra-02: Utilizado para facilitar la comunicación de largo alcance entre los Arduino Nano y el ESP32 Gateway, este componente juega un papel crucial en la conectividad eficiente del sistema.

Sensor DHT11: Este sensor desempeña la función de medir la temperatura y humedad en el entorno circundante, proporcionando datos fundamentales para el monitoreo ambiental y contribuyendo a la recopilación precisa de información relevante.

3.3.2 Capa de Red

Actuando como intermediaria entre la capa de dispositivos y la capa de aplicación, esta capa incluye a la puerta de enlace para facilitar la comunicación. Gestiona la conectividad, seguridad y eficiencia en la transmisión de datos entre los dispositivos y la plataforma.

ESP32 Gateway: Microcontrolador central de recopilación de datos que recibe la información de los dispositivos Arduino Nano a través del módulo LoRa y la

enruta hacia la capa de aplicación.

Módulo LoRa Ra-02: Similar a la capa de dispositivos, permite la comunicación de largo alcance con los Arduino Nano.

3.3.3 Capa de Aplicación

En esta capa, los datos se presentan de manera comprensible a través de un panel de control, permitiendo a los usuarios finales tomar decisiones informadas.

App de Python Flask: Aplicación web que recibe, procesa y visualiza datos de temperatura y humedad provenientes de los dispositivos Arduino Nano a través del ESP32 Gateway.

En la tabla 1 se detallan las especificaciones técnicas de cada componente, proporciona una visión detallada de las especificaciones técnicas de cada componente utilizado en la arquitectura, facilitando la comprensión de sus características fundamentales.

Además de las capas e interacciones entre estas, durante la implementación se tuvieron en cuenta las topologías de las redes de sensores inalámbricos, iniciando con una comunicación punto a punto entre el dispositivo de adquisición de datos y la puerta de enlace mediante la tecnología LoRa. Para lograr un esquema escalable, se incorporaron dos dispositivos adicionales a la red, resultando en tres puntos de monitoreo activos. Todos estos puntos establecen una comunicación directa con el ESP32, que a su vez envía los datos recopilados a la plataforma IoT a través

Tabla 1.
Especificaciones Técnicas de Componentes.

Componente	Especificaciones
Sensor DHT11	Rango de humedad: 20-90% de humedad relativa. Precisión de la humedad: $\pm 5\%$ RH. Rango de temperatura: 0-50°C. Precisión de la temperatura: $\pm 2\%$ °C. Tensión de funcionamiento: 3 V a 5,5 V. Corriente de funcionamiento: 2,5 mA. Peso: 1,8 gramos.
Arduino Nano	Microcontrolador: ATmega328P Voltaje de entrada: 7-12 V. Voltaje de operación: 5 V. Memoria flash: 32 KB. SRAM: 2 KB. EEPROM: 1 KB.
ESP32	Microcontrolador: Tensilica LX6 dual-core. Velocidad de reloj: hasta 240 MHz. Memoria flash: 4 MB5. SRAM: 520 KB. Tensión de entrada: 2,2 V a 3,6 V.
Módulo LoRa Ra-02	Frecuencia de trabajo: 433 MHz. Sensibilidad: -148 dBm. Potencia de transmisión: 20 dBm. Tensión de entrada: 1,8 V a 3,7 V. Corriente de funcionamiento: 100 mA. Peso: 10 g.

Fuente: Elaboración propia

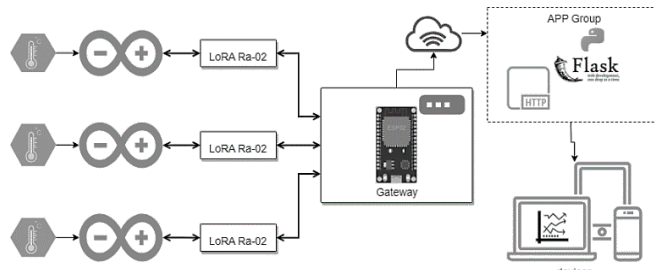


Figura 1. Diagrama de componentes.
Fuente: Elaboración propia

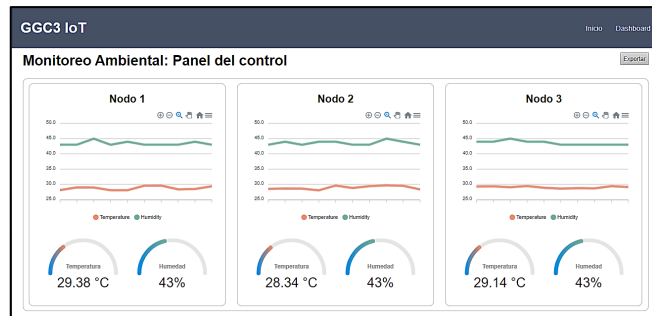


Figura 2. Interfaz de visualización.
Fuente: Elaboración propia

de la conexión Wi-Fi, como se muestra en la Fig. 1. Para garantizar la integridad y seguridad de los datos, se implementaron medidas de autenticación en la comunicación entre los dispositivos.

Adicionalmente, la implementación se llevó a cabo de forma modular mediante la implementación de funciones en los algoritmos, lo que contribuye a que este esquema sea más adaptable y escalable.

3.4 Desarrollo de la interfaz de visualización

Esta interfaz web presenta gráficos en tiempo real de los datos capturados por el sensor de temperatura y humedad en los tres nodos del sistema. Esta es una alternativa a soluciones comerciales que busca ofrecer adaptabilidad sin variaciones monetarias, facilitando el acceso y comprensión de datos, y estableciendo un flujo de trabajo flexible según las necesidades específicas (ver Fig. 2).

En el proceso, el esp32 actuó como cliente iniciando el protocolo de comunicación HTTP mediante el método POST. Los datos recibidos se almacenan internamente para su posterior exportación a través de una solicitud de la aplicación web. Para visualizar y permitir la exportación de los datos en formato JSON y CSV, se emplearon plantillas HTML que incluyen el formato en CSS y funciones para la visualización y actualización de datos mediante JavaScript

4. Discusión

El diseño e implementación de la arquitectura IoT para monitoreo de temperatura y humedad demuestra la eficacia

de la integración de tecnologías de código abierto, como Arduino y ESP32, junto con módulos LoRa y el sensor DHT11. La estructura modular y las medidas de autenticación mejoran la escalabilidad y seguridad del sistema, facilitando la adquisición, procesamiento y monitoreo de datos ambientales. La implementación de Python Flask para la interfaz de usuario contribuye a hacer el sistema fácil de utilizar, brindando visualizaciones claras y en tiempo real de los datos capturados.

Los resultados reflejan la aplicación efectiva de la teoría de IoT en un contexto práctico. La selección de componentes, la planificación detallada de interacciones y la validación iterativa del sistema siguen principios teóricos sólidos. La práctica demuestra que la tecnología de código abierto puede usarse efectivamente para desarrollar soluciones de monitoreo ambiental, destacando la viabilidad y beneficios de esta aproximación.

Como se mencionó anteriormente, este sistema puede beneficiar diversos sectores en Colombia. En agricultura, el monitoreo de temperatura y humedad contribuirá a una gestión más eficiente de cultivos, mejorando las prácticas agrícolas. En salud pública, la capacidad para evaluar la calidad del aire y del agua en tiempo real es crucial para abordar problemas de contaminación. En infraestructuras, como puentes, el seguimiento estructural puede prevenir incidentes relacionados con colapsos. En geomecánica, el monitoreo de taludes permitirá la prevención de desastres por deslizamientos en masa y el monitoreo en socavones podrá prevenir riesgos por derrumbes y el aumento en la concentración de gases nocivos para la salud de los trabajadores. La flexibilidad de esta arquitectura la hace adaptable a múltiples contextos.

5. Conclusiones

El uso de plataformas de IoT y hardware de código abierto como Arduino y ESP32 ha facilitado la adquisición, procesamiento y monitoreo de datos relacionados con la temperatura y la humedad. Estas tecnologías han permitido la comunicación a larga distancia con dispositivos Arduino Nano, posibilitando la visualización y análisis de datos en tiempo real. Además, la implementación de algoritmos modulares y las medidas de autenticación han mejorado la escalabilidad y seguridad del sistema. Esta arquitectura proporciona un marco sólido para recopilar y analizar parámetros ambientales en áreas remotas con recursos limitados.

El diseño e implementación de la arquitectura de IoT demostraron la viabilidad de utilizar hardware de bajo costo y de código abierto para desarrollar un sistema de monitoreo efectivo. La integración de la tecnología LoRa ha resultado fundamental para habilitar la comunicación a larga distancia entre los nodos de los sensores y la puerta de enlace, superando barreras geográficas.

En el futuro, más investigación y desarrollo adicionales podrían centrarse en mejorar la interfaz de usuario de la aplicación web para proporcionar herramientas más completas de visualización y análisis de datos. Además,

explorar la integración de sensores adicionales y expandir las capacidades del sistema para monitorear y analizar más parámetros ambientales podría ser de utilidad. En general, la arquitectura propuesta de IoT presenta una solución flexible y de bajo costo para monitorear y analizar parámetros ambientales en áreas remotas o con recursos limitados.

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Framework for modeling and simulation of maritime cyberdefense - MARCIM: state of the art and methodology

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Abstract

The article presents the state of the art and methodology of the doctoral research project "Framework for modeling and simulation of maritime cyberdefense - MARCIM". The state of the art defined the background of the research problem, the state of scientific activity, trends and challenges related to MARCIM: cyberdefense, modeling and simulation in cyber security and cyberdefense; and maritime cybersecurity and cyberdefense. The methodology was established with a focus on modeling complex systems, by phases and application actors. The article mainly concludes that maritime cyberdefense at a strategic level behaves like a complex system, with dynamics, processes and elements that cannot be clearly identified, which require modeling and simulation, with a metaheuristic approach, to study the set of actions and interactions between its entities.

Keywords: ciberdefensa; cybernetics; cybersecurity; defense; informatics; maritime; simulation models.

Marco de referencia para el modelamiento y simulación de la ciberdefensa marítima - MARCIM: estado del arte y metodología

Resumen

El artículo presenta el estado del arte y metodología del proyecto de investigación doctoral "Marco de referencia para el modelamiento y simulación de la ciberdefensa marítima - MARCIM". El estado del arte definió los antecedentes del problema de investigación, estado de la actividad científica, tendencias y retos de las temáticas del MARCIM: ciberdefensa, modelamiento y simulación en ciberseguridad y ciberdefensa; y ciberseguridad y ciberdefensa marítima. La metodología se planteó con un enfoque en modelamiento de sistemas complejos, por fases y actores de aplicación. El artículo concluye principalmente que la ciberdefensa marítima a nivel estratégico se comporta como un sistema complejo, con dinámicas, procesos y elementos que no se pueden identificar claramente, que requieren del modelamiento y simulación, con un enfoque metaheurístico, para estudiar el conjunto de acciones e interacciones entre sus entidades.

Palabras clave: ciberdefensa; cibernética; ciberseguridad; defensa; informática; marítimo; modelo de simulación.

1. Introducción

El artículo presenta los antecedentes, estado del arte y metodología desarrollada para el proyecto de investigación doctoral "Marco de referencia para el modelamiento y simulación de la ciberdefensa marítima - MARCIM" asociado a la Escuela Naval de Cadetes "Almirante Padilla", el cual aborda cuatro problemáticas [1]: falta de

estandarización en la gestión de la ciberdefensa a nivel nacional e internacional; pocas iniciativas de modelamiento y simulación para mejorar la rentabilidad y la eficacia operacional de la ciberdefensa; un incremento de los ciberataques al sector marítimo, que evidencian las debilidades y amenazas del sector marítimo en el ciberespacio; y la necesidad de enfocar los esfuerzos de la ciberdefensa marítima a nivel estratégico.

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El proyecto MARCIM cobra importancia para el sector marítimo por la necesidad de protección ante ciberataques que salvaguarden las infraestructuras críticas que lo componen y mantengan su estabilidad; por su contribución al Plan de Desarrollo Naval 2042 de la Armada de Colombia [2]; y por la ausencia de investigaciones relacionadas con la ciberdefensa marítima.

El desarrollo del estado del arte y metodología en el MARCIM, contempló dos etapas, la primera etapa, el estado del arte, consistió en definir el marco teórico y los antecedentes del problema de investigación y posteriormente abordar las temáticas más importantes relacionadas con él para determinar el estado de la actividad científica, tendencias y retos alrededor del MARCIM. Las temáticas identificadas y desarrolladas fueron: ciberdefensa, modelamiento y simulación en ciberseguridad y ciberdefensa, y ciberseguridad y ciberdefensa marítima.

La segunda etapa, metodología de modelamiento de sistemas complejos para el MARCIM, es el resultado de la elaboración de los antecedentes, marco teórico y estado del arte, por medio de estudios bibliométricos y análisis bibliográficos de la primera fase. Los resultados de este proceso investigativo permitieron plantear la metodología para responder a la pregunta problema del proyecto de investigación MARCIM y estar acorde a sus necesidades. La metodología se planteó con un enfoque sistémico, con aproximación en sistemas complejos, en fases y actores de aplicación (experto, modelador, ordenador), definiendo el diagrama de flujo y caracterización por cada paso en la fase respectiva.

Este artículo es el resultado de la primera etapa de investigación del proyecto MARCIM, permitiendo el inicio del desarrollo de los objetivos específicos formulados.

2. Marco teórico

2.1 Descripción del problema

La ciberdefensa entendida como el uso de las “capacidades militares ante amenazas cibernéticas, ataques cibernéticos o ante actos hostiles de naturaleza cibernética que afecten la sociedad, la soberanía nacional, la independencia, la integridad territorial, el orden constitucional o los intereses nacionales” [3, pp.88] es un campo académico con pocos años de madurez, empieza desde el 2003 y la producción científica tiene un índice de vida media de 3.4 años, acompañada por una producción anual baja [4], en comparación con áreas como la ciberseguridad con valores de aproximadamente tres veces más [5].

A pesar de la poca producción científica en ciberdefensa, esta es una prioridad internacional. Miembros de la OTAN, como Estados Unidos, Alemania, Francia, Estonia y España; iniciaron desde 2011 la implementación de medidas de ciberdefensa como parte de su estrategia de ciberseguridad nacional, llegando a niveles de desarrollo suficientes para enfrentar las amenazas y retos que supone el ciberespacio con

un enfoque en cooperación internacional público y privado, capacidades avanzadas de ciberdefensa, investigación científica, educación, conciencia situacional cibernética y adopción de marcos conceptuales [6, pp.68–78], [7, pp.7–11], así como la implementación de iniciativas de modelamiento y simulación para mejorar la rentabilidad y eficacia operacional en defensa [8, pp.6–10].

En América Latina, se ha avanzado en la gestión de la ciberseguridad y ciberdefensa con la creación de organismos nacionales de ciberseguridad, implementaciones tecnológicas de cobertura nacional, cooperación interinstitucional para la atención de incidentes cibernéticos, entre otros progresos. Sin embargo, su nivel de preparación no es suficiente y se presentan diversas necesidades como la adopción de marcos y modelos conceptuales de ciberdefensa, definición de objetivos y responsabilidades en las estructuras destinadas a atender los asuntos del ciberespacio, implementación de lineamientos para la gestión de los asuntos del ciberespacio a nivel nacional, cooperación en ciberdefensa, diseño de tecnologías de ciberdefensa, desarrollo de leyes orientadas a regular los sectores público y privado en actividades cibernéticas, etc. [9, pp.178], [10, pp.49–62].

Colombia desde el 2011, a través de tres políticas de desarrollo económico y social (CONPES), viene implementando políticas y estrategias de seguridad y defensa en el ciberespacio con un enfoque en gestión de riesgos. Estas medidas han propiciado el fortalecimiento y la generación de capacidades en el ciberespacio, así como la estructura organizacional para su gestión al interior del Ejecutivo [11, pp.10–27], lo que ubica a Colombia en el puesto número 81 del índice de ciberseguridad global, con debilidades manifiestas en las medidas legales y organizacionales y con fortalezas en las medidas técnicas [12].

Sin embargo, el Departamento Nacional de Planeación [11, pp.10–27] asegura que Colombia tiene moderadas capacidades de ciberdefensa que requieren ser mejoradas a razón de tres aspectos: la debilidad en las capacidades en seguridad digital de los ciudadanos, el desarrollo inadecuado del marco de gobernanza de la seguridad digital y la no adopción de modelos, estándares y marcos de trabajo en seguridad digital con énfasis en nuevas tecnologías.

La situación nacional e internacional expuesta refleja la necesidad para los Estados de fortalecer la ciberdefensa en gestión, capacidades y cooperación, como parte de la proyección estratégica de su ciberseguridad nacional [13], [14], adicionalmente, denota la necesidad de desarrollar marcos y modelos teóricos bajo el enfoque de la anticipación [15, pp.20], utilizando herramientas de modelado y simulación de escenarios, redes, efectos y comportamientos [16, pp.65] que optimicen la toma de decisiones.

Dado el contexto expuesto, la ciberdefensa marítima cobra gran importancia por estar enfocada en un sector que mueve más del 90% de la carga económica, además de su fuerte componente tecnológico y enlace con los demás sectores productivos [17], consolidándose como un sector vital para la economía, que debe ser protegido de las amenazas en el ciberespacio, teniendo en cuenta que los

ciberataques a este sector han aumentado un 900% en los últimos 3 años [18–20]. Los ataques dirigidos tanto a tecnologías de información como de operación son una de las principales preocupaciones del sector ya que pueden provocar pérdida de vidas, pérdida de control sobre los barcos y/o carga o los datos confidenciales [18], [21, pp.132,135–136].

En síntesis, el problema de investigación se sustenta en cuatro aspectos [1]:

- Falta de estandarización en la gestión de la ciberdefensa a nivel nacional e internacional.
- Pocas iniciativas de modelamiento y simulación para mejorar la rentabilidad y la eficacia operacional de la ciberdefensa.
- Incremento de los ciberataques al sector marítimo, que evidencian las debilidades y amenazas del sector marítimo en el ciberespacio.
- Necesidad de enfocar los esfuerzos de la ciberdefensa marítima a nivel estratégico.

2.2 Proyecto de investigación MARCIM

Dado el problema planteado se requiere implementar marcos y modelos para optimizar la toma de decisiones y gestión de recursos de la ciberdefensa marítima a nivel estratégico que garanticen el normal desempeño de las actividades marítimas en el ciberespacio y la resiliencia en el caso de una afectación. Lo anterior, llevó a plantear la siguiente pregunta de investigación [1]: ¿Cuál es el comportamiento de la ciberdefensa marítima a nivel estratégico dentro de un conjunto de acciones e interacciones entre sus entidades?

Para abordar la pregunta de investigación se formuló el proyecto de investigación doctoral “Marco de referencia para el modelamiento y simulación de la ciberdefensa marítima – MARCIM” asociado a la Escuela Naval de Cadetes “Almirante Padilla”, que tiene como objetivo general formular un marco de referencia para el modelamiento y simulación de la ciberdefensa marítima a nivel estratégico, y como objetivos específicos:

- Explicar los requerimientos del marco de referencia para el modelamiento y simulación de la ciberdefensa marítima a nivel estratégico.
- Diseñar un modelo de simulación de las acciones e interacciones entre las entidades de la ciberdefensa marítima a nivel estratégico.
- Validar conceptual y operativamente el modelo de ciberdefensa marítima a través de simulaciones.

2.3 Justificación del MARCIM

La ciberdefensa marítima en Colombia es liderada por la Armada Nacional a través de la Dirección Cibernética Naval, contando con unos avances destacados en ciberseguridad, ciberdefensa y ciberinteligencia, aumentando así las capacidades de detección, gestión y análisis de eventos e incidentes en el ciberespacio. Adicionalmente, las estrategias

de defensa de la Armada “contemplan el crecimiento y desarrollo tecnológico de capacidades de detección, contención y respuesta a las amenazas cibernéticas que afecten las operaciones militares y la infraestructura crítica cibernética de la nación” [22].

Dichas estrategias de defensa de la Armada, estipuladas en el Plan de Desarrollo Naval 2042, incluyen dentro de sus objetivos de desarrollo tecnológico “generar autonomía, reducir dependencia tecnológica y obtener ventajas operacionales a través de los procesos de I+D+i que fortalezcan el desarrollo tecnológico de la institución” a través del desarrollo de “software y hardware para detectar, contener y responder a las amenazas cibernéticas que afecten las operaciones militares y la infraestructura crítica cibernética de la nación” [2, pp.102–103].

Por otra parte, a pesar de la importancia de la ciberdefensa marítima, esta tiene una producción científica muy baja que se ha estado enfocando principalmente en los buques y no en el poder marítimo como sistema [18], desconociendo que las amenazas cibernéticas, los buques, las terminales portuarias y otros sistemas marítimos evolucionan simultáneamente y que los efectos negativos de los ciberataques son evidentes no solo a bordo del buque víctima, sino en un sector mucho más amplio que incluye compañías navieras, puertos, sistemas de interconexión, etc. [21, pp.138].

Teniendo en cuenta lo anterior, el proyecto MARCIM se justifica por lo siguiente [1]:

- La importancia que reviste para el sector marítimo y la protección ante ciberataques que salvaguarde las infraestructuras críticas que lo componen y mantengan la estabilidad del sector.
- Su contribución al Plan de Desarrollo Naval 2042 de la Armada de Colombia [2] en su objetivo de desarrollo tecnológico con el consecuente fortalecimiento del programa Nacional de Ciencia y Tecnología del Sector Defensa elaborado por el Ministerio de Ciencia, Tecnología e Innovación [23].
- La ausencia de investigaciones relacionadas con la ciberdefensa marítima. Las investigaciones existentes tienen un enfoque en los buques y no en el poder marítimo como sistema.

3. Métodos

El artículo se enfoca en el estado del arte y metodología desarrollada para el proyecto de investigación titulado “Marco de referencia para el modelamiento y simulación de la ciberdefensa marítima – MARCIM”, como resultado de la investigación preliminar y que permitió la formulación e inicio del proyecto de investigación. En este sentido, se contemplaron dos etapas de desarrollo.

La primera etapa, el estado del arte, consistió en definir los antecedentes del problema de investigación y posteriormente abordar las temáticas más importantes relacionadas con el tema de investigación para determinar el estado de la actividad científica, tendencias y retos alrededor del MARCIM. Las temáticas identificadas y desarrolladas

fueron: ciberdefensa, modelamiento y simulación en ciberseguridad y ciberdefensa, y ciberseguridad y ciberdefensa marítima.

El procedimiento metodológico en esta etapa consistió primero en realizar un estudio bibliométrico por temática, que inicia con la delimitación espacio temporal, definición de las palabras clave y la sentencia de búsqueda utilizando los diferentes operadores booleanos y conectores. Posteriormente, se aplicó la sentencia de búsqueda en el metabuscador científico Scopus® [24] y los resultados fueron descargados en un archivo de formato “BibTeX”. Utilizando el software R [25] y la librería “Bibliometrix” con Biblioshiny [26], con el fin de realizar el respectivo análisis estadístico y de indicadores bibliométricos, teniendo en cuenta las metodologías dispuestas para ello [27–29]. Producto del análisis bibliométrico se identificó la documentación científica relevante para el estudio de la temática, realizando un análisis bibliográfico de cada documento, y posteriormente un análisis global de los resultados para generar las conclusiones respectivas que constituyen el estado del arte para el MARCIM, y determinan la forma de abordar el problema de investigación.

La segunda etapa, metodología de modelamiento de sistemas complejos para el MARCIM, parte de las conclusiones de la primera etapa, en las que se define, entre otros, el tipo de modelamiento y simulación con el que se abordará la formulación del MARCIM. En este sentido, se realizó un análisis bibliográfico y caracterización de las diferentes metodologías para el modelamiento de sistemas complejos y se desarrolló una metodología acorde a las necesidades del MARCIM. La metodología se planteó con un enfoque en fases y actores de aplicación (experto, modelador, ordenador), posteriormente se determinó el diagrama de flujo respectivo y la explicación de cada paso en la fase respectiva.

4. Resultados

4.1 Estado del Arte

4.1.1 Antecedentes

El estudio bibliométrico y análisis de bibliografía del tema [30] dio como resultado que no se han realizado investigaciones que respondan a la pregunta de investigación planteada para el MARCIM. A continuación, se presentan los trabajos de investigación más cercanos al objetivo general y que muestran el contexto del problema con relación a la teoría y su importancia.

La propuesta de modelado y simulación basado en agentes para el entendimiento de la guerra cibernética entre malefactores y agentes de seguridad en internet de Kotenko [31] aborda el modelado y simulación mediante un análisis de procedimientos de ataque y defensa para “Denegación de Servicio Distribuida” (DDoS), teniendo en cuenta los siguientes aspectos: “actores de diferentes equipos compiten para alcanzar intenciones adversarias, actores del mismo equipo cooperan en intenciones conjuntas, ontologías de los

ataques DDoS, y los mecanismos de protección contra ellos” [30]. Estos aspectos son abordados desde un enfoque sistémico, “determinando las variantes de estructuras de equipos de los agentes, mecanismos de interacción y coordinación y especificaciones de jerarquía de planes de acción” [30]. Este trabajo establece unas bases para el desarrollo de modelos más flexibles y dinámicos desde el punto de vista teórico de sistemas complejos, permitiendo valorar y optimizar las capacidades de los equipos de ciberseguridad y ciberdefensa, así como entender el impacto de la cooperación entre organizaciones y componentes. Kotenko también desarrolló una propuesta de modelamiento y simulación de múltiples agentes en escenarios de ciberataque y ciberdefensa a la seguridad nacional [32], con un enfoque en los componentes distribuidos de ciberdefensa de forma cooperativa, utilizando simulación basada en agentes y simulación de eventos discretos aplicada a ciberataques y mecanismos de protección cibernética multiagente, llegando hasta el nivel de intercambio de paquetes en protocolos de red. La investigación propone un marco común para implementar entornos de simulación multiagente, realizar experimentación y probar escenarios de ataques a redes distribuidas y mecanismos de defensa; “evidenciando cómo la cooperación en ciberdefensa, la identificación de múltiples escenarios de ataque y defensa cibernética y el cálculo de la probabilidad de éxito conducen a la mejora esencial de la efectividad de la defensa” [30].

Dobson y Carley [33] formulan un marco común para simular la guerra cibernética con un enfoque basado en agentes, el Cyber Forces Interactions Terrain - Cyber FIT (Fuerzas Cibernéticas de Interacción en Terreno), que proporciona los elementos necesarios para facilitar el planeamiento militar de la fuerza cibernética en diferentes terrenos y contra varias fuerzas adversas, mediante una simulación y predicción de los resultados de la guerra cibernética, determinando aspectos como vulnerabilidades, degradación de activos y tasa de capacidad de la misión, por medio del análisis de tres elementos principales: fuerzas, interacciones y terreno. El desarrollo se hizo bajo una visión sistémica y holística de la conducción de la guerra, utilizando el modelado basado en agentes en el software NetLogo [34], obteniendo como resultado un entorno de simulación de la guerra cibernética que necesita perfeccionarse mediante el uso de datos operacionales reales. Se resalta el uso de técnicas de modelamiento de sistemas complejos, como el modelamiento basado en agentes, tratando a cada fuerza de tarea como un agente complejo que toma decisiones inciertas que dependen de los otros elementos, terreno e interacciones; lo que la hace una aproximación de interés para abordar la complejidad de acciones e interacciones entre los agentes del poder marítimo.

El marco de referencia para la evaluación del riesgo cibernético marítimo basado en modelamiento—MACRA de Tam y Jones [35] considera una combinación de amenazas cibernéticas y factores marítimos, enfrentados con una variedad de funcionalidades, configuraciones, usuarios y factores ambientales del ambiente marítimo, con el objetivo de presentar de manera integral los riesgos cibernéticos marítimos y apoyar la toma de decisiones en seguridad cibernética marítima. Considera tres ejes de evaluación de

riesgo: atacante, vulnerabilidad y medidas de mitigación, con sus respectivas variables y atributos, permitiendo el análisis de diferentes combinaciones de efectos de amenazas cibernéticas sobre sistemas y tecnologías a bordo de los buques. Los diferentes escenarios de evaluación de riesgo descritos en el trabajo muestran que, aunque la metodología y función objetivo del modelo tiene un enfoque de ciberseguridad de buque, estos son aplicables al desarrollo del objetivo de la presente investigación, constituyéndose como una de las pocas aproximaciones de modelamiento de amenazas cibernéticas en el escenario marítimo, mostrando una gran flexibilidad de adaptación y aplicabilidad por el uso de datos situacionales.

Finalmente, el estudio de modelamiento y simulación de sistemas complejos para gobernanza de Katina y otros [36] presenta opciones para utilizar el modelamiento y simulación en sistemas complejos relacionados con la gobernanza, evaluando diferentes paradigmas de compatibilidad a través de una revisión extensa de literatura en las que se definen las tendencias actuales de modelamiento y simulación, incluyendo software, para finalmente proponer la necesidad de desarrollar un modelo híbrido basado en tres paradigmas de modelamiento y simulación: agentes, eventos discretos y dinámica de sistemas; ajustados a las necesidades de gobernanza de sistemas complejos actuales y proyectados. Este trabajo es un referente importante porque establece un estado del arte de modelamiento y simulación de estos sistemas, sugiriendo para su abordaje la combinación de técnicas de modelado y simulación. Igualmente, pone a consideración las restricciones de datos e información en sistemas de gobernanza por temas de reserva, situación que puede llegar a limitar la precisión de los modelos y hacerlos poco realistas.

Los antecedentes evidencian que la aproximación al modelamiento y simulación en ciberdefensa marítima debe hacerse desde el enfoque sistémico, principalmente como un sistema complejo por tener varios niveles de organización e interacción y múltiples agentes (actores, entidades, sistemas, etc.) con un grado de autonomía significativo. Adicionalmente, debe incluir la identificación y estudio de escenarios de ataque y defensa, junto con sus respectivos cálculos de riesgo y probabilidad de éxito, que permitan a los experimentadores probar cuantitativamente hipótesis de trabajo o cursos de acción.

4.1.2 Ciberdefensa

En la temática ciberdefensa, la bibliometría [4] presenta un total de 641 documentos afines al tema, elaborados en el lapso entre 1992 y 2020 con un porcentaje de crecimiento anual del 22.16%, mostrando el auge y actual interés en el tema. El país con mayor producción en el tema es Estados Unidos, con una producción de 325 artículos, seguido por Reino Unido (38), India (21) y China (19). Los autores más productivos son Liu P., Pal P., Jacobson D., Rursch J.A., Mehtre B. M.; los más citados son Liu P., Hwang K., Ku W.-S. y Chen Y., quienes representan el 50 % de las citaciones en el campo de la ciberdefensa, el 34,5 % de los autores no cuentan con ninguna citación. Las tendencias de

investigación están centradas en la gestión de la ciberseguridad, cibercrimen y ciberataques [4].

Del análisis bibliográfico de los documentos encontrados se resaltan seis de ellos, adicionales a los trabajos de Kotenko [31,32] abordado en los antecedentes. El artículo Teoría de juegos para ciberseguridad [37], resalta que las soluciones de ciberseguridad escasean principalmente en los casos de marcos de decisión cuantitativo, por lo cual no responden a los cambios dinámicos de los escenarios de ataque. Los autores utilizan la teoría de juegos para crear un marco analítico sólido para analizar la interacción entre los ataques y los mecanismos de ciberdefensa y proponen una arquitectura de ciberdefensa inspirada en esta teoría. La aproximación metodológica es holística, siguiendo las bases de un juego estocástico de información imperfecta.

El marco basado en agentes para el conocimiento de la situación cibernética de Bradshaw y otros [38], busca aumentar la percepción y la cognición humana alrededor de la ciberseguridad y ciberdefensa, y optimizar cualitativamente en la conciencia situacional cibernética. El enfoque metodológico usa un marco basado en agentes que explora la comprensión de situaciones complejas a través de la colaboración y el entendimiento de la ciberseguridad y ciberdefensa, lo que los autores denominan ‘construcción de sentido distribuida’. Un aporte importante de este trabajo es la incorporación del factor humano como eje central del marco de ciberseguridad y ciberdefensa propuesto, y su tratamiento como un agente imperfecto y de comportamiento aleatorio.

El marco para la asignación y ubicación óptima de sistemas de ciberdefensa en redes de detección de intrusiones – DEFIDNET de Pastrana y otros [39], presenta un modelo de distribución de contramedidas cibernéticas basadas en algoritmos de optimización multiobjetivo, con el propósito de implementar estrategias de asignación que optimicen la gestión del riesgo [18], [39]. El esquema propuesto se centra en un análisis nodal de la probabilidad de propagación de un ciberataque en toda la red y las posibles rutas de afectación, generando la información suficiente para optimizar los sistemas de ciberdefensa.

El marco para mejorar los juegos de guerra cibernéticos (*Cyber Wargaming*) en un contexto empresarial realista de Bodeau [40] y el marco conceptual para el desarrollo de juegos serios de ciberseguridad propuesto por Katsantonis [41], tienen en común el uso de juegos serios y enfoques de aprendizaje basados en juegos para generar conocimiento en ciberseguridad y ciberdefensa, ambos se presentan de forma general, pero muestran facilidades de adaptación para garantizar que los ejercicios de juegos de guerra reflejen con precisión la eficacia del entorno tecnológico y de gestión de riesgos. Para el caso de Bodeau y otros [40], el marco se describe en términos de protección de sistemas en el sector de servicios financieros (FSS), pero que tiene aplicación en otras infraestructuras críticas, equilibrando el fuerte enfoque de la tecnología de ciberdefensa de los ejercicios de formación de equipos cibernéticos, con el enfoque sólido del impacto comercial y operativo, típico de los ejercicios de mesa de alto nivel centrados en el ciberespacio. El documento resalta que los marcos existentes de juegos de

guerra son suficientes para apalancar modelos de escenarios compuestos de juegos de guerra cibernéticos para que una institución pueda producir un realismo mejorado, reducir el impacto y el riesgo de los adversarios cibernéticos. Sin embargo, requiere un componente tecnológico avanzado que mejore la simulación, orquestación y medición de los resultados de los ejercicios. El marco de Katsantonis y otros [41], se encuadra en la educación y concientización en ciberseguridad y ciberdefensa, promoviendo enfoques basados en juegos que prevean la mejora de la eficacia pedagógica de la educación en ciberseguridad y ciberdefensa mediante la adopción de teorías de aprendizaje modernas y enfoques de enseñanza innovadores, en el marco de un ciclo de vida de aprendizaje sostenible.

La Guía de Ciberdefensa: orientaciones para el diseño, planeamiento, implantación y desarrollo de una ciberdefensa militar, elaborada por la Junta Interamericana de Defensa [16] proporciona un modelo operativo de la ciberdefensa a nivel estratégico, desde una perspectiva operativa militar que facilite la interacción con los diferentes dominios de la guerra. Aunque el documento se enmarca en el mundo organizacional, es un referente para entender la ciberdefensa desde el punto de vista de seguridad nacional y de cooperación internacional, que evidencia la necesidad de establecer marcos de referencia en la gestión de la ciberdefensa y la aplicación de modelamiento y simulación para optimizar la toma de decisiones en el dominio del ciberespacio, el quinto dominio de la guerra.

4.1.3 Modelamiento y simulación en ciberseguridad y ciberdefensa

En la temática de modelamiento y simulación en ciberseguridad y ciberdefensa la bibliometría [30] se encontraron 994 documentos del tema, entre los años 2002 y 2021 con un porcentaje de crecimiento anual del 23.26%, que refleja la importancia actual del tema para el ambiente académico. El país con mayor producción es “Estados Unidos con 155 artículos, seguido de China (36) y otros países como India (27), Reino Unido (21) y Australia (17). Los autores más productivos son Lakhno V., Mylrea M., Gourisetti SNG., Li S. y Pietre-Cambaces L.” [30]; el mayor nivel de dominancia lo tienen Gourisetti SNG., Quinn EL. y Lakhno V.; el mayor índice h son los de Mylrea y Ekstedt; el índice g más alto es el de Chen y Ekstedt; y el mejor índice m son los de Lakhno y Gourisetti. El país con más cooperación y coautorías es Estados Unidos, cooperando con siete países principalmente: Reino Unido, Corea, China y Arabia Saudita; “así mismo, India está unido con seis países, destacando conexiones con Canadá, España, Australia y China; y por su parte Italia se relaciona también con seis países, destacando las conexiones con Estados Unidos, Australia, Suecia y Polonia [30].

A través de un ACM (Análisis de Correspondencias Múltiples) de las coocurrencias del tema se determinaron cuatro áreas de investigación: la primera, la transmisión de energía eléctrica y microrredes; la segunda, los sistemas de control industrial e infraestructuras críticas cibernéticas

industriales; la tercera, la gestión de riesgos cibernéticos, gestión de la información y controles de seguridad de la información; y la cuarta, la ciencia de datos, modelamiento y simulación [30].

Del análisis bibliográfico de los documentos encontrados se resaltan seis de ellos, adicionales a los trabajos de Dobson y Carley [33] y Katina y otros [36] abordados en los antecedentes. El estudio de la ciberdefensa como un sistema adaptativo complejo [42] resalta que las tecnologías cibernéticas empresariales a menudo se implementan sin tener en cuenta las interacciones que ocurren entre los humanos y la nueva tecnología. Además, las interacciones que ocurren entre individuos a menudo también pueden tener un impacto en la tecnología recientemente empleada. Teniendo en cuenta lo anterior, el documento presenta el estudio de un escenario en el que una agencia gubernamental hipotética aplica una perspectiva de la ciencia de la complejidad, respaldada por modelos basados en agentes, para comprender mejor los impactos de las decisiones de política estratégica, que lleva a la construcción de un modelo para explorar la dinámica sociotécnica de estos sistemas.

El modelo de ciberataques y ciberdefensas en sistemas de medición local [43], el modelo dinámico de mitigación de ataques para el análisis de vulnerabilidades de seguridad en un sistema de energía ciber-físico [44], y el modelo para la defensa de los sistemas de energía contra ciberataques dinámicos con enfoque en teoría del juegos [45], tienen en común que abordan la ciberseguridad y ciberdefensa en sistemas de energía buscando la mitigación del riesgo a ciberataques, mediante la metodología de teoría de juegos dinámicos con información incompleta, modelando las interacciones entre un atacante y un defensor, para facilitar los procesos de asignación y distribución de recursos de ciberdefensa en los sistemas de energía; mejorar la resiliencia de los sistemas ante ataques dinámicos; evaluar las vulnerabilidades; y generar estrategias de protección efectivas contra diferentes combinaciones de ataques.

El modelo *Hybrid Cyber Kill Chain* (Cadena de Muerte Cibernética Híbrida) [46], presenta el estudio de diferentes modelos aceptados de ciberataques y proponen una nueva aproximación de modelamiento de la *Cyber Kill Chain* (Cadena de Muerte Cibernética) bajo un concepto híbrido, considerando las fortalezas de los actores de amenazas y defensores, utilizando la metodología de redes de petri de colores para el análisis. El marco de referencia y modelo resultante permite ayudar a las organizaciones empresariales a tomar medidas para hacer frente a los incidentes cibernéticos, minimizando o eliminando el impacto, y estableciendo los controles y contramedidas necesarias.

El modelo de apoyo a la toma de decisiones para la estimación de efectos y evaluación de proporcionalidad en operaciones cibernéticas [47], permite el cálculo y clasificación de los efectos de las operaciones cibernéticas, y la evaluación de la proporcionalidad para apoyar las decisiones en las operaciones cibernéticas mediante el diseño e implementación de un modelo difuso de varias capas, que incluye el análisis de operaciones cibernéticas reales y virtuales, combinadas con entrevistas y grupos focales con expertos técnicos y militares.

Esta investigación deja en evidencia la necesidad de metodologías y modelos para planificar, ejecutar y evaluar la ciberdefensa de forma responsable, y presenta una metodología aplicable a otros escenarios.

4.1.4 Ciberseguridad y ciberdefensa marítima

Finalmente, en la temática de ciberseguridad y ciberdefensa marítima la bibliometría [18] encontró 153 del tema, entre 1999 y 2021 con un porcentaje de crecimiento anual del 3.2%, indicando un limitado interés y desarrollo científico a pesar de que la investigación va en aumento. China es el país con mayor producción, 13 artículos, seguido de Reino Unido (9), Estados Unidos (7) y Noruega (5). Kavallieratos G., Silverajan B., Svilicic B., Brosset D. y Deng R son los autores con mayor producción científica; Kavallieratos, Svilicic y Kamahara el índice h más alto; Svilicic B., Tam K. y Yang T. tienen el mayor nivel de dominancia; Kavallieratos y Svilicic el índice g más alto y; Svilicic y Kamahara el índice m más alto. Reino Unido y Noruega son los países con más cooperación de coautorías, trabajando con países como Grecia y Alemania; adicionalmente, se resalta la cooperación entre China y Canadá, Estados Unidos con Nueva Zelanda y, Japón con Croacia y Suecia [18].

Analizando las coocurrencias de palabras mediante un ACM (Análisis de Correspondencias Múltiples) se determinaron cuatro áreas de investigación: la primera, criptografía y sistemas de seguridad de la información; la segunda, sistemas de control industrial y sistemas ciberfísicos; la tercera, gestión de riesgos cibernéticos, seguridad marítima y crimen cibernético; y la cuarta, sistemas de control marítimo, ciencia de datos, actividades marítimas, y conciencia cibernética [18].

Del análisis bibliográfico de los documentos encontrados se resaltan tres trabajos, adicionales al trabajo de Tam & Jones [35] abordado en los antecedentes. El estudio de la detección de ciberataques en tiempo real como herramienta para generar una conciencia situacional de los riesgos cibernéticos en los sistemas navales de Jacq y otros [48], que resalta el aumento de los sistemas tecnológicos a bordo de los buques entendiéndolos como un sistema complejo de información en movimiento, con todas las funciones de un sistema convencional. Por lo anterior, la generación de conciencia situacional de los riesgos cibernéticos en los sistemas navales se vuelve una tarea fundamental para el sector marítimo, y la investigación presenta como curso de acción el estudio de ataques en tiempo real, que incluye la recopilación y fusión de datos provenientes de los buques, visualización de datos y el intercambio de situaciones entre los actores marítimos.

El estudio de la gestión del riesgo cibernético marítimo desde el punto de vista de Tam y Jones [35], evidencia la necesidad de estudiar la ciberseguridad marítima con un enfoque holístico, por el incremento de la complejidad, la digitalización y la automatización de los sistemas en la industria marítima, así como por el gran número de sistemas interconectados entre el barco y la tierra. Dada esta

complejidad, la preocupación del entorno marítimo se está volcando a reducir la vulnerabilidad a los ciberataques y por consiguiente los incidentes cibernéticos, ya que estos en el entorno marítimo “pueden provocar pérdida de vidas, pérdida de control sobre los barcos o los datos confidenciales, así como el secuestro de barcos y/o carga” [18,21, pp.132, 135–136].

El marco de referencia para la ciberinteligencia de amenazas a la infraestructura marítima desarrollado por Pitropakis y otros [49] propone un marco de inteligencia de amenazas para las infraestructuras marítimas que se adapte a la recopilación y análisis de inteligencia de amenazas en estos entornos, combinando la recopilación de datos de sensores de barcos, datos disponibles públicamente de las redes sociales, variedad de *honeypots* (señuelos cibernéticos) que emulan diferentes componentes de hardware y software, detección de eventos asistida por aprendizaje profundo, implementación de *blockchain* (cadenas de bloques) para mantener un registro de auditoría de actividades y transacciones, identificaciones electrónicas y análisis visual de amenazas. La investigación tiene un enfoque centrado en las necesidades marítimas, mostrando sistemáticamente las relaciones entre diferentes actores y las interacciones que se pueden dar entre estos, pero dejando abiertas las posibilidades a investigaciones que orquesten sistemáticamente los diversos escenarios que se dan en el ejercicio de la ciberdefensa.

4.2 Metodología de modelamiento de sistemas complejos para el MARCIM

Para abordar el proyecto de investigación del MARCIM, se desarrolló una propuesta de procedimiento metodológico orientado al modelamiento de sistemas complejos, enfoque sistémico, teniendo en cuenta los resultados del marco teórico, antecedentes y estado del arte. Para ello se establecen tres fases como se muestra en la Fig. 1.

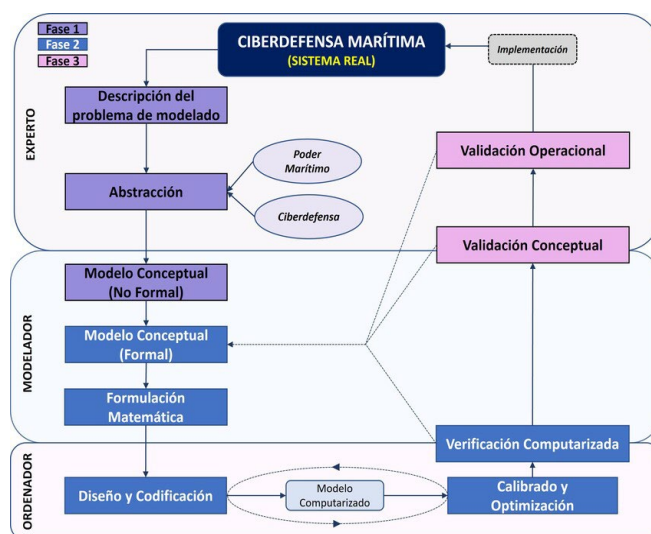


Figura 1: Proceso metodológico MARCIM.

Fuente: Elaboración propia adaptado de [50–52,53, p.186].

4.2.1 Fase 1 – Requerimientos del modelo

La primera fase busca explicar los requerimientos del marco de referencia para el modelamiento y simulación de la ciberdefensa marítima a nivel estratégico, siguiendo los procedimientos relacionados a continuación:

Descripción del problema de modelado: define la perspectiva del modelo así como los aspectos más relevantes del sistema real con el propósito de definir los objetivos que se pretenden alcanzar [50, p. 14], [51, pp. 93–95], describiendo aspectos como: objetivos de modelado, hipótesis de modelado (asunciones), restricciones, tipos de datos y tipos de resultados.

Abstracción: identificación de los componentes más importantes de los sistemas reales, taxonomías, interacciones que pueda existir entre ellos y relaciones causales más significativas, dando como resultado un grupo de modelos no formales que en su conjunto representan el objetivo de modelado [51, pp.93–97], que para esta investigación se concentran en dos sistemas principales: sistema del poder marítimo y sistema de la ciberdefensa.

Modelo conceptual del sistema de ciberdefensa marítima (Modelo no formal): modelo no formal que representa el objetivo de modelado en su contexto general, integrando los sistemas caracterizados en la abstracción. Este procedimiento incluye el desarrollo de taxonomías que apoyen el entendimiento del sistema y estandaricen los elementos de mando y control esenciales para la toma de decisiones y definición de cursos de acción en ciberdefensa marítima, de manera que se puedan generar respuestas colaborativas y coordinadas en todo el sistema, cuando una situación ponga en riesgo algún activo o infraestructura crítica cibernética marítima [54].

4.2.2 Fase 2 - Modelado

La segunda fase aborda el diseño del modelo de simulación de las acciones e interacciones entre las entidades de la ciberdefensa marítima a nivel estratégico, partiendo del modelo conceptual no formal de la primera fase, y se seguirán los siguientes procedimientos:

Modelo conceptual del sistema de ciberdefensa marítima (Modelo formal): caracterización detallada del modelo conceptual que incluye [50, pp. 15–28]: caracterización de variables y componentes del sistema, caracterización de acciones e interacciones, descripción de las relaciones causales (causa-efecto) y descripción de las relaciones funcionales.

El modelo conceptual permite al experimentador, investigador o tomador de decisiones entender “la dinámica del fenómeno estudiado en los correspondiente a actores, acciones e interacciones, y se enmarca como una herramienta de trabajo para la toma de decisiones a nivel estratégico, con miras al cumplimiento de los objetivos de ese nivel” [55].

Formulación matemática del modelo: revisión del modelo formal y concretar la representación del modelo bajo un marco matemático [56].

Diseño y codificación: diseño e implementación del modelo o conjunto de modelos formales en un soporte dinámico, a través de un modelo para computadora, que satisfaga las especificaciones y representaciones planteadas, utilizando herramientas computacionales para modelamiento y simulación, e incluye los siguientes pasos [50, pp.28–29], [51, pp.93–97]: análisis y gestión de la información del modelo (inferencia), selección de las técnicas de modelado para la implementación del modelo conceptual en las herramientas computacionales, selección de las herramientas computacionales e implementación computacional del modelo.

Calibrado y optimización del modelo: permite corregir los parámetros del modelo no determinados y ajustar los parámetros desconocidos [50, pp.33–34].

Verificación computarizada del modelo: comprueba que la implementación del modelo conceptual da los resultados esperados cuando trabaja con escenarios conocidos, mediante el análisis e interpretación del modelo [50, pp.33–34], [51, pp. 97], [53, pp.188–189].

Para la formulación matemática se utilizarán los métodos de simulación y modelado descritos por Alfonso Urquía y Carla Marín (2016), principalmente los estocásticos para simulación probabilística; métodos matemáticos para modelos basados en agentes [56]; y lo descrito en el libro *Simulation Modeling and Analysis* (Modelos de simulación y análisis) [57], principalmente en los métodos de modelamiento de sistemas complejos, modelamiento basado en agentes y sistemas dinámicos. Finalmente, para el diseño, calibrado y verificación computarizada del modelo se contempla el software NetLogo [34], un entorno de modelado programable de múltiples agentes desarrollado por el Center for Connected Learning and Computer-Based Modeling (Centro de aprendizaje conectado y modelado basado en computadora) de la Universidad de Northwestern, caracterizado por su alta escalabilidad, gran fuerza de modelado computacional y baja complejidad de esfuerzo de desarrollo en comparación con otras soluciones [58].

La aplicación de Netlogo será complementada con desarrollos en el área de análisis de datos y algoritmos de aprendizaje (*Machine Learning*) con el software Python [59].

4.2.3 Fase 3 – Validación del modelo

Por último, la tercera fase busca validar el modelo de ciberdefensa marítima a través de simulaciones, para ello se establecen dos tipos de validación:

Validación conceptual (juicio de expertos): determina que las teorías y los supuestos subyacentes al modelo conceptual son correctos y la representación de la entidad problemática, estructura, lógica y relaciones causales del modelo son acordes para el objetivo previsto [53, pp.188].

Validación operacional (juegos de guerra - simulación militar): establece “si el comportamiento de salida del modelo de simulación tiene la precisión requerida para el propósito previsto del modelo sobre el dominio de la aplicabilidad prevista” [53, pp.189]. Para ello se utilizarán los juegos de guerra como herramienta metodológica [60] que

permite explorar las posibilidades de toma de decisiones en un entorno con información incompleta e imperfecta [61], en un escenario hipotético del poder marítimo colombiano.

5. Discusión

5.1 Estado del Arte

5.1.1 Ciberdefensa

Es importante tener presente que la ciberdefensa viene considerando la teoría de juegos y el uso de juegos serios como herramientas metodológicas para optimizar la gestión de sus actividades, así como reducir el impacto y el riesgo de los ciberataques. Igualmente, se evidencia la presencia de escenarios de ataque y defensa dinámicos, que demandan soluciones que evalúen las situaciones desde un enfoque holístico, adaptándose a la complejidad y que incluyan aspectos como el factor humano y la información imperfecta.

5.1.2 Modelamiento y simulación en ciberseguridad y ciberdefensa

La ciberdefensa involucra la interacción entre los humanos y la nueva tecnología, por lo que toma una connotación de sistema complejo que requiere de la implementación de metodologías y modelos para su planificación, ejecución y evaluación, así como el modelamiento de las interacciones entre atacantes y defensores para hacer frente a los incidentes cibernéticos, minimizando o eliminando el impacto, y estableciendo los controles y contramedidas necesarias. Entre las metodologías más usadas en los estudios está el modelamiento basado en agentes, dinámica de sistemas y la teoría de juegos dinámicos con información incompleta.

5.1.3 Ciberseguridad y ciberdefensa marítima

Los estudios de ciberseguridad y ciberdefensa marítima se vienen enfocando principalmente en el buque y son pocos los estudios que abordan la problemática desde un enfoque holístico, es decir, del sistema marítimo en su complejidad, a pesar de que ya se ha evidenciado esta necesidad.

A nivel general, las tres temáticas analizadas (ciberdefensa, modelamiento y simulación en ciberseguridad y ciberdefensa, y ciberseguridad y ciberdefensa marítima) muestran una baja producción científica, con vacíos en la literatura, principalmente en el área de ciberseguridad y ciberdefensa marítima, con diversas oportunidades de investigación, centradas principalmente en los enfoques holísticos de la ciberseguridad y ciberdefensa, así como el uso de metodologías de modelamiento y simulación. Adicionalmente, el análisis bibliográfico establece que para el desarrollo del objetivo de investigación es importante tener presente la multiplicidad y complejidad de las dinámicas de los actores de la ciberdefensa, por lo que se contempla el uso de aspectos relacionados con el enfoque de sistema,

específicamente sistemas complejos, abordando el modelamiento y simulación con métodos de ciencia de datos, modelamiento basado en agentes y dinámica de sistemas.

Así pues, el proyecto de investigación MARCIM pretende aportar al estudio de la ciberdefensa marítima desde el modelamiento y simulación con el propósito de establecer un marco de referencia que permita comprender la complejidad de la ciberdefensa marítima y sus procesos fundamentales.

5.2 Metodología de modelamiento de sistemas complejos para el MARCIM

La metodología desarrollada se plantea con un enfoque de sistema (pensamiento sistémico), específicamente sistemas complejos, buscando ofrecer un entorno de simulación en ciberdefensa marítima a nivel estratégico que permita a experimentadores comprender la complejidad del sistema y sus procesos fundamentales, así como estudiar dinámicas, procesos, acciones e interacciones, y elementos que no se pueden identificar claramente, que requieren del modelamiento y simulación.

Adicionalmente, esta metodología puede ser adaptada a entornos de ciberseguridad y ciberdefensa, diferentes al marítimo, en los que existan agentes conectados, interdependientes, diversos, adaptativos y complejos, que requieren de la experimentación con un enfoque metaheurístico para ser estudiados. Entendiendo la metaheurística como la exploración con espacios, conjuntos o redes de soluciones, donde el investigador busca que el sistema se comporte como él desearía [62, pp. 10].

6. Conclusiones

La elaboración de los antecedentes, marco teórico y estado del arte, por medio de estudios bibliométricos y análisis bibliográfico, permitieron plantear la metodología que para responder la pregunta problema del proyecto de investigación MARCIM. Esta metodología tiene un enfoque sistémico, sistemas complejos, y aborda principalmente el ejercicio de la ciberdefensa en el contexto de la ciberseguridad marítima.

La ciberdefensa tiene un comportamiento complejo que involucra la interacción entre los humanos y la nueva tecnología, requiriendo herramientas metodológicas para planificar, ejecutar, evaluar y optimizar la gestión de sus actividades, así como reducir el impacto y el riesgo de los ciberataques. En este sentido, la ciberdefensa se apoya de herramientas como: la teoría de juegos y el uso de juegos serios; teoría de sistemas complejos; modelamiento y simulación de las interacciones entre atacantes y defensores para hacer frente a los incidentes cibernéticos; modelamiento basado en agentes, dinámica de sistemas y la teoría de juegos dinámicos con información incompleta.

Son pocos los estudios relacionados con ciberseguridad y ciberdefensa marítima, y los que existen se enfocan principalmente en el buque, siendo pocos los estudios con un enfoque holístico. Enfoque necesario por la multiplicidad de

actores y dinámicas complejas en el sector marítimo, que requieren su estudio como sistema.

La ciberdefensa marítima a nivel estratégico se comporta como un sistema complejo, con dinámicas, procesos y elementos que no se pueden identificar claramente, que requieren del modelamiento y simulación, con un enfoque metaheurístico, para estudiar el conjunto de acciones e interacciones entre sus entidades.

El proyecto de investigación MARCIM pretende aportar al estudio de la ciberdefensa marítima desde el modelamiento y simulación con el propósito de establecer un marco de referencia que ofrezca un entorno de simulación en esta área que permita a experimentadores comprender la complejidad del sistema y sus procesos fundamentales; desarrollar y probar hipótesis de trabajo o cursos de acción; lograr ver emergencias, dinámicas, procesos, elementos clave a nivel estratégico; prever el comportamiento de las entidades en la ciberdefensa marítima y determinar posibles escenarios de ataque y defensa cibernética en el ámbito marítimo.

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- A view of agile organizations: bibliometric analysis
- Bibliometric study of distribution system state estimation: advances and challenges
- Predicting the flowability of UHPC and identifying its significant influencing factors using an accurate ANN model
- Simulation analysis of school road traffic characteristics
- Factorial analysis of road infrastructure related to traffic accidents occurred in Neiva in the years 2017-2018
- Correcting misinterpretations on the distribution of feasible solution lengths in the traveling salesman problem
- Detection of white spot syndrome virus in seston from a coastal ecosystem and a shrimp farm in the Gulf of California
- Effects of saline and water stress on sweet sorghum
- Quantification and analysis of flexibility in a power distribution network with penetration of non-conventional renewable sources
- LoRa-based IoT platform for remote soil parameter monitoring
- Modeling the impact of supplementary cementitious materials on compressive strength of recycled aggregate concrete forest-random approach
- Personnel selection system based on the selection algorithm
- Smart sensors/actuators based in amorphous nanostructures, according to enhance robotic arms energy transmission
- Influence of partial replacement of cement by biomass ashes on cement-wood composites properties
- Use of steel slag to improve the mechanical properties of subgrades in clayey soils
- Structuring of an energy requirements guide for the feasibility study of private investment projects
- Comparative technical analysis of the current state of small-scale mining titles in California, Santander, Colombia
- Performance of an unpaved roads reinforced with geogrid: construction of a physical model in laboratory and numerical validation
- Development of an IoT architecture for environmental monitoring: integrating open source technologies with application projection in the mining sector
- Framework for modeling and simulation of maritime cyberdefense - MARCIM: state of the art and methodology
- Una mirada a las organizaciones ágiles: análisis bibliométrico
- Estudio bibliométrico de la estimación del estado de los sistemas de distribución: avances y retos
- Predicción de la trabajabilidad del UHPC e identificación de sus factores de influencia significativos utilizando un modelo ANN preciso
- Análisis de simulación de las características del tráfico escolar
- Análisis factorial de la infraestructura vial relacionada con los accidentes de tránsito ocurridos en Neiva en los años 2017-2018
- Corrección de interpretaciones erróneas sobre la distribución de longitudes de solución factibles en el problema del viajante
- Detección del virus del síndrome de la mancha blanca en un ecosistema costero y una granja de camarón en el Golfo de California
- Efectos del estrés salino e hídrico en el sorgo dulce
- Cuantificación y análisis de la flexibilidad en una red de distribución de energía eléctrica con penetración de fuentes renovables no convencionales
- Plataforma IoT basada en LoRa para monitoreo remoto de parámetros del suelo
- Modelación del impacto de los materiales cementantes suplementarios en la resistencia a compresión de los concretos con agregados reciclados - enfoque por bosques aleatorios
- Sistema de selección de personal basado en el algoritmo de selección
- Sensores/actuadores inteligentes basados en nanoestructuras amorfas, para mejorar la transferencia de energía en brazos robóticos
- Influencia de la sustitución parcial de cemento por cenizas de biomasa en las propiedades de compuestos de cemento y madera
- Uso de escoria de acero para mejorar las propiedades mecánicas de las subrasantes en suelos arcillosos
- Estructuración de una guía de requerimientos energéticos para el estudio de viabilidad de proyectos de inversión privada
- Análisis técnico comparativo del estado actual de títulos mineros de minería a pequeña escala en California, Santander, Colombia
- Desempeño de una vía no pavimentada reforzada con geomalla: construcción de un modelo físico en laboratorio y validación numérica
- Desarrollo de una Arquitectura IoT para monitoreo ambiental: integración de tecnologías de código abierto con proyección de aplicación en el sector minero
- Marco de referencia para el modelamiento y simulación de la ciberdefensa marítima - MARCIM: estado del arte y metodología