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Tecnura

Tecnología y cultura, afirmando el conocimiento

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REVISTA TECNURA

La revista Tecnura es una publicación institucional de la Facultad Tecnológica de la Universidad Distrital Francisco José de Caldas de carácter científico-tecnológico, arbitrada mediante un proceso de revisión entre pares de doble ciego. La periodicidad de la conformación de sus comités Científico y Editorial está sujeta a la publicación de artículos en revistas indexadas internacionalmente por parte de sus respectivos miembros.

PERIODICIDAD

Es una publicación de carácter científico-tecnológico con periodicidad trimestral, que se publica los meses de enero, abril, julio y octubre. Su primer número apareció en el segundo semestre del año 1997 y hasta la fecha ha mantenido su regularidad.

COBERTURA TEMÁTICA

Las áreas temáticas de interés de la revista Tecnura están enfocadas a todos los campos de la ingeniería, como la electrónica, telecomunicaciones, electricidad, sistemas, industrial, mecánica, catastral, civil, ambiental, entre otras. Sin embargo, no se restringe únicamente a estas, también tienen cabida los temas de educación y salud, siempre y cuando estén relacionados con la ingeniería. La revista publicará únicamente artículos de investigación científica y tecnológica, de reflexión y de revisión.

MISIÓN

La revista Tecnura tiene como misión divulgar resultados de proyectos de investigación realizados en el área de la ingeniería, a través de la publicación de artículos originales e inéditos, realizados por académicos y profesionales pertenecientes a instituciones nacionales o extranjeras del orden público o privado.

PÚBLICO OBJETIVO

La revista Tecnura está dirigida a docentes, investigadores, estudiantes y profesionales interesados en la actualización permanente de sus conocimientos y el seguimiento de los procesos de investigación científico-tecnológica, en el campo de la ingeniería.

INDEXACIÓN

Tecnura es una publicación de carácter académico indexada en los indices regionales publindex indexada y clasificada en categoria B, Scielo Colombia y Redalyc (México); además de las siguientes bases bibliográficas: INSPEC del Institution of Engineering and Technology (Inglaterra), Fuente Académica Premier de EBSCO (Estados Unidos), CABI (Inglaterra), IndexCorpernicus (Polonia), Informe Académico de Gale Cengage Learning (México), Periódica de la Universidad Nacional Autónoma de México (México), Oceanet (España) y Dialnet de la Universidad de la Rioja (España); también hace parte de los siguientes directorios: Sistema Regional de Información en Línea para Revistas Científicas de América Latina, el Caribe, España y Portugal Latindex (México); Índice Bibliográfico A ctualidad I beroamericana (Chile), e-Revistas (España), DOAJ (Suecia), Ulrich de Proquest (Estados Unidos).

FORMA DE ADQUISICIÓN

La revista Tecnura se puede adquirir a traves de canje o suscripcion en el portal de la de la revista.

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Julio - Septiembre de 2021

TECNURA JOURNAL

Tecnura Journal is an institutional scientific-technological publication from the Faculty of Technology at District University Francisco José de Caldas, arbitrated by means of a double-blinded peer review process. The periodicity for its Scientific and Editorial committees line-up is subject to the publication of articles in internationally indexed magazines by its own members.

PERIODICITY

Tecnura journal is a scientific-technological publication with quarterly periodicity, published in January, April, July and October. Its first edition appeared in the second term, 1997 and its editions have normally continued from that year and on.

THEMATIC COVERAGE

The thematic areas of interest at Tecnura journal are focused on all fields of engineering such as electronical, telecommunications, electrical, computer, industrial, mechanical, cadastral, civil, environmental, etc. However, it is not restricted to those, there is also room for education and health topics as well, as long as they are related to engineering. The journal will only publish scientific and technological research, reflection and review articles.

MISSION

Tecnura journal is aimed at publishing research project results carried out in the field of engineering, through the publishing of original and unpublished articles written by academics and professionals from national or international public or private institutions.

TARGET AUDIENCE

Tecnura journal is directed to professors, researchers, students and professionals interested in permanent update of their knowledge and the monitoring of the scientific-technological research processes in the field of engineering.

INDEXING

Tecnura is an academic publication indexed in the Regional Index Scielo Colombia (Colombia) and Redalyc (México); as wel as the following bibliographic databases: INSPEC of the Institution of Engineering and Technology (England), Fuente Académica Premier of EBSCO (United States), CABI (England), Index Copernicus (Poland), Informe Académico of Gale Cengage Learning (México), Periódica of the Universidad Nacional Autónoma de México (México), Oceanet (Spain) and Dialnet of the Universidad de la Rioja (Spain); it is also part of the following directories: Online Regional Information System for Scientific j ournals f rom L atin A merica, Caribbean, Spain and Portugal Latindex (México), bibliographic index Actualidad Iberoamericana (Chile), e-Revistas (Spain), DOAJ (Sweden), Ulrich of Proquest (United States).

FORM OF ACQUISITION

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Declaración de ética y buenas Prácticas

https://revistas.udistrital.edu.co/index.php/Tecnura/about

El comité editorial de la revista **Tecnura** está comprometido con altos estándares de ética y buenas prácticas en la difusión y transferencia del conocimiento, para garantizar el rigor y la calidad científica. Es por ello que ha adoptado como referencia el Código de Conducta que, para editores de revistas científicas, ha establecido el Comité de Ética de Publicaciones (COPE: Committee on Publication Ethics) dentro de los cuales se destaca:

Obligaciones y responsabilidades generales del equipo editorial

En su calidad de máximos responsables de la revista, el comité y el equipo editorial de Tecnura se comprometen a:

- Aunar esfuerzos para satisfacer las necesidades de los lectores y autores.
- Propender por el mejoramiento continuo de la revista.
- Asegurar la calidad del material que se publica.
- Velar por la libertad de expresión.
- Mantener la integridad académica de su contenido.
- Impedir que intereses comerciales comprometan los criterios intelectuales.
- Publicar correcciones, aclaraciones, retractaciones y disculpas cuando sea necesario.

Relaciones con los lectores

Los lectores estarán informados acerca de quién ha financiado la investigación y sobre su papel en la investigación.

Relaciones con los autores

Tecnura se compromete a asegurar la calidad del material que publica, informando sobre los objetivos y normas de la revista. Las decisiones de los editores para aceptar o rechazar un documento para su publicación se basan únicamente en la relevancia del trabajo, su originalidad y la pertinencia del estudio con relación a la línea editorial de la revista. La revista incluye una descripción de los procesos seguidos en la evaluación por pares de cada trabajo recibido. Cuenta con una guía de autores en la que se presenta esta información. Dicha guía se actualiza regularmente y contiene un vínculo a la presente declaración ética. Se reconoce el derecho de los autores a apelar las decisiones editoriales. Los editores no modificarán su decisión en la aceptación de envíos, a menos que se detecten irregularidades o situaciones extraordinarias. Cualquier cambio en los miembros del equipo editorial no afectará las decisiones ya tomadas, salvo casos excepcionales en los que confluyan graves circunstancias.

Relaciones con los evaluadores

Tecnura pone a disposición de los evaluadores una guía acerca de lo que se espera de ellos. La identidad de los evaluadores se encuentra en todo momento protegida, garantizando su anonimato.

Proceso de evaluación por pares

Tecnura garantiza que el material remitido para su publicación será considerado como materia reservada y confidencial mientras que se evalúa (doble ciego).

Reclamaciones

Tecnura se compromete responder con rapidez a las quejas recibidas y a velar para que los demandantes insatisfechos puedan tramitar todas sus quejas. En cualquier caso, si los interesados no consiguen satisfacer sus reclamaciones, se considera que están en su derecho de elevar sus protestas a otras instancias.

Fomento de la integridad académica

Tecnura asegura que el material que publica se ajusta a las normas éticas internacionalmente aceptadas.

Protección de datos individuales

Tecnura garantiza la confidencialidad de la información individual (por ejemplo, de los profesores y/o alumnos participantes como colaboradores o sujetos de estudio en las investigaciones presentadas).

Seguimiento de malas prácticas

Tecnura asume su obligación para actuar en consecuencia en caso de sospecha de malas prácticas o conductas inadecuadas. Esta obligación se extiende tanto a los documentos publicados como a los no publicados. Los editores no sólo rechazarán los manuscritos que planteen dudas sobre una posible mala conducta, sino que se consideran éticamente obligados a denunciar los supuestos casos de mala conducta. Desde la revista se realizarán todos los esfuerzos razonables para asegurar que los trabajos sometidos a evaluación sean rigurosos y éticamente adecuados.

Integridad y rigor académico

Cada vez que se tenga constancia de que algún trabajo publicado contiene inexactitudes importantes, declaraciones engañosas o distorsionadas, debe ser corregido de forma inmediata.
En caso de detectarse algún trabajo cuyo contenido sea fraudulento, será retirado tan pronto como se conozca, informando inmediatamente tanto a los lectores como a los sistemas de indexación.
Se consideran prácticas inadmisibles, y como tal se denunciarán las siguientes: el envío simultáneo de un mismo trabajo a varias revistas, la publicación duplicada o con cambios irrelevantes o parafraseo del mismo trabajo, o la fragmentación artificial de un trabajo en varios artículos.

Relaciones con los propietarios y editores de revistas

La relación entre editores, editoriales y propietarios estará sujeta al principio de independencia editorial. **Tecnura** garantizará siempre que los artículos se publiquen con base en su calidad e idoneidad para los lectores, y no con vistas a un beneficio económico o político. En este sentido, el hecho de que la revista no se rija por intereses económicos, y defienda el ideal de libre acceso al conocimiento universal y gratuito, facilita dicha independencia.

Conflicto de intereses

Tecnura establecerá los mecanismos necesarios para evitar o resolver los posibles conflictos de intereses entre autores, evaluadores y/o el propio equipo editorial.

Quejas/denuncias

Cualquier autor, lector, evaluador o editor puede remitir sus quejas a los organismos competentes

Code of ethics and good practice

https://revistas.udistrital.edu.co/index.php/Tecnura/about

The editorial board of Tecnura journal is committed to ethics high standards and good practice for knowledge dissemination and transfer, in order to ensure rigour and scientific quality. That is why it has taken as reference the Code of Conduct, which has been established by the Committee on Publication Ethics (COPE) for scientific journal editors; outlining the following:

General duties and responsibilities of the editorial board

As most responsible for the journal, **Tecnura** committee and the editorial board are committed to:

- Joining efforts to meet the readers and authors' needs.
- Tending to the continuous improvement of the Journal.
- Ensuring quality of published material.
- Ensuring freedom of expression.
- Maintaining the academic integrity of their content.
- Prevent commercial interests compromise intellectual standards.
- Post corrections, clarifications, retractions and apologies when necessary.
- Relations with readers.
- Readers will be informed about who has funded re- search and their role in the research.

Relations with authors

Tecnura is committed to ensuring the quality of published material, informing the goals and standards of the journal. The decisions of publishers to accept or reject a paper for publication are based solely on the relevance of the work, originality and pertinence of the study with journal editorial line. The journal includes a description of the process for peer evaluation of each received work, and has an authors guide with this information. The guide is regularly updated and contains a link to this code of ethics. The journal recognizes the right of authors to appeal editorial decisions Publishers will not change their decision in accepting or rejecting articles, unless extraordinary circumstances or irregularities are detected. Any change in the editorial board members will not affect decisions already made, except for unusual cases where serious circumstances converge.

Relations with evaluators

Tecnura makes available to reviewers a guide to what is expected from them. Reviewers' identity is protected at all times, ensuring anonymity.

Peer review process

Tecnura ensures that material submitted for publication will be considered private and confidential issue while being reviewed (double blind).

Claims

Tecnura is committed to respond quickly to complaints and ensure that dissatisfied claimant can process all complaints. In any case, if applicants fail to satisfy their claims, the journal considers that they have the right to raise their protests to other instances.

Code of ethics and good practice

https://revistas.udistrital.edu.co/index.php/Tecnura/about

Promoting Academic Integrity

Tecnura ensures that the published material conforms to internationally accepted ethical standards.

Protection of individual data

Tecnura guarantees the confidentiality of individual information (e.g. participant teachers and/or students as collaborators or subjects of study in the presented research).

Tracking malpractice

Tecnura accepts the obligation to act accordingly in case of suspected malpractice or misconduct. This obligation extends both to publish and unpublished documents. The editors not only reject manuscripts with doubts about possible misconduct, but they are considered ethically obligated to report suspected cases of misconduct. From the journal every reasonable effort is made to ensure that works submitted for evaluation are rigorous and ethically appropriate.

Integrity and academic rigour

Whenever evidence that a published work contains significant misstatements, misleading or distorted statements, it must be corrected immediately.
In case of any work with fraudulent content is detected, it will be removed as soon as it is known, and immediately informing both readers and indexing systems.
Practices that are considered unacceptable and as such will be reported: simultaneous sending of the same work to various journals, duplicate publication with irrelevant changes or paraphrase of the same work, or the artificial fragmentation of a work in several articles.

Relations with owners and journal editors

The relation between editors, publishers and owners will be subject to the principle of editorial independence. **Tecnura** will ensure that articles are published based on their quality and suitability for readers, and not for an economic or political gain. In this sense, the fact that the journal is not governed by economic interests, and defends the ideal of universal and free access to knowledge, provides that independence.

Conflict of interest

Tecnura will establish the necessary mechanisms to avoid or resolve potential conflicts of interest between authors, reviewers and/or the editorial board itself.

Complaints / allegations

Any author, reader, reviewer or editor may refer their complaints to the competent authorities.

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Tabla de Contenidos

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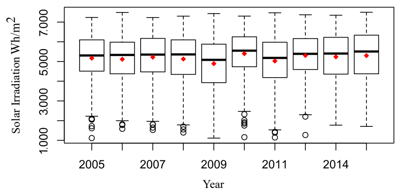

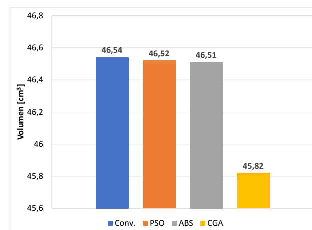

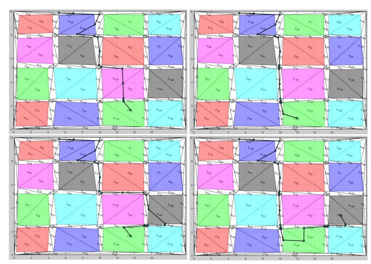

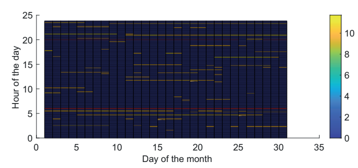

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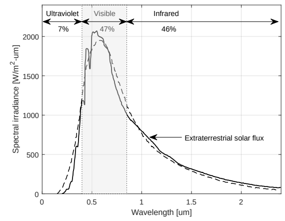

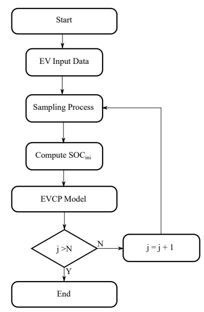

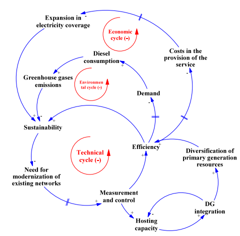

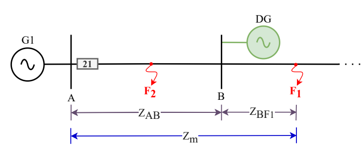

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Editorial

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Climate change constitutes one of the greatest challenges humanity faces. According to the report prepared by IDEAM, 'Climate Change in the Region of Bogotá, Cundinamarca, and its implications for regional development:' "***Climate change*** *refers to statistically significant variation, either in average climatic conditions or in its variability, which is maintained over a long period of time. This change can be produced by natural processes, external reinforcements, or long-lasting anthropogenic changes in the composition of the atmosphere and land use."* It is worth highlighting that what arouses concern about this phenomenon is not the climatic variability generated but the speed this variability has shown in recent years.

In Colombia, climate change arouses interest given that its effects are materialized in human and material losses, mainly due to the intensification of climate variability events such as the El Niño and La Niña phenomena. The **El Niño phenomenon** refers to the warm current that flows from the coast of Ecuador and Peru, which is associated with the fluctuation of intertropical pressure on the surface and the circulation of the Pacific and Indian oceans—called the Southern Oscillation. It generates changes in winds, sea temperatures, and precipitation in the tropical Pacific. The opposite effect is called the **La Niña phenomenon** (IDEAM, 2012).

Additionally, it should be mentioned that climate change is also associated with changes in the **vocation of the soil**, that is, the use of a soil unit defined by the capacity to support the characteristics of an activity on the analysis of its biophysical basis. Within the established classes are agricultural, livestock, agroforestry, forestry, and conservation. This change has generated **soil degradation**, which is the decrease or negative alteration of ecosystem functions caused by natural or anthropic processes and affects **associated ecosystem services** such as food production (that directly depends on the availability and quality of the soil), the reserve of fresh water in the soil (that determines the quantity-quality supplied to natural environment), and carbon capture (estimated to be two-thirds of the carbon fixed on the planet) (FAO, 2018). The change in the vocation of the soil (and its waterproofing due to urban expansion) directly affects **the hydrological cycle**, defined as the global water balance that helps to understand the interactions between the ocean and the continent. It represents the circulation-transformation of water in different states of matter and its interactions between the atmosphere, lithosphere, and the biosphere (IDEAM, 2010).

There are several proposals and strategies to face and mitigate the effects of climate change in our country; one of them is to integrate the development of nature-based solutions (NBS) into the Development and Land Use Plans, as an option for urban growth (Keesstra, Nunes, Novara, Finger, & Avelar, 2018). NBS refer to the implementation of management measures in which natural dynamics are simulated or reconstructed, considering the interaction flows between the phases involved: soil, sediments, water, and pollutants. These measures are divided into two categories: the first corresponds to NBS that seek to maintain the functionality of the soil and enhance its resilience, while the second refers to those that seek to transform the flows between the matrices involved based on the concept of connectivity (Keesstra, Nunes, Novara, Finger, & Avelar, 2018).

Within the framework of these solutions are the so-called Green Infrastructure, which correspond to the integration of green spaces in construction systems (forests, wetlands, parks, and green roofs, among others) to promote ecosystem resilience and achieve benefits for the society through the potentiation of ecosystem services. Forests, wetlands, and floodplains help control peak flows and remove pollutants from the water, among other ecosystem services (Demuzere, Orru, & Heidrich, 2014).

Cesar Augusto García-Ubaque
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Editorial

https://revistas.udistrital.edu.co/ojs/index.php/Tecnura/issue/view/1088

El cambio climático constituye uno de los retos más grandes que enfrenta la humanidad. Según el informe "Cambio Climático en la Región de Bogotá, Cundinamarca y sus implicaciones para el desarrollo regional" elaborado por el IDEAM, *"el **cambio climático**, se refiere a la variación estadísticamente significativa, ya sea de las condiciones climáticas medias o de su variabilidad, que se mantiene durante un periodo de tiempo prolongado. El cambio puede producirse por procesos naturales, reforzamientos externos o cambios antropogénicos duraderos en la composición de la atmosfera y el uso de la tierra."* Cabe notar que, lo que despierta preocupación ante este fenómeno no es la variabilidad climática generada sino la rapidez con la que ésta ha ocurrido en los últimos años.

En Colombia, el cambio climático despierta interés dado que sus efectos se ven materializados en pérdidas humanas y materiales, principalmente por la intensificación de eventos de variabilidad climática como los fenómenos del Niño y de la Niña. Entendiéndose como **fenómeno de El Niño** a la corriente cálida que fluye desde la costa de Ecuador y Perú, que está asociado a la fluctuación de la presión intertropical en la superficie y la circulación de los océanos Pacifico e Indico, llamada Oscilación Meridional. Generando cambios en los vientos, la temperatura marina y la precipitación del Pacifico tropical. Al efecto contrario se le denomina **el fenómeno de La Niña** (IDEAM, 2012).

Adicionalmente, se debe mencionar que el cambio climático también está asociado a cambios en la **vocación del suelo**, la cual se refiere al uso de una unidad de suelo definido por la capacidad de soportar las características de una actividad sobre el análisis de la base biofísica del mismo. Dentro de las clases establecidas están: agrícola, ganadera, agroforestal, forestal, y de conservación. Dicho cambio ha generado la **degradación** de los suelos, la cual se entiende como la diminución o alteración negativa de las funciones ecosistémicas ocasionada por procesos naturales o antrópicos, afectando los **servicios ecosistémicos asociados**, como lo son la producción de alimentos que depende directamente de la disponibilidad y calidad del suelo, la reserva de agua dulce en el suelo que determina la cantidad-calidad suministrada al miedo natural y la captura de carbono que se estima en dos tercios del carbono fijado en el planeta (FAO, 2018).

El cambio en la vocación del suelo (impermeabilización por efectos de la expansión urbana) también afecta directamente el **ciclo hidrológico**, el cual se define como el balance de agua global para entender las interacciones entre el océano y el continente. Representa la circulación-transformación del agua en diferentes estados de la materia y sus interacciones entre la atmosfera, litosfera y la biosfera (IDEAM, 2010).

Dentro de las posibles estrategias para enfrentar y mitigar los efectos del cambio climático en nuestro país está el integrar en los Planes de Desarrollo y de Ordenamiento territorial, la inclusión de soluciones basadas en la naturaleza (siglas en inglés NBS), como una opción frente al crecimiento urbano (Keesstra, Nunes, Novara, Finger, & Avelar, 2018). Las NBS se refieren a la implementación de medidas de manejo en las que se simulan o reconstruyen las dinámicas naturales teniendo en cuenta los flujos de interacción entre las fases involucradas: el suelo, los sedimentos, el agua, y los contaminantes. Estas medidas se dividen en dos categorías: la primera corresponde a las NBS que buscan mantener la funcionalidad del suelo y potencializar su resiliencia; y la segunda corresponde a las que buscan transformar los flujos entre las matrices involucradas basándose en el concepto de conectividad (Keesstra, Nunes, Novara, Finger, & Avelar, 2018).

Dentro del marco de estas soluciones se encuentran las llamadas *Green Infrastructure* (GI) que corresponden a la integración de espacios verdes en los sistemas de construcción (bosques, humedales, parques, y techos verdes, entre otros) para promover la resiliencia ecosistémica y lograr beneficios para la sociedad mediante la potencialización de servicios ecosistémicos. Los bosques, los humedales y las llanuras de inundación, generan entre otros servicios ecosistémicos el control de picos de flujo y la remoción de contaminantes en el agua (Demuzere, Orru, & Heidrich, 2014).

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INVESTIGACIÓN

Statistical Analysis of the Global Solar Radiation in Cúcuta using the ANOVA Model

Análisis estadístico de la radiación solar global en Cúcuta utilizando el modelo ANOVA

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Abstract

Objective: This paper presents a statistical analysis of solar radiation in the city of Cúcuta, aiming to provide a detailed description of its variability between 2005 and 2015. This information represents an assessment tool to study the solar potential of the region for photovoltaic system design, motivated by the need to improve the cost-effectiveness of this technology, and thus increase its penetration in the Colombian electric grid.
Methodology: Three weather databases with hourly data were studied, from which the one with the largest amount of data available was selected. By means of the R Studio software, two types of statistical methods were executed: single factor variance analysis (ANOVA) and Bonferroni test. From this, graphs representing the statistical summary of solar radiation values in the last decade were obtained.
Results: The ANOVA showed a p-value of $6{,}28 \times 10^{-7}$, indicating that there is a statistically significant difference in the sample mean between the different years of study. Likewise, the years and months with the greatest deviation and the possible causes for the variability of this parameter were identified.
Conclusions: Despite showing a stable behavior, the radiation of the city of Cúcuta requires a very specific analysis for its use in applications that need a high sensitivity in the handling of this information, since there are statistically significant variations that can occur for its use.
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Keywords: ANOVA, global solar radiation, R Studio, Bonferroni test

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Resumen

Objetivo: Esta investigación presenta un análisis estadístico de la radiación solar en la ciudad de Cúcuta, con el objetivo de brindar una descripción detallada de su variabilidad entre los años 2005 y 2015. Esta información representa una herramienta evaluativa en el estudio del potencial solar de la región para el diseño de sistemas fotovoltaicos, partiendo de la necesidad de mejorar la relación costo/beneficio de esta tecnología, y así incrementar su penetración en la matriz eléctrica colombiana.

Metodología: Se realizó un estudio de tres bases de datos climatológicas con información horaria, seleccionando aquella con la mayor cantidad de datos disponibles. Por medio del software R Studio, se ejecutaron dos tipos de métodos estadísticos: análisis de la varianza de un solo factor (ANOVA) y test de Bonferroni. A partir de esto, se obtuvieron gráficas que representan el resumen estadístico de los valores de radiación solar en la última década.

Resultados: El análisis ANOVA arrojó un valor p de $6{,}28 \times 10^{-7}$, indicando que existe una diferencia estadísticamente significativa de la media muestral entre los diferentes años de estudio. Asimismo, se identificaron los años y meses con mayor desviación y las posibles causas de la variabilidad de este parámetro.

Conclusiones: A pesar de tener un comportamiento estable, la radiación de la ciudad de Cúcuta requiere de un análisis muy específico para su uso en aplicaciones que necesiten una alta sensibilidad en el manejo de esta información, ya que hay variaciones estadísticamente significativas que se pueden presentar para su uso.

Financiamiento: Universidad Francisco de Paula Santander.

Palabras clave: ANOVA, radiación solar global, R Studio, test de Bonferroni

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INTRODUCTION

The sun is the main source of light and heat for planet Earth. This celestial body generates a constant flow of energy known as solar radiation, which is defined as the radiant energy coming from the sun as electromagnetic waves that propagate in all directions and determine the dynamics of atmospheric processes, as well as the climate on Earth. The incident power of solar radiation per unit area is the solar irradiance with SI unit of Wh/m^2 (IDEAM, 2015, Markvart, 2000).

Solar energy is one of the mainstream sources of renewable energy in the world due to its great abundance and its positive impact on the environment. Thanks to its simplicity, it has become the most attractive alternative to provide electricity in areas of difficult access where large conventional grids do not have coverage (Mejía-Calderón *et al.,* 2017). Thus, quantifying the potential of renewable resources, in this case solar energy, is essential to properly size photovoltaic systems that transform irradiance into electricity or for thermal applications that convert irradiance into useful heat (Perpiñán-Lamigueiro, 2020).

An increasing number of studies have tried to identify the importance of accurately characterizing solar information for photovoltaic system design. For instance, Diagne *et al.,* (2013) present a review of forecasting techniques for solar irradiance including statistical approaches based on cloud images and numerical weather prediction models. Basha *et al.,* (2015) proposed an algorithmic model to predict solar radiation using multiple linear regression. The input parameters of their model were local weather conditions, and the output was solar irradiance.

In another study, Ruiz-Cárdenas *et al.,* (2016) used a Deep Belief Network (DBN) to predict solar radiation. This type of machine learning model improves computation time and requires less training epochs; with it, the authors achieved error values near 2 %.

Mihailov & Stoyanov, (2009) performed a statistical analysis of solar radiation levels based on a stochastic process, in order to determine whether the city of Rousse, Bulgaria, has optimal conditions for the deployment of hybrid photovoltaic systems. They found that the solar potential is significant and concluded that the maximum levels of irradiance occur between May and June.

Some authors have developed statistical models to assess and identify the relevant variable inputs for predicting the energy output of photovoltaic systems. For instance, Hernández-Mora *et al.,* (2014) used statistical functions of probability densities to characterize irradiance and ambient temperature through real on-field measurements. Likewise, Rodríguez-Patarroyo *et al.,* (2015) installed a pyranometer to conduct a detailed analysis of the behavior of solar radiation based on *in situ* measurements of Bogotá. Then, they performed a statistical analysis of the atmospheric clearness index.

In Túquerres, Nariño, Colombia, Eraso-Checa & Escobar-Rosero, (2018) conducted a statistical analysis to find out the wind energy potential by measuring wind speed. They modeled the electric generation curve in that region. This case is similar to our work, but with another kind of renewable energy technology.

Finally, in the study conducted by Gallegos *et al.,* (2009), an analysis of solar radiation was performed to estimate the solar resource in different zones of Argentina through the use of charts with the spatial-temporal distribution of irradiance. The authors identified the San Carlos region as the most appropriate for the use of photovoltaic solar systems.

In this sense, worldwide research on this issue has begun to arouse interest in applying this type of studies in the city of Cúcuta, Colombia, which, according to historical records seems to have very high levels of solar radiation throughout the year, thus making it suitable for the deployment of small-, medium-, and large-scale photovoltaic projects.

A descriptive statistical study of the solar radiation in the city of Cúcuta was carried out to analyze the behavior of this variable. Monthly and annual irradiance plots, together with statistical diagrams, helped the authors to calculate an average of 5,335 sun peak hours (Contreras-Sepúlveda *et al., 2018*). In a subsequent work, the authors proposed an empirical model to estimate solar radiation in the same region using an empirical model with sunshine duration as input (Contreras-Sepúlveda *et al.,* 2021). Similarly, Leal-González & Hernández Cely, (2013) studied the solar potential for power generation in the city of Cúcuta. They determined the months of the year with higher and lower potential and suggested installation methods for photovoltaic systems.

Consequently, the adequate characterization of solar resources aids in the proper sizing of photovoltaic systems that use irradiance as energy input. In turn, this allows more accurate designs, better system performance, and an improved bankability of this type of systems. For these reasons, an inferential statistical analysis of solar radiation historic data can provide insightful information on the behavior of this variable in the future. Additionally, it aids in identifying the factors that influence the fluctuation, and it serves as a tool to define the criteria for using solar radiation data on photovoltaic or thermal solar systems for a specific region. This research aims not only to determine the solar potential and spatial-temporal characteristics of irradiance, but also to analyze their variability over the years in the city of Cúcuta (Norte de Santander, Colombia) in order to evaluate its applicability in the design of photovoltaic systems. The data set used in this work corresponds to available measured data between 2005 and 2015 of global solar radiation for Cúcuta.

This paper is organized as follows: after the introduction, section 2 describes the methodology we used in the statistical analysis, which includes a one-way ANOVA to identify whether there are any significant differences between the mean value of irradiance across different years. This type of analysis allows us to determine if there is a difference between the average values among a categorical factor or a treatment (Hossain *et al.,* 2019). Additionally, we conducted a Bonferroni test to pinpoint which years had the largest difference, as well as to complement the ANOVA analysis. Then, in section 3, the results are presented in tables and charts, along with insights about each finding. Finally, in section 4, we draw conclusions from the results and deduct possible reasons to explain the observed variability.

METHODOLOGY

Cúcuta is one of the 32 capital cities in Colombia. Due to its proximity to the equator, it is not subject to climatological seasons throughout the year. Thus, the environmental conditions are very stable all the time. Based on that, climatological variables, such as solar radiation, which has a high intensity in this region, are considered to be relatively constant on average year after year. For this reason, in the design of solar energy systems for this region, average values of solar radiation are typically used, without the need of long or complex preliminary studies about this variable.

The main motivation of this work, similar to other studies around the world, is to obtain an accurate characterization of solar radiation, specifically for the city of Cúcuta, to determine whether assuming a constant value for system designs is reasonable or not and then have a better criterion to design and deploy solar energy systems in the region.

Regarding the above, we seek to accept or reject the hypothesis that the mean value of global solar radiation is constant throughout the years in Cúcuta. Thereupon, we define the null hypothesis (Ho) as the assumption that all years from 2005 to 2015 have the same average value of solar radiation. To that end, this work is structured in two stages: firstly, we carefully analyze three databases containing available data of solar radiation for Cúcuta. Secondly, we conduct a one-way Analysis of Variance (ANOVA) and Bonferroni test using R Studio software, where the variable under consideration is solar radiation.

In the first part of this analysis, we identified three databases with historic records of global solar radiation for Cúcuta. One of them comes from the Colombian Institute of Hydrology, Meteorology, and Environmental Studies (IDEAM). The other two are freely available international databases, provided by the National Aeronautics and Space Administration (NASA) from the United States and the Joint Research Centre (JCR) of the European Commission through their Photovoltaic Geographical Information System (PVGIS).

The IDEAM and PVGIS databases provide solar radiation information in watts per square meter (W/m^2) per hour. However, the data from NASA contain the cumulative sum of solar radiation given in watt per square meter (W/m^2) per day. Considering that IDEAM is a Colombian government institution and the data from that database comes from on-site sensors, this information is prioritized in this study. Nevertheless, as it will be described in the results section, a large fraction of data from IDEAM is missing, and there are data points outside the solar radiation normal range. Hence, the data from IDEAM are not reliable enough to conduct the proposed analysis.

Accordingly, the purpose of this part of the analysis is to find out how accurate the data from NASA and PVGIS are with respect to the IDEAM data. To that end, after cleaning and organizing all the data, we synchronized all databases with the goal of having them within the same time periods.

Once the database was selected, we proceeded to perform the ANOVA statistical analysis. This is an inferential statistical model that consists of evaluating the behavior of a variable through hypothesis testing by means of the data variance across different categorical groups or treatments. The goal is to find out whether there is a difference between the mean values according to a categorical factor (Hossain *et al.,* 2019). In this study, the variable under consideration is global solar radiation in Cúcuta (7°53’38,08"N latitude and 72°30’28,15"W longitude) for a time span of 10 years (from 2005 to 2015).

Finally, as mentioned before, in order to perform a detailed analysis of the ANOVA results, we used the Bonferroni test. To this effect, we adjusted a new alpha value (α'), where the new alpha is calculated by dividing the initial one (0,05) by the number of possible pairs that could be made among the treatments, which are the years in our case (Navidi, 2006). Using R Studio, we performed multiple t-tests on all possible pairs of treatments, aiming to find the most significant difference among the years under study.

In the first step of the preliminary database analysis, we used two software packages: first, Microsoft Excel (2016) to do some data manipulation and plot some statistical metrics; and second, Matlab (version 8.6.0.267246 – R2015b) for data cleaning and the calculation of coefficients and statistical errors. For the second step involving the ANOVA and Bonferroni test, we used R Studio (version 1.1.463 © 2009-2018 RStudio, Inc.).

RESULTS

Similarity analysis

Solar radiation data were selected for a period of 10 years. Once we had the information from the three databases, we compared them to verify the quantity of datapoints available. The results are shown in Figure **1**, where the three sources of information are compared according to the number of days per year when data is available. In this Figure, 365 days of data are equivalent to 100 %.

As seen in Figure **1**, the amount of information from the IDEAM database is scarce in comparison with NASA and PVGIS. In 2005 and 2009, there is a complete absence of data from IDEAM. Therefore, using these years would negatively affect the accuracy of the statistical analysis.

Based on the above, the purpose of the first analysis is to identify how accurate the data from NASA and PVGIS are compared to the available IDEAM data. The idea is to validate which external database (NASA or PVGIS) is more reliable for further analysis. Since the data from PVGIS is 100 % complete for all years except 2012, we will exclude that year from subsequent analyses.

The similarity analysis among databases consists of calculating statistical coefficients and errors to validate the information. The results of this analysis are listed in Table 1.

The correlation coefficient indicates the linear association level between two quantitative variables. From Table 1, the correlation coefficient between IDEAM and NASA is moderate, while the correlation coefficient between IDEAM and PVGIS shows a strong linear relationship. R^2 can be in-

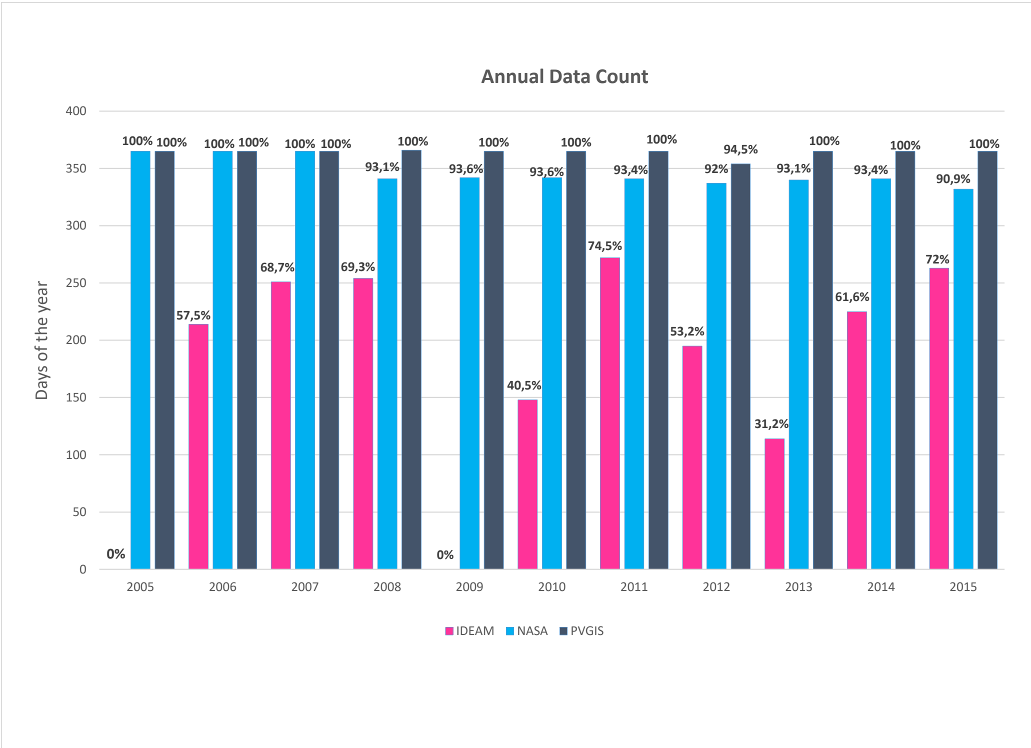

Figure 1. Data count per year in all databases

Source: Authors.

terpreted as the percentage of variability in the dependent variable that is explained by the independent variable, which is about 45 % for NASA and 73 % for PVGIS. The Root Mean Square Error (RMSE) indicates the spread level between the predicted and the actual values. The lower the RMSE, the better the model for predicting the variable of interest. The RMSE for PVGIS is almost half the NASA value. The Mean Absolute Percentage Error (MAPE) measures the accuracy of the model as a percentage using the average difference between the true (IDEAM) and the predicted (NASA and PVGIS) values (Chiteka & Enweremadu, 2016). PVGIS has a MAPE that is more than 10 percentage points lower than that of NASA. Finally, the Mean Bias Error (MBE) represents a systematic error where negative errors cancel out with positive error, so it is typically lower than other error metrics. Remarkably, the MBE for PVGIS is more than 10 times lower than that of NASA.

The results presented in Table 1 indicate that the PVGIS database is significantly closer to the data from IDEAM, with R^2= 0,73. Compared to NASA, PVGIS yields better results not only in the correlation coefficients, but also in all the statistical errors. Based on this, we selected PVGIS as the database to conduct the subsequent inferential statistical analysis.

One-way Analysis of Variance (ANOVA)

As mentioned before, solar radiation is one of the key parameters to design photovoltaic systems; by having a clear understanding of how this variable behaves, we can avoid over- or under-sizing a solar energy system.

Knowing the variability of global solar radiation for a specific location helps validate whether it is suitable for the generation of photovoltaic solar energy. For this reason, we chose to conduct an ANOVA to evaluate if there is any significant variability of solar radiation in Cúcuta, with the purpose of establishing whether there are behavior patterns for future radiation projections or whether a large amount of data should be grouped together to assess the solar potential that can be harnessed in the following years. Table 2 displays the ANOVA results for all years in general.

The parameters listed in Table 2 summarize the results for the ANOVA analysis and are discussed below.

Table 1. Coefficients and statistical errors

Statistical error	IDEAM-NASA	IDEAM-PVGIS
Correlation Coefficient	0,64315719	0,846947483
R^2	0,4486	0,7299
RMSE	1425,3 W/m^2	770,64 W/m^2
MAPE	23,12 %	12,63 %
MBE	13,45 %	1,31 %

Source: Authors.

Table 2. Analysis of variance of global solar radiation for all years

ANOVA	df	Sum of Sq	Mean Sq	F value	p value
Factor (YEAR)	9	7,19x10^7	7,99x10^3	5,13	6,28x10^{-7}
Residuals	3641	5,58x10^9	1,56x10^3	-	-

Source: Authors.

- *Factor (YEAR):* These are the results of different analysis performed to each year with respect to all other years in the data set.
- *Residuals:* This refers to the results of the possible analysis between each year with respect to the means of each one.
- *df:* These are degrees of freedom of the model, defined in Equations (1) and (2), where I represents the treatments (years) under analysis, and N is the total number of data points.

$$df(Factor(YEAR)) = I - 1 \tag{1}$$

$$df(Residuals) = N - 1 \tag{2}$$

- *Sum of Sq:* The total sum of squares refers to the variation of the sample means around the total sample mean, and the sum of the squared error is the difference between the individual sample points around their sample mean according to each treatment.
- *Mean Sq:* The mean square of the treatment and the mean square of the error are defined by the coefficient between the total sum of squares of the treatment and Equation (1) and the coefficient between the sum of squared error and Equation (2).
- *F value:* It is the quotient between the quadratic mean of the treatment and the square mean of the error. This value indicates whether the null hypothesis can be accepted or rejected. When H_o is true, the numerator and denominator of F are, on average, of the same size, so that F tends to be close to 1 (Navidi, 2006).
- *p-value:* It is the probability that defines whether H_o will be accepted or rejected. If p is lower or equal to alpha (0,05), H_o is rejected. Therefore, a p value of 6,28x10^{-7} means that the global solar radiation has changed during the time span under consideration. An F value greater than one and a p value much lower than 0,05 demonstrates that at least one of the means of the treatments is different than the others, which means that the null hypothesis is rejected.

Considering that the first conclusion from the ANOVA analysis was that there is a statistically significant difference in the average solar radiation for at least one of the ten years under study, we proceeded to evaluate the effect on individual years. The individual differences can be observed in the boxplots presented in Figure **2**. Other than the distribution, outliers, and quartiles, the boxplots in Figure **2** also include the mean for each year as red diamonds. To quantify solar radiation over a day, it needs to be integrated over time, thus resulting in the solar irradiation, which is given in watt-hours per square meter (Wh/m^2) as shown in the y-axis of Figure **2**.

In Figure **2**, we can see that solar irradiation remains relatively constant except for three years. The lowest mean values correspond to years 2009 and 2011 while the highest mean value occurred

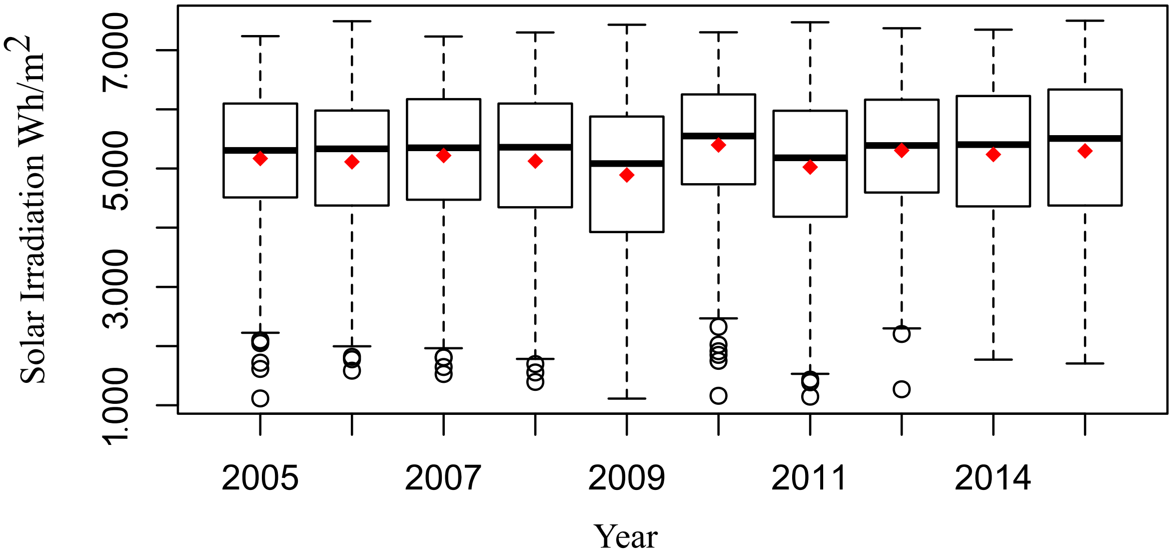

Figure 2. Summary of solar irradiation in Cúcuta from 2005 to 2015

Source: Authors.

in 2010. The inter-quartile range (boxes containing 50 % of data points) is also relatively constant throughout the decade under consideration. For all years, the mean is slightly below the median, thus indicating that the data is left-skewed.

Moreover, Figure 3 shows the average sun peak hours (equivalent to solar irradiation per day) for each year under consideration.

The differences in solar radiation (as well as sun peak hours) are much clearer and evident in Figure 3. The lowest solar irradiation corresponds to 2009, and the largest one to 2010. No other year has an abrupt change with respect to the others.

Bonferroni test

Although Figures 3 and 4 show clear, significant differences between the mean values of solar irradiation and sun peak hours of some years for the city of Cúcuta (thus supporting the findings from the ANOVA), we conducted the Bonferroni test to find out what years had a statistically significant p-value using the adjusted alpha (α') in Equation (3).

$$\alpha' = \frac{\alpha}{m} \tag{3}$$

Where α' is the quotient between the nominal alpha (pre-established at 0,05) and the number of possible pairs among the treatments m (Navidi, 2006). With the new adjusted alpha, a hypothesis test

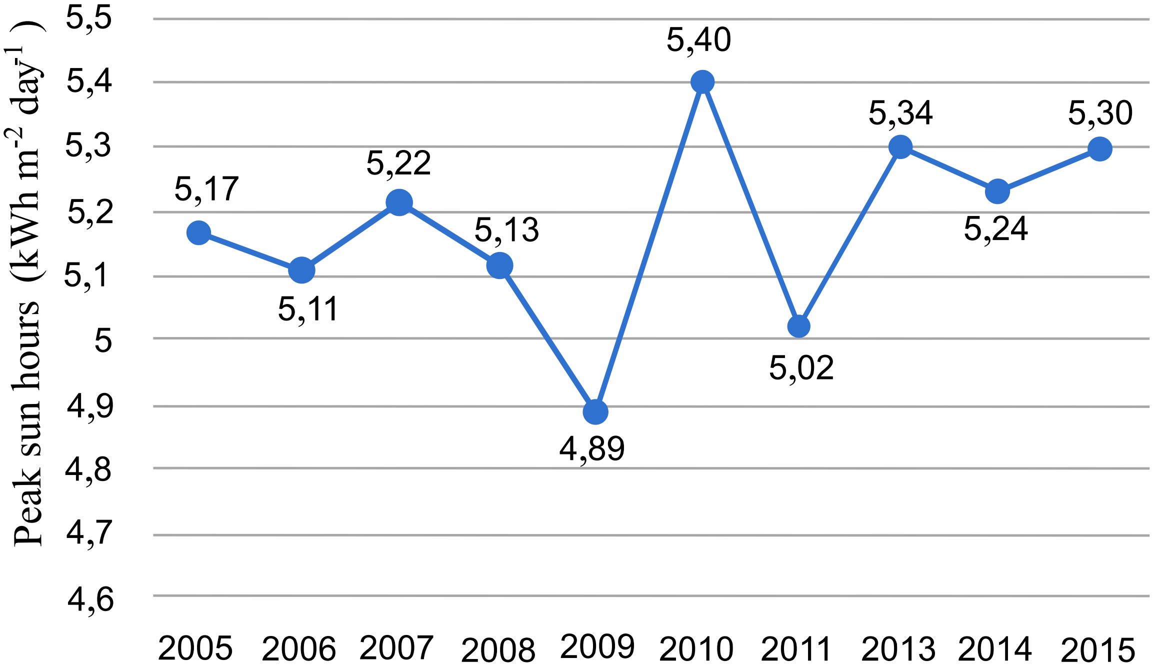

Figure 3. Average annual sun peak hours in Cúcuta from 2005 to 2015

Source: Authors.

was conducted to identify if there were probability values less than the adjusted alpha and, if so, to reject H_o.

The shadowed cells in Table 3 are the p-values that are significant ($p < \alpha'$). Unsurprisingly, most of them correspond to 2009. The lowest p-value (greatest significance) is for the pair 2009-2010 with p = $2x10^{-6}$. This means that the largest difference of means is reported for those years, which is consistent with the boxplots shown in Figure **2**.

ENSO phenomenon in Colombia

The El Niño-Southern Oscillation (ENSO) is a recurring climate pattern that involves temperature changes in the waters of the Pacific Ocean. El Niño and la Niña are the extreme stages of ENSO.

In 2009, 2010, and 2011 El Niño and La Niña affected most of Colombian territory. The lowest mean value of solar irradiation occurred in 2009, likely due to the fact that, during the first three months of the year, La Niña struck the Andean region (Colombian region where Cúcuta is located), as shown in Table **4**.

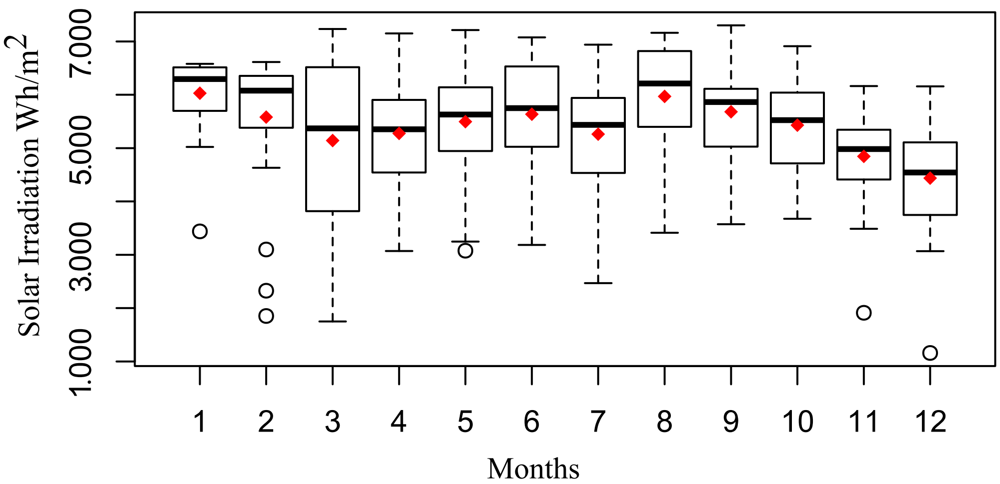

Figure 4. Monthly variability of solar irradiation in Cúcuta for 2010

Source: Authors.

Table 3. Bonferroni test results

Bonferroni test	2005	2006	2007	2008	2009	2010	2011	2013	2014	2015
2006	1,000	x	x	x	x	x	x	x	x	x
2007	1,000	1,000	x	x	x	x	x	x	x	x
2008	1,000	1,000	1,000	x	x	x	x	x	x	x
2009	0,117	0,713	0,017	0,500	x	x	x	x	x	x
2010	0,609	0,097	1,000	0,146	2×10^{-6}	x	x	x	x	x
2011	1,000	1,000	1,000	1,000	1,000	0,002	x	x	x	x
2013	1,000	1,000	1,000	1,000	$0{,}36 \times 10^{-3}$	1,000	0,106	x	x	x
2014	1,000	1,000	1,000	1,000	0,008	1,000	0,918	1,000	1,000	x
2015	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000

Source: Authors.

Table 4 classifies the months with significant rainfall anomalies as 'above normal' or 'below normal'. The criterion to define if a month is significant or not, is that the affected area was greater or equal to 50 % of the total territory of the corresponding region. A cell with a red shadow in Table 4 identifies a month with 'below normal' precipitation, whereas a green shadow represents a month

Table 4. Rainfall percentage in Colombia during 2009

Months	01	02	03	04	05	06	07	08	09	10	11	12
Below normal (<90 %)	1	2	1	76	74	25	78	39	97	67	61	69
Normal (90-100)	5	5	8	21	19	24	14	30	2	23	25	17
Above normal (>90 %)	93	93	91	4	7	51	7	30	1	9	3	13

Source: Authors.

with 'above normal' precipitation (Hurtado-Moreno & González, 2011).

The first three months of 2009 show a precipitation greater than 90 %. This could have caused a decrease in the average value of solar irradiation, thus yielding values below 3.000 Wh/m^2 per day. These very low values are the main factor that influenced 2009 to have the lowest mean value of solar irradiation compared to all other years.

El Niño phenomenon intensified during the first 6 months of 2010, which could have caused a lack of precipitation, which, in turn, could have caused an increase in the sun peak hours. During that period, there are months with median values above 6.000 Wh/m^2 per day as seen in Figure 4.

In the second half of 2010 (Figure 4), there is a decrease in the median and the mean of solar irradiation, likely due to the Niña phenomenon, which affected the mean values of irradiation in 2011 (as seen in Figure 3).

Monthly analysis of solar radiation in Cúcuta

Using the data from PVGIS, we conducted a study of the monthly solar radiation, where each month was subject to an ANOVA analysis, and the F- and p- values were calculated in order to identify which months have significantly different mean solar irradiation values.

The months with the largest differences were January, February, and March. The month with the largest spread was March, denoted by the long inter-quartile range in Figure 4, with a minimum value around 2.000 Wh/m^2 and a maximum value above 7.000 Wh/m^2. Additionally, September showed the highest single value of irradiation beyond 7.000 Wh/m^2 and an average value of 5.917 Wh/m^2, and December has the record below 1.200 Wh/m^2 and a mean value of 4.653 Wh/m^2 per day.

CONCLUSIONS

Solar radiation in the city of Cúcuta, Norte de Santander, Colombia, remains relatively constant on average, and its mean value does not fluctuate significantly over the years. However, significant fluctuations above and below are expected when the region is affected by a natural phenomenon such as El Niño or La Niña. In other words, the mean value of solar radiation in Cúcuta is roughly constant unless there is a high-impact natural phenomenon.

From our results, we conclude that a large amount of historical data of solar radiation is not strictly necessary to design and size solar photovoltaic and thermal systems in Cúcuta because solar radiation has proven to be fairly constant over the years. However, given the anomalies in 2009 and 2010 caused by El Niño and La Niña phenomena, we believe that accounting for these abnormal variations allows a more robust design and a better techno-economic analysis of renewable energy systems.

Aiming to make a statistical projection of the analyzed data, we expect a low variation on the mean solar radiation value for the next few years. This represents a strategic basis to justify the performance of a solar system in the long run, which makes sense because the current lifetime of solar panels is 25 years or more. This could require establishing a monthly energy assessment framework, which can consider solar radiation by month and create a table of electric generation showing the behavior of the return on investment over time. These monthly average values can elucidate the times of the year with the best and the worst efficiency and profit margins, which in turn allow increasing or reducing the capacity of solar panels to be installed, mainly for off-grid applications with the continuous use of a battery bank.

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INVESTIGACIÓN

Optimal Design of a Helical Spring by Using a Genetic Continuous Algorithm

Diseño óptimo de un resorte helicoidal usando un algoritmo genético continuo

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Abstract

Objective: In this paper, a continuous genetic algorithm (CGA) for the optimal design of a closed-coil helical spring is proposed.
Methodology: The solution methodology uses the minimization of the total spring volume as objective function, considering the wire diameter, mean diameter and number of active coils as main variables. As set of constraints, the technical and physical requirements for the correct and safe design of the aforementioned element are implemented. A CGA is employed as a solution method, and, as comparison methods, different optimization algorithms were used, which were employed in the specialized literature for solving the problem addressed in this study.
Results: The results obtained show that the CGA achieved the minimum value of volume, 1.5 % less than the best reported technique, with a processing time lower than 1 s, which proves that the proposed methodology obtains the best results in terms of solution quality and processing time.
Conclusions: The simulation results show that the CGA obtains the best solution in comparison with the other techniques, at a low computational cost and providing a solution that meets the physical and technical constraints of the design.

Keywords: mechanical design, metaheuristic optimization, helical springs, genetic algorithm

Resumen

Objetivo: En este artículo de investigación se propone un algoritmo genético continuo (CGA) para realizar el diseño óptimo de un resorte helicoidal de bobina cerrada.

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Metodología: La metodología de solución emplea como función objetivo la minimización del volumen total de un resorte helicoidal, considerando como variables principales el diámetro del alambre, el diámetro promedio y el número de bobinas activas. Como conjunto de restricciones se implementan los requerimientos físicos y técnicos para el diseño seguro y adecuado del elemento mencionado. Como método de solución se emplea un CGA, y como métodos de comparación son usados diferentes algoritmos de optimización que han sido implementados en la literatura especializada para dar solución al problema abordado.
Resultados: Los resultados obtenidos muestran que el CGA obtiene el mínimo valor de volumen, siendo menor en un 1,5 % en comparación con la mejor técnica reportada, con un tiempo de procesamiento menor a 1 s, lo cual demuestra que la metodología propuesta obtiene los mejores resultados en términos de calidad de la solución y tiempo de procesamiento.
Conclusiones: Los resultados de simulación muestran que el CGA obtiene la mejor solución en comparación con las demás técnicas, a un bajo costo computacional y entregando una solución que cumple con los requerimientos físicos y técnicos del diseño.

Palabras clave: diseño mecánico, optimización metaheurística, resortes helicoidales, algoritmo genético

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INTRODUCTION

Helical springs are elements that can be subjected to traction or compression. These are usually manufactured with metal alloys bent in a cylindrical way. The spring has a constant pitch, and its cross-section depends on the application of the spring, be it cylindrical or square (Bidabadi *et al.,* 2013). The end of the coil spring can be an open or closed coil. The main difference lies in the angle formed between the coil and the vertical (Shevale & Khaire, 2016). Some of the most common applications for coil springs are absorbing shocks, applying forces to brakes and clutches, controlling movement by acting as a stabilizer, and for energy storage in toys and watches (Bidabadi *et al.,* 2013). When designing a helical spring, the geometry, the loads it supports, and the deflection must be specified based on spatial limitations (Mott, 2004). The main variables for the design of a helical spring are the diameter of the wire, the internal diameter, and the number of turns. From these, the other factors associated with it are calculated, such as length and maximum performance, as well as the points where the design will withstand the stress to which it will be subjected.

The optimization of the design of a helical spring was performed in an article published by Thamaraikannan & Thirunavukkarasu, 2014. The objective function was to minimize the volume of the spring. The main variables were the physical dimensions of the spring, and the set of constraints were constructive criteria associated with each variable, the maximum forces, and the deflections allowed. Optimization techniques play an important role, as they are widely used in the specialized literature to solve engineering problems such as minimizing weights, volume, size, costs, among others (Azad & Amidpour, 2011, Giri *et al.,* 2008, Shi *et al.,* 2016). Obtaining viable solutions at low computational costs is desirable, but it depends on each problem's physical restrictions. One of the most important characteristics of these optimization methodologies is the fact that they can be implemented in free software such as Python, octave, or Scilab, which implies zero investment costs in terms of software and constitutes an important advantage over commercial optimization tools such as General Algebraic Models (GAMS).

In the field of mechanical design and the industry in general, focus has been given in recent years to improving efficiency in the construction processes of mechanical devices, optimizing production costs through weight and volume reduction and thus complying with the limits of mechanical forces. The reduction of the weight and size of the elements of the different mechanical devices leads to an improvement in the efficiency of industrial processes by achieving a reduction in the consumption of materials, and therefore in their processing and manufacturing times (Szabó & Actis, 2012). At the same time, this allows reducing energy consumption within its particular applications, given that less effort is required for movement (Jang & Jang, 2014, Ke *et al.,* 2020). All this helps to reduce the carbon footprint from the perspective of the manufacturing industry (Denkena *et al.,* 2020).

In terms of optimization techniques, in the specialized literature, there are works where metaheuristic optimization algorithms, such as genetic algorithms, have been used to reduce the weight of transmission shafts, improve the heat transfer coefficient of spiral plate heat exchangers, reduce the volume of a pressure vessel, among others, obtaining good results by resolving nonlinear, non-convex mathematical models with reduced computing times (Espitia-Cüchango & Sofrony-Esmeral, 2014,Gaikwad & Kachare, 2014,Kar *et al.,* 2020,Sealy *et al.,* 2016). In addition, coil springs have high applicability in the industry, thus making it necessary to establish methodologies that allow obtaining more efficient designs from a constructive point of view, complying with the conditions of maintainability, safety, and reliability, since these mechanical elements fulfill vital functions in machines and equipment, as the axis is in charge of transmitting power to the different elements and springs. This has applications in shock absorbers, clutches, and machines in which energy storage in the form of compression is necessary. This article proposes to reduce the weight and size of a coil spring by meeting its technical and operational constraints at all times through optimal design. To optimize the design of this type of geometry, it is necessary to carry out calculations and iterative processes in order to ensure that the dimensions are given so that each element meets the requirements of each particular case (economic and technical).

As mentioned above, genetic algorithms have certain advantages over the others, which is why they are used for this study, where a comparison is made with a similar work. The objective function is to minimize the volume of the spring and use restrictions such as length, maximum deflection, efforts, and other physical parameters. The first part of this article presents the mathematical approach with its restrictions and parameters. Then, the technique used to solve the problem is fully explained, and, finally, the results of the study are presented.

MATHEMATICAL FORMULATION

Helical springs are made from a wire, whose cross-section can be circular, square, or triangular, and they are rolled onto a helical form. This type of spring is designed to support compression and traction loads, aiming to find the dimension that supports the loads with a minimum volume. For this reason, the design of helical springs employs the main geometrical variables to establish the volume, the wire diameter (d), the mean diameter (D), and the number of coils (N_c), as shown in Equation (1).

$$V = \left(\frac{\pi}{2}\right)^2 (N_c + 2)Dd^2 \tag{1}$$

As mentioned above, geometrical parameters must support the applied load without exceeding the allowed stresses and the geometrical values associated with the available space according to the technical design conditions. These constraints are mentioned below.

SET OF CONSTRAINTS

The first constraint represents the allowable stresses, where a relation between stress, the maximum load applied, and the geometrical parameters is established. Here, the stress exerted by the maximum force (F_{max}) cannot exceed the allowable stress (S). This is represented by Equation (2).

$$g_1 = \pi d^3 S - 8C_f F_{max} D \geq 0 \tag{2}$$

where C_f is the geometrical parameter defined in Equation (3).

$$C_f = \frac{4C^2 + 1,46c - 2,46}{4C(C-1)}, \quad \text{where } C = \frac{D}{d} \tag{3}$$

As for spring configuration, it is important to mention that the free length must be less that a specified value. To define it, it is necessary to know the spring constant k, which is defined in Equation (4), where G is the shear modulus.

$$K = \frac{Gd^4}{8N_c D^3} \tag{4}$$

The deflection under maximum working load can be expressed by Equation (5).

$$\delta_l = \frac{F_{max}}{K} \tag{5}$$

To define the free length (l_f), it is assumed that l_f is α times the solid length, as shown in Equation (6).

$$l_f = \delta_l + \alpha(N_c + 2)\, d \tag{6}$$

This implies that the free length of the spring must not be less that the maximum value l_{max}, which is a design parameter (Equation (7)).

$$g_2 = l_{max} - l_f \geq 0 \tag{7}$$

The wire diameter must not exceed the minimum specified value, which is expressed in Equation (8).

$$g_3 = d - d_{min} \geq 0 \tag{8}$$

Additionally, the outside diameter of the coil cannot exceed the maximum specified value, which is defined in Equation (9).

$$g_4 = D_{max} - D - d \geq 0 \tag{9}$$

Based on the physical spring characteristics, the mean diameter must be at least β times the wire diameter to ensure the correct installation of the spring. This constraint is expressed in Equation (10).

$$g_5 = C - \beta \geq 0 \tag{10}$$

Under load operation, spring deflection must be less than a specified value (Equation (11))

$$\delta_p = \frac{F_p}{K} \tag{11}$$

This implies that:

$$g_6 = \delta_{pmax} - \delta_p \geq 0 \tag{12}$$

Note that the combined deflection must be consistent with the free length, which can be formulated as Equation (13).

$$g_7 = l_f - d_p \geq 0 \tag{13}$$

The deflection under preload conditions must be consistent with the design value. This is defined in Equation (14), where δ is a constant value.

$$g_8 = F_{max} - F_p - k\delta_w \geq 0 \tag{14}$$

Finally, to solve the mathematical model, the variables are constrained in order to define a concrete solution space. The constraints are defined in Equations (15) to (17).

$$d_{min} \leq d \leq d_{max} \tag{15}$$

$$D_{min} \leq D \leq D_{max} \tag{16}$$

$$N_{cmin} \leq N_c \leq D_{cmax} \tag{17}$$

After knowing and interpreting each constraint, the set of penalties are presented. These are expressed in Equations (18) to (25), which are related to each previously mentionedconstraint and defined by the maximum function, where px takes the maximum value, being 0 if the constraint is satisfied, and g if the constraint is violated.

$$p_1 = \max\{0, g_1\} \tag{18}$$

$$p_2 = \max\{0, g_2\} \tag{19}$$

$$p_3 = \max\{0, g_3\} \tag{20}$$

$$p_4 = \max\{0, g_4\} \tag{21}$$

$$p_5 = \max\{0, g_5\} \tag{22}$$

$$p_6 = \max\{0, g_6\} \tag{23}$$

$$p_7 = \max\{0, g_7\} \tag{24}$$

$$p_8 = \max\{0, g_8\} \tag{25}$$

The parameters considered for the design of the helical spring solved in this paper are reported in Table 1, and they are taken from Thamaraikannan & Thirunavukkarasu, 2014.

Table 1. Design parameters of the closed-coil helical spring

Parameter	Value	Unit	Parameter	Value	Unit
F_{max}	453,6	kgf	S	808543,6	kgf/cm^2
G	808543,6	kgf/cm^2	α	1,05	-
L_{max}	35,56	cm	β	3	-
δ_w	3,175	cm	d_{max}	1,016	cm
d_{min}	0,508	cm	D_{max}	7,620	cm
D_{min}	1,270	cm	N_{max}	25	-
N_{cmin}	15	-	-	-	-

Source: Authors.

SOLUTION TECHNIQUE

The presented mathematical model is a non-convex, nonlinear problem with a single objective function and continuous variables. For this reason, it is necessary to determine solution techniques that allow dealing with the constraints by penalty factors which are added to the objective function. In order to solve this optimization problem, a continuous genetic algorithm (CGA) is proposed. CGAs are a classic optimization technique, which has been used in the specialized literature to solve continuous optimization problems, as well as for the optimization of nonlinear continuous functions with

Table 2. Population used for the problem under study

$$\begin{vmatrix} D_{11} & d_{12} & d_{13} \\ d_{21} & d_{22} & d_{23} \\ \vdots & \vdots & \vdots \\ da_1 & da_2 & da_3 \end{vmatrix} a \times s$$

Source: Authors.

acceptable solutions (Giri *et al.,* 2008,Montoya *et al.,* 2018,Moradi & Abedini, 2012,Rodríguez-Cabal *et al.,* 2019). Genetic algorithms work with five main characteristics, which are described below (Solarte-Martínez *et al.,* 2015).

Initial population

As the CGA is an optimization technique based on population, the latter must be generated. It is proposed as a matrix with a rows and s columns, where a corresponds to the number of potential solutions and s to the number of variables of the problem. The matrix is represented in Table 2, where d, D, and N_c are the three variables of the problem under study.

Fitness function

Before the population is generated, each individual has to be evaluated with the fitness function (FF). It is worth noting that the CGA turns a constrained problem into a conditional one; for this optimization problem, the FF is Equation (1), added with the sum of each evaluated constraint and multiplied by a penalty factor (θ). The FF is expressed in Equation (26) and the penalty factor in Equation (27).

$$FF = V + Pen \tag{26}$$

$$Pen = (p_1 + p_2 + p_3 + p_4 + p_5 + p_6 + p_7 + p_8)\,\theta \tag{27}$$

Descendant population

As CGAs imply an iterative process, the generation of new potential solutions is necessary at each iteration. This, with the purpose of replacing the bad solutions contained in the population. To achieve this, the mutation and recombination operators are adapted; a classic selection allows good solutions within the population and enables them to improve its position. The selection methods are explained below:

- *Selection:* The descending population starts selecting, in a random way, a subgroup of individuals in the actual population. In this selection, a random number between r and 1 is chosen. Then, a new matrix is generated with a potential solution by employing the same strategy as the initial population. Finally, the total group of the selected individuals is formed through both strategies mentioned above.
- *Recombination:* This process alters the descendant population as follows; if the probability of recombination r_p is less than 50 %, then two random individuals are averaged in order to create a new potential candidate. Note that this operation always generates feasible individuals, since the initial population, like the new candidates, is generated inside the solution space.
- *Mutation:* At this point, the probability of mutation m_p is explored, *i.e.*, if m_p is greater than 50 %, a new random position of the potential solution is modified for a random value that ensures compliance. If m_p is under 50 %, the potential solution is not modified. This process is applied to each individual in the descendant population.

Once the descendant population is generated, the FF is evaluated once more.

NEW POPULATION

Once the new population has been evaluated, the group with the best solutions found by the CGA is saved. Then, a new population is generated by combining the group of descendant individuals, which produce a population with $2a$ following potential solutions. If two potential solutions are identical, one of them is removed from the list. This procedure is repeated until it is guaranteed that all potential solutions are different. Now, the list of resulting potential solutions is organized in an ascending form, the best solutions are selected as the new population, and they move on to the new iteration.

STOPPING CRITERION

The proposed CGA ends the optimization process when one of the following conditions is satisfied:

- The total iteration number has been reached.
- The best potential solution does not improve its value after m continuous iterations.

Finally, Algorithm 1 shows the pseudo-code that describes the iterative process of the genetic algorithm.

Algorithm 1 Pseudocode used for the CGA

```
Data: Parameters for the implementation of CGA,
      Parameters of the mathematical model.
for t = 1 : t_max do
    m = 0;
    if t == 1 then
        Generate the initial population;
        for i = 1 : a do
            Evaluate the fitness function;
        end
    else
        Generate the descending population;
        for i = 1 : a do
            Evaluate the fitness function;
        end
        Determine the new population;
        if (m > m_max || t == t_max) then
            Result: Impress results
            Break;
            ;
        end
    end
end
```

Source: Authors.

RESULTS

The solution technique was programmed in MATLAB with a desktop computer (HPZ600, with 8GB RAM and 4 processor cores). In order to compare the numerical results, different optimization techniques were used, such as the conventional method, particle swarm optimization (PSO), and artificial bee colony (ABS), as published by Thamaraikannan & Thirunavukkarasu, 2014.

In Figure 1, it can be observed that the CGA obtained the lowest value compared with the other techniques; the best objective value went from 46,51 cm^3, as obtained by the best reported technique, to 45,80 cm^3, which represents an improvement of 1,5 %. Compared to the reported techniques, CGA shows an improvement in the fitness function, with a feasible solution taking an average computing time of 1 s, which finds the following values of the decision variables: $d = 0,6739$ cm, $D = 2,4048$ cm, and $N_c = 15$. When the set of constraints were evaluated, it was found that the values obtained by the purposed method were satisfied, which shows the feasibility of the design, not only with respect

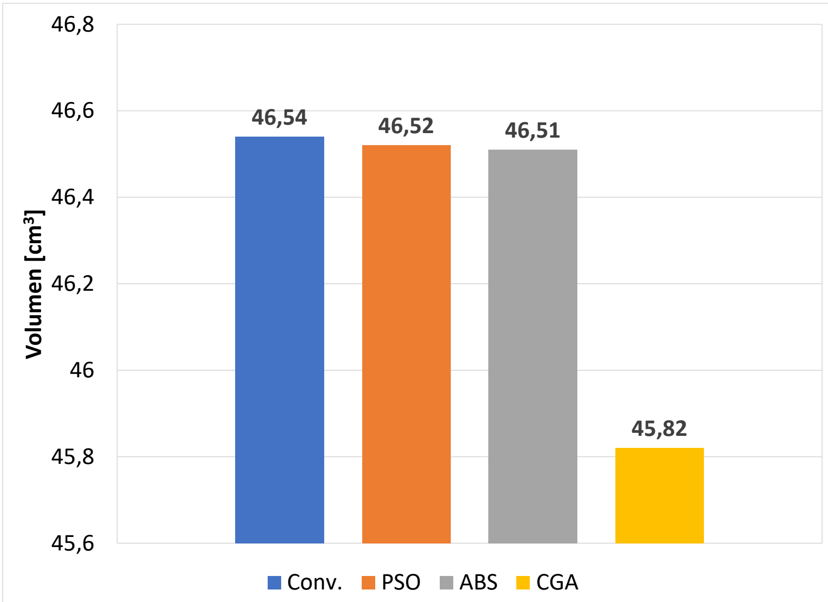

Figure 1. Fitness function values found by the optimization techniques

Source: Authors.

to the available space, determined by the free length, but also regarding the constraints related to the stresses and deflection under maximum load, which guarantees the quality of the solution.

Therefore, the CGA proves to be an efficient and fast technique for solving problems such as the one addressed in this study. The difference between the values of the techniques may be due to the tuning and programming of the algorithms, which not only affects the quality of the response, but also the processing times, which are not reported by Thamaraikannan & Thirunavukkarasu, 2014.

Conclusions

In this paper, the optimization of a closed coil helical spring was carried out through a continuous genetic algorithm, where the objective function was the minimization of the volume of the spring by means of an adequate selection of the wire diameter, the mean diameter, and the number of coils; and, as a set of constraints, the technical and physical conditions that should be considered in this type of devices to ensure a reliable and safe design. For the sake of comparison, particle swarm optimization, artificial bee colonies, and the conventional method were employed, which have been proposed in the literature to solve the problem addressed in this research. Computational simulations showed that the CGA obtained the best results in terms of quality of the solution, with a volume 1,5 % less that the best value reported by the comparison methods, while taking only 1 s to obtain the solution and meeting all the set of constraints. This proves that the proposed method can be used to solve not only the mathematical model employed, but also a problem with non-convex, nonlinear functions, at a low computational cost. This can be achieved by the way in which the algorithm explored and exploited the solution space.

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INVESTIGACIÓN

Methodology for the Synthesis of Automata in the Planning of Movements for Autonomous Systems with Multiple Agents

Metodología para la síntesis de autómatas en la planificación de movimientos en sistemas autónomos con múltiples agentes

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Abstract

Objective: To present a methodology for motion planning in autonomous systems with multiple agents.
Methodology: The physical behavior of a team of autonomous navigation systems is parameterized and defined. Then, a control policies algorithm is described and implemented, which interprets these descriptions, which are converted into LTL formulas, and a model is generated which allows making automatic abstractions. From generic solution configurations, the case of multiple robots with a single task in an environment with fixed obstacles is derived. The methodology is validated in different scenarios, and the results are analyzed.
Results: The proposed methodology for motion planning in autonomous systems with multiple agents combines two state-of-the-art techniques, thus allowing to mitigate the combinatorial explosion of states in traditional approaches.
Conclusions: The proposed methodology solves the automaton synthesis problem for high- level control with task changes during the execution. Under certain criteria, the problem of combinatorial explosion of states associated with these systems is mitigated. The solution is optimal with regard to the number of transactions performed by the team members.
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Keywords: Büchi automata, formal languages, linear temporal logic (LTL), motion planning, Petri networks, cooperative systems with multiple agents

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Resumen

Objetivo: Presentar una metodología para la planificación de movimientos de sistemas autónomos con múltiples agentes.
Metodología: Se define y parametriza el comportamiento físico de un equipo de sistemas de navegación autónoma. Luego se describe e implementa un algoritmo de síntesis de políticas de control que interpreta estas descripciones convertidas a fórmulas LTL y se genera un modelo que permite hacer abstracciones automáticas. A partir de configuraciones genéricas de solución, se deriva en el caso de múltiples robots con una única tarea en un entorno con obstáculos fijos. La metodología se valida en diferentes escenarios y se analizan los resultados.
Resultados: La metodología propuesta para planificación de movimientos en sistemas con múltiples agentes combina dos técnicas del estado del arte, permitiendo mitigar la explosión combinacional de estados presente en los enfoques tradicionales.
Conclusiones: La metodología que se presenta resuelve el problema de síntesis de autómatas para el control de alto nivel, con cambio de tareas durante la ejecución. Bajo ciertos criterios, se mitiga el problema de explosión combinacional de estados asociado a estos sistemas. La solución es óptima respecto al número de transiciones seguidas por los miembros del equipo.

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Palabras clave: autómatas de Büchi, lenguajes formales, lógica temporal lineal (LTL), planificación de movimientos, redes de Petri, sistemas cooperativos de múltiples agentes

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INTRODUCTION

With the great advances in the technology that supports autonomous systems, the variety of tasks for which they may be required has also expanded. This has aroused the particular interest of the scientific community in solving movement planning problems in autonomous systems, focusing on calculating the necessary trajectories for a system to fulfill a task (Choset, 2005,LaValle, 2006).

This problem has been studied, not only for the case of an autonomous system, but also for the case of multiple agents (Ding *et al.,* 2014,Franceschelli *et al.,* 2013). Most of the existing works that carry out this type of tasks lack the expressiveness to capture the requirements (Ma *et al.,* 2016, van den Berg & Overmars, 2005), they are based on simplifying the abstractions, which results in a conservative behavior (Aksaray *et al.,* 2016), or they do not consider the time restrictions in the execution of the task (Saha *et al.,* 2014). In addition to these limitations, many of the planning methods are computationally intractable (and therefore do not scale well or work in real-time) and provide guarantees only in a simplified abstraction of system behavior (Aksaray *et al.,* 2016).

One of the main challenges in this area is the development of a computationally efficient framework that meets the physical constraints of the robot and the complexity of the environment while allowing a broad spectrum of task specifications (Ding *et al.,* 2011). Some authors suggest that, by using linear temporal logic (LTL), such as the task specification language, the flexibility to incorporate explicit time constraints is preserved, as well as a variety of behaviors (Clarke *et al.,* 1999), i.e., LTL can be used as a rich specification language in autonomous systems such as mobile robotics (Karaman & Frazzoli, 2009, Wongpiromsarn *et al.,* 2009). LTL is often found as a formalism to express high-level tasks for autonomous systems (Ding *et al.,* 2014, Guo & Dimarogonas, 2015a, Kloetzer & Mahulea, 2015), and such tasks can refer to a single robot (Ding *et al.,* 2014), specify individual requirements for mobile robots (Guo & Dimarogonas, 2015a), or impose a global specification for robotic equipment (Kloetzer & Mahulea, 2015). In Kloetzer & Mahulea, 2016 an iterative algorithm is proposed which plans the movements of a team of robots that unfolds in a workspace modeled as a Petri net. The main part of the algorithm is represented by specific mathematical programming formulations that produce trajectories for the robots, without considering the collisions between them. Petri nets have been used previously in different robotic problems, for example, in Costelha & Lima, 2012 to model the real execution of the movement plan, in Kloetzer & Mahulea, 2014 to solve accessibility problems under probabilistic information, or in (Mahulea & Kloetzer, 2014) to satisfy the tasks given as Boolean formulas. In a multi-robot configuration, Guo & Dimarogonas, 2015b propose a bottom-up approach to plan actions, given an LTL specification for each robot. In Karaman & Frazzoli, 2011 the routing problem of a vehicle with LTL restrictions is expanded, and a solution based on Mixed

Integer Linear Programming (MILP) is planned. In Ulusoy *et al.,* 2012 and Chen *et al.,* 2012, a single mission is assumed for a robotic team, and "trace-closed" languages are used to distribute the mission, but possible collisions are not considered between robots.

Computational complexity is still a major challenge in planning multi-robot systems. To reduce complexity, in Tumova & Dimarogonas, 2015, summaries of independent movements of individual agents are made; and, in Schillinger *et al.,* 2016, a way to identify independent parts of a given mission is proposed as a finite LTL formula. Some works have proposed algorithmic solutions for movement planning problems in various scenarios, such as synthesis of high-level tasks (Guo & Dimarogonas, 2015a,Kloetzer & Mahulea, 2015), consensus problems (Aragues *et al.,* 2012,Franceschelli *et al.,* 2014), and leading follower (Garrido *et al.,* 2013).

Therefore, from the above, the objective of this work is to present a methodology for planning the movements of autonomous systems with multiple agents. The methodology is validated in different scenarios and the results are analyzed.

PRELIMINARIES

Büchi automata

A Büchi automaton corresponding to an LTL formula on set Π has the structure
$B = (S, S_0, \sum_B, \rightarrow B, F)$, where:

- S is a finite set of states
- $S_0 \subseteq S$ is the set of initial states
- $\sum_B = 2^{\Pi}$ is the set of initial states
- $\rightarrow_B \subseteq S \times \sum_B \times S$ is the input character set
- $F \subseteq S$ is the set of final states

For s_i, $s_j \in S$, $\rho(s_i, s_j)$ is the set of all entries in B that allow the transition from s_i to s_j. The transitions in B can be non-deterministic, which means that, from a given state, there can be multiple outgoing transitions enabled by the same input, that is, it can be stated that $(s, \tau, s') \in\rightarrow B$ and $(s, \tau, s') \in\rightarrow B$ with $s' \neq s''$. Therefore, an input sequence can produce more than one sequence of output states. A non-deterministic finite automaton can be made deterministic, but, in this case, a non-deterministic automaton is preferable given the lower number of states. An infinite input word, that is, a sequence of elements of $\sum_B$, is accepted by B if the word produces at least one sequence of states of B, which, when traversed, allow visiting the future state of the set F.

Petri nets

There are multiple known configurations of Petri nets (RdP), and their application to modeling movements in robotic systems is of interest. This type of RdP system for robot movement (RMPN) is a quadruple $Q = (N, m_0, \Pi, h)$, where:

- N = (P, T, Post, Pre) is the structure of the RdP with P being the set of places.
- T is the set of transitions modeling the possibilities of movement of the robots between the places; Post $\in \{0,1\} \wedge (|P| \times |T|)$ is the post-incidence matrix defining the arcs of the transitions to the places, and Pre $\in \{0,1\} \wedge (|P| \times |T|)$ is the pre- incidence matrix defining the arcs of the places to the transitions. $\forall t \ \in T, |\bullet \ t| = |t \ \bullet| = 1$, where $\bullet \, t$ and $t \, \bullet$ are the set of inputs and outputs of the t places ($\bullet \, t = \{p \in P|Pre[p,t] > 0\}$ and $t \, \bullet = \{p \in P|Post[p,t] > 0\}$).
- m_0 is the initial markup, where $m_0[p]$ reflects the state of the system at startup.
- $\Pi \cup \{\emptyset\}$ is the output alphabet, where $\emptyset$ denotes an empty observation.
- $h : P \rightarrow 2^{\Pi}$ is the observation map, where 2^{Π} is the set of all subsets of Π, including the empty set $\emptyset$, and $h(p_i)$ produces the output of the place $p_i \in P$. If p_i has at least one mark, then the propositions of $h(p_i)$ are active.

Linear temporal logic (LTL)

The syntax to construct the π formulas can be defined recursively according to the following grammar (Piterman *et al.,* 2006): $\varphi ::= \pi \mid \neg\varphi \mid \varphi \vee \varphi \mid \circ\varphi \mid \varphi u \varphi$. Starting from the previous grammar, it is known that the Boolean constants True and False are defined as True = $(\varphi \vee \neg\varphi)$ and False = ¬True. From the negation (¬) and the disjunction (∨), we can define the conjunction (∧), the implication (→), and the equivalence ($\iff$). Furthermore, by counting in the grammar with the temporary operators "next"(∘) and üntil"(U), additional temporary operators such as .Eventually"($\diamond\varphi =$ True $U\varphi$) and .always"($\square \ \varphi \ = \ \neg \diamond \neg\varphi$) can be used. The semantics of an LTL formula φ are defined over an infinite sequence σ of assignments of truth to the atomic sentences $\pi \in$ AP. Table 1 recursively defines $\sigma, I \models \varphi$, where $\sigma(i)$ is the set of atomic sentences that are true at position i. The formula $\circ\varphi$ expresses that φ is true at the next position in the sequence (the next time state), and the formula φ_1 $U\varphi$_2 expresses that φ_1 is true until φ_2 begins to be true. The sequence σ satisfies the formula φ if (σ, $0 \models \varphi$). The sequence σ satisfies the formula $\square\varphi$ if φ is true in all positions of the sequence. Furthermore, it satisfies the formula $\diamond\varphi$ if ϕ is true in some position of the sequence. The sequence σ satisfies the formula $\square \diamond \varphi$ if, at any position, φ becomes true, that is, φ frequently begins to be true infinitely. For a formal definition of LTL, see the work by Emerson, 1990.

Table 1. Recursive definition of semantics for LTL formulas

Relation	Definition
$(\sigma, i, \models \pi)$	IF $(\pi \in \sigma(i))$
$(\sigma, i \models \neg\varphi)$	IF $(\sigma, i \neg \models \varphi)$
$(\sigma, i \models \varphi_1 \vee \varphi_2)$	IF $(\sigma, i \models \varphi_1)$ *or* $(\sigma, i \models \varphi_2)$
$(\sigma, i \models \circ\varphi)$	IF $(\sigma, i+1 \models \varphi)$
$\sigma, i \models \varphi_1 \mathrm{U} \varphi_2$	IF, in the future is a $(k \geq i)$ so the $(\sigma, k \models \varphi_2)$, and for every $(i \leq j \leq k) t(\sigma, j \models \varphi_1)$

Source: Authors.

Some of the properties that can be expressed using LTL are:

- Reaching a target while avoiding obstacles $(\pi_1 \vee \pi_2 \vee \ldots \vee \pi_n)\ U\pi$, capturing the property that eventually π is going to be true and, until that happens, obstacles labeled $\pi_i; i = 1, 2, \ldots,$ must be avoided n.
- Sequencing: $\diamond(\pi_1 \wedge \diamond(\pi_2 \wedge \diamond\pi_3))$ captures the requirement that the robot first visit the region π_1, then the region π_2 and then the region π_3, respecting that order.
- Coverage: $\diamond\pi_1 \wedge \diamond\pi_2 \wedge \ldots \wedge \diamond\pi_m$ specifies that the robot will eventually reach π_1, eventually reach $\pi_2, \ldots,$ and eventually reach π_m. The robot will at some point visit all regions of interest in any order.

Another particular class of LTL formula is known as syntactically co-safe formulas (Kupferman & Vardi, 2001). Any solution that satisfies a co-safe LTL formula consists of a finite string known as a good prefix, followed by an infinite continuation of statements, thus ensuring that this continuation does not affect the truth value of the formula. It was shown by Kupferman & Vardi, 2001 that any LTL formula that contains only temporary operators $\diamond$ and U when written in positive normal form, that is, when the negation $\neg$ appears only before atomic sentences, is syntactically safe.

For this case of LTL formulas, the Büchi automaton, B, accepts an input word if it starts with a good finite prefix that takes B to the set of final states (the continuation of the prefix is irrelevant). Therefore, the satisfaction of the co-safe LTL formulas is decided based on the finite executions of the RMPN model defined in the next section.

Methodology

This section begins by defining and parameterizing the physical behavior of an autonomous navigation system equipment. Then, the control policy synthesis algorithm is described and implemented, which interprets the descriptions previously converted to LTL formulas, and, based on these specifications, it generates a model that allows automatic abstractions, thus guaranteeing that said model allows meeting the specifications given for the environment. Some of the solution configuration possibilities for the proposed problem are considered, and a different case is evaluated for each one, thus defining the case of a single robot located in an environment with fixed or mobile obstacles, and the case of multiple robots with a single task located in an environment with fixed obstacles modeled through a Petri net. Finally, a series of simulations is proposed which allows validating the proposed methodology in the different scenarios and comparing the results obtained.

Definition and parameterization of a team of autonomous land navigation systems

It is assumed that the type of mobile robots used operates in a polygonal workspace P. The movement of a robot is expressed by $\dot{p}(t) = u(t), p(t) \in P \subseteq R, u(t) \in U \subseteq R^2$, where $p(t)$ is the robot's position at time t, and $u(t)$ is the control input. It is assumed that the workspace P is partitioned into a finite number of cells $P\_1, \ldots, P\_n$, where $P = U\_(i=1)^\wedge nP\_i$ and $P\_i \wedge P\_j = \Phi$ if $i \neq j$. Furthermore, each of the cells is considered as a convex polygon. When partitioning the workspace, a series of Boolean statements $r\_1, r\_2, \ldots, r\_n$ is generated, which is true if the robot is in position P_i. Then, the RMPN that models the work environment is automatically generated. A workspace like the one shown in Figure 1a is proposed, partitioned into five cells duly labeled as $a\_1, \ldots, a\_5$, with two robots initially located at a_1 and a_5, and five regions of interest $\pi\_1, \pi\_2, \pi\_3, \pi\_4, \pi\_5$, so that region π_1 corresponds to cell a_1 and place p_1, region π_2 corresponds to a_2 and place p_2, and so on.

For the environment described above, an RMPN model is obtained which can be seen in Figure 1b, where $P = p_1, \ldots, p_5$ and $T = t_1, \ldots, t_16$.. Since the set of input transitions of p_1 is $\bullet p1 = t_2, t_4, t_6$, then Post[$p_1, t_2$] = Post[$p_1, t_4$] = Post[$p_1, t_6$] = 1, while Post[$p_1, t_j$] = 0 for all $t_j \in T \bullet p_1$. Furthermore, since the set of output transitions of p_1 is $p_1 \bullet = t_1, t_3, t_5$, then Post[$p_1, t_2$] = Post[$p_1, t_4$] = Post[$p_1, t_6$] = 1, while Post[$p_1, t_j$] = 0 for all $t_j \in Tp_1\bullet$.

Case 1 - a robot and multiple obstacles

A single robot is located in the workspace R shown in Figure 2, which is partitioned into 16 regions related to the location propositions of the robot $R = r_1, r_2, \ldots, r_{16}$, initially located in region 2, and with a specification given in natural language such as "Go from region 2 to region 15 and then back to region 2. If an obstacle is encountered on the road, turn on a light and stay in the same place until the obstacle disappears. If the obstacle disappears, turn off the light and get back on your way".

As the obstacles are part of the environment, the set of surveyed propositions contains only one proposition $X = S^\wedge obs$, which becomes true if the robot detects an obstacle. The assumptions about the obstacles are captured by $\varphi\_e = \varphi\_i^\wedge e \wedge \varphi\_t^\wedge e \wedge \varphi\_g^\wedge e$. Initially, the robot does not detect any obstacles; therefore, $\varphi\_i^\wedge e = (\neg S^\wedge obs)$. It is assumed that the robot can only detect obstacles

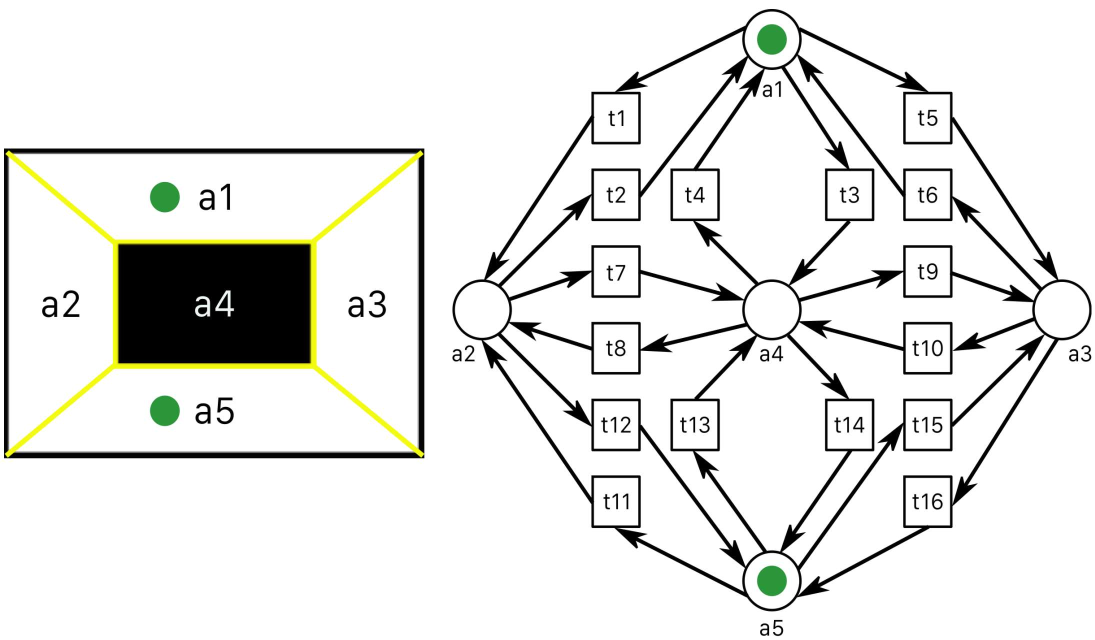

Figure 1. a) Workspace; b) modeling of a workspace through Petri nets

Source: Authors.

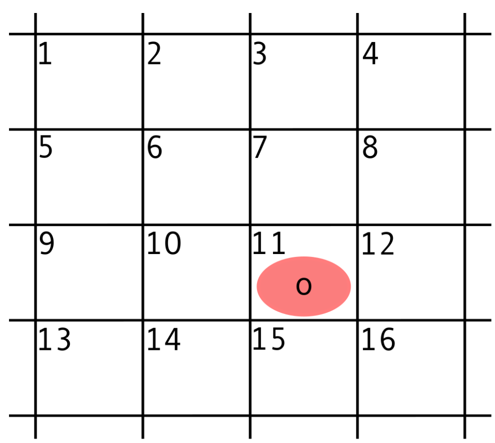

Figure 2. Workspace R

Source: Authors.

in regions other than region 2 and region 15, so the restriction is coded in such a way that, in regions 2 and 15, the value of $S\ ^\wedge\ obs$ cannot change. This requirement is captured by the formula: $\varphi\_t\ ^\wedge\ e = \Box((\neg r\_1 \wedge \neg r\_3 \wedge \ldots \wedge \neg r\_13 \wedge \neg r\_14 \wedge \neg r\_16) \rightarrow (\circ S\ ^\wedge\ obs \iff S\ ^\wedge\ obs))$. Since no more hypotheses are assumed about the surrounding propositions, we have $\varphi\_g\ ^\wedge\ e =$ (True).

Now, to model the robot and the desired specifications that are captured by $\varphi\_s = \varphi\_i \wedge s \wedge \varphi\_t \wedge s \wedge \varphi\_g \wedge s$, 17 robot propositions are defined, which are expressed in $Y = r\_1, r\_2, r\_16, a \wedge$ (light_On) . As an initial location condition, the robot can start in region 2, or in region 15 with the light off, since, in these regions, there should be no obstacles. We then have the equation $\varphi\_i \wedge s = \{(r\_2 \wedge_i \in \{1, 3, 16\} \neg r\_i \wedge \neg a \wedge$ light On$) \vee (r_15 \wedge _i \in \{1, \ldots, 13, 14, 16\} \neg r_i \wedge \neg a \wedge$ (light_On)).

$$\varphi_t^s = \begin{cases} \begin{cases} \wedge\Box(r_1 \rightarrow (\ \circ\ r_1 \vee \circ\, r_2 \vee \circ\, r_5)) \\ \wedge\, r_2 \rightarrow (\circ\, r_2 \vee \circ\, r_1 \vee \circ\, r_3 \vee \circ\, r_6) \\ \vdots \\ \wedge\Box(r_{16} \rightarrow (\circ\, r_{16} \vee \circ\, r_{15} \vee \circ\, r_{12})) \end{cases} \\ \wedge\Box((\circ\, r_1 \wedge_{i\neq 1} \neg \circ\ r_i) \\ \vee(\circ\, r_2 \wedge_{i\neq 2} \neg \circ\ r_i) \\ \vdots \\ \vee(\circ\, r_{16} \wedge_{\neq 16} \neg \circ\ r_i)) \\ \begin{cases} \wedge\, \Box\, (\circ\, S^{obs} \rightarrow (\wedge_{i\in\{1,2,\ldots,16\}} \circ\ r_i \iff r_i) \wedge \circ\, a^{lightOn}) \\ \wedge\, \Box(\neg \circ\ S^{obs} \rightarrow \circ\, a^{lightOn}) \end{cases} \end{cases} \quad (1)$$

The formula $\varphi\_t \wedge s$ is defined in Equation (3), and it models the possible changes in the state of the robot. The first block of sub-formulas that compose it represents the possible transitions between the regions. For example, from region 1, the robot can move to region 2, or to region 5, or it can remain in region 1. The following sub-formula represents the mutual exclusion constraint between regions that specifies that, at any one time, only one region of R can be true. The last block of sub-formulas represents the desired specifications for the system and establishes that, if the robot encounters an obstacle, it must remain motionless with the light on until it is removed, considering in turn that, if the robot does not encounter an obstacle, the light must be off. Finally, $\varphi\_g \wedge s$ captures the requirement that the robot keep moving between regions 2 and 16, unless it encounters an obstacle. The synthesis of the problem consists of the construction of an automaton whose behaviors satisfy the formula φ. It is proven that the size of this automaton is equal to the double exponential of the size of the formula (Pnueli & Rosner, 1989). However, if the problem is restricted to the special class of LTL formulas GR (1), the algorithm introduced by Piterman *et al.,* 2006 can be used, which is of polynomial time O ($n \wedge 3$), where n is the size of the state space. In this case, each of the states corresponds to an assignment of admissible truth for the set of propositions of the environment and the robot.

The synthesis process is seen as a game between the robot and the environment, with the latter as the adversary. Starting from some initial state, the robot and the environment make decisions that determine the next state of the entire system. The condition to win the game is given by a class of formula ϕ of generalized reactivity GR (1), which are formulas with the structure $(\Box\ \diamond p\_1 \wedge \ldots \wedge \Box\ \diamond p\_m) \rightarrow (\Box\ \diamond q\_1 \wedge \ldots \wedge \Box\ \diamond q\_n)$, where p_i and q_i are a Boolean combination of atomic statements. The way to play is that, at each step, first the environment makes a movement according to its transition relationships, and then the robot makes its own move, if the robot manages to satisfy the formula ϕ no matter what the environment does, then the robot is the winner, and you get an automaton. If the environment manages to make the robot not satisfy the formula ϕ, that is, that, after the movements of the environment and the robot, ϕ is not true, then it can be said that the environment won, and that the desired behavior for the robot was not obtained or is not achievable. For the case at hand, the initial states of the players are given by $\varphi\_i^\wedge e$ and $\varphi\_i^\wedge s$, the possible transitions that the players can make are given by $\varphi\_t^\wedge e$ and $\varphi\_t^\wedge s$, and the condition to win is given by the formula of generalized reactivity (GR (1)) $\phi = (\varphi\_g^\wedge e \rightarrow \varphi\_g^\wedge s)$. According to the formula that specifies the conditions, the system can win if $\varphi\_g^\wedge s$ is true or if $\varphi\_g^\wedge e$ is false. In addition, there is the option that the environment does not play fair and the generated automaton is not valid, which can occur if the environment places an obstacle in region 2 or region 15.

The automaton obtained in this case by using Algorithm 1 is a non-deterministic automaton that focuses on reaching the objectives in the fewest number of transitions. Figure 3 shows one of the multiple automata that can be obtained in the synthesis and can comply with the desired behavior, where the circles represent the states of the automaton, and the propositions that are written within each of the circles are the state labels that indicate the exit statements that are true in that state. The initial state r_2 is denoted by a double circle, and the arrows are labeled with the sense statements that must be true for the transition to take place. Unlabeled arrows correspond to proposition ($S^\wedge obs$). For this case, the automaton makes the robot stay in the region it is in if it detects an obstacle. Otherwise, it makes it advance to the next region on the route. In case the environment behaves differently from the assumption, for example, that the robot senses an obstacle at r_15, the automaton will not have a defined transition, and it will not be valid. The automaton obtained is not the only one that can meet the specifications using the fewest possible transitions (Martínez *et al.,* 2018).

Algorithm 1. Continuous synthesis of control policies for case 1

Require: Environment , Regionsofinterest, specificationLTL

Ensure: trajectory

P ← GetPartTriang (Environment, Regionsofinterest)
AutEntorno ← GetAutEnt (P)
If AutEntorno = **false then**
    return Error in defining Environment
end if
AutBachi ← GetAutBachi(specificationLTL)
if AutBachi = **false then**
    return Error formula LTL
end if
AutGeneral ← GetAutGeneral(AutEntorno,AutBachi)
trajectory ← findRunAcep(AutGeneral)
return trajectory

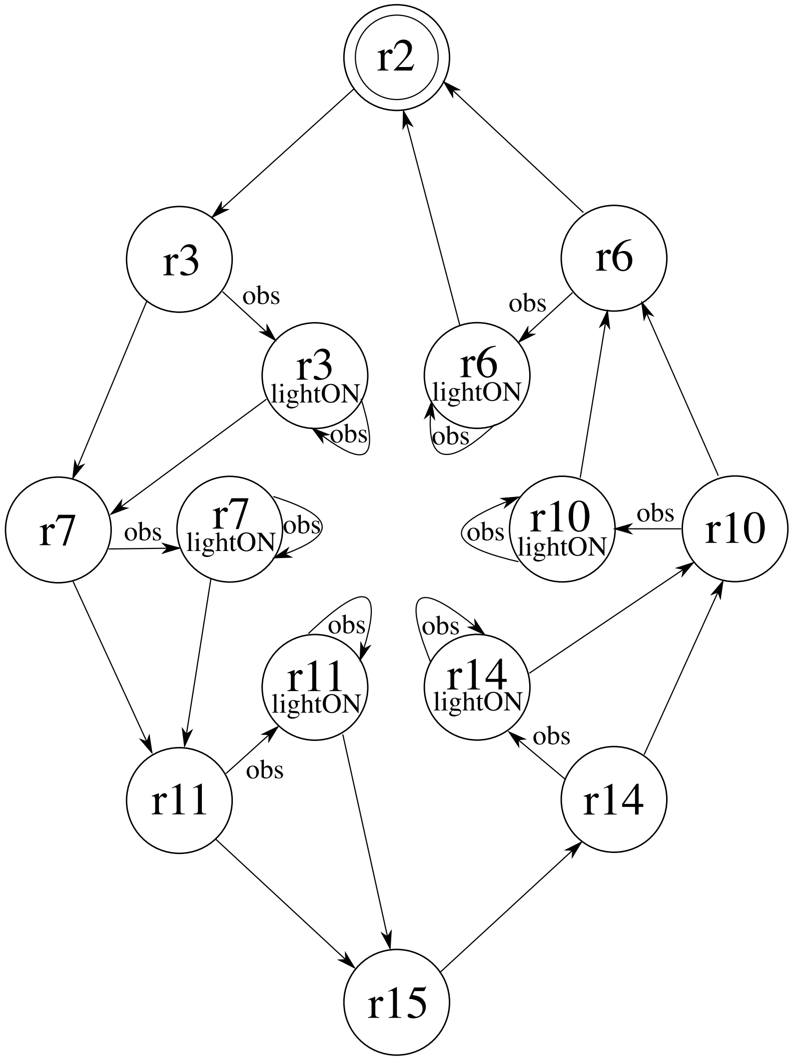

Figure 3. Automaton solution for a robot that interacts with the environment

Source: Authors.

The function that calculates the next state requires, as an input argument, to know the present state of the path in which the robot is located, as well as the census information to execute the actions defined in case any obstacles come across (stay at the same point until the obstacle disappears, recalculate the route avoiding the obstacle, generate an alert).

Case 2 - multiple robots and fixed obstacles

For the case of a team of identical robots modeled, which move in a rectangular environment, initially, it can be assumed that, with an adaptation of Algorithm 1, the problem can be solved. However, the need for synchronization between the automatons of each of the robots make the automaton in the environment grow in a way $|P|^\wedge\ n^*|B|$, where $|P|$ is the number of partitions present in the workspace, n is the number of robots, and $|B|$ is the number of states in the Büchi automaton. This implies that, as the number of robots increases, the consumption of resources for processing increases, until a point is reached where there is a combinational explosion of states. A methodology is then proposed which involves the use of Petri nets to describe the workspace. A finite set of atomic sentences is assumed $\Pi = \pi\_1, \pi\_2, \ldots, \pi\_|\Pi|$, where π_i labels a specific region of interest that corresponds to one or more cells in the environment, and, if at least one robot is in any of these cells, the π_i proposition is said to be true (True).

The set Π is used to provide an LTL formula that defines the task to be accomplished by the robot team. The initial marking of the network system is $m\_0 = [1, 0, 0, 0, 1]^\wedge\ T$, the output alphabet is $\Pi = \pi\_1, \pi\_2, \pi\_3, \pi\_4, \pi\_5$, and the observation map:$h(a\_1) = \pi\_1, h(a\_2) = \pi\_2, h(a\_3) = \pi\_3, h(a\_4) = \pi\_4$, and $h(a\_5) = \pi\_5$. The characteristic vector of π_i is $v\_i = [p\_0, p\_1, \ldots, p\_n]$, with n being the number of cells into which the workspace is divided and $p\_i = 1$ if and only if π_i is observable in a_i. With the previous vectors the transition matrix is constructed,

$$V = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

Since V $\cdot m\_0 = [1, 0, 0, 1]^\wedge\ T$, observations π_1 and π_5 are active at m_0 because the initial location of the robots is a_1 and a_5. An execution (or trajectory) of Q is a finite sequence $r = m\_0[\models t\_j1\rangle m\_1[\models t\_j2\rangle m\_2[\models t\_j3 \ldots t\_(j\_|r|)\rangle m\_|r|$, which produces an output word, which is the observed sequence of $2^\wedge\Pi$ elements, and LTL formulas are interpreted over infinite chains of observations from 2Π (Clarke *et al.*, 1999). As in this case, only the co-safe LTL formulas are considered. Any LTL formula on the set Π can be transformed into a Büchi automaton, which accepts only the input strings that satisfy the formula (Wolper *et al.*, 1983). Some available software tools that allow such conversions are described in the literature (Gastin & Oddoux, 2001, Holzmann, 2003). Considering that the activation specifications for the RdP are generated based on a requirement given as a Boolean formula, a finite set of atomic sentences is defined $\Pi = \{\Pi\_1, \Pi\_2, \Pi\_3, \ldots, \Pi\_|\pi|\}$, where the Π_i tags represent a specific region of interest in the environment. The requirements are expressed as a Boolean logical formula on the set of variables $P = P\_t\ \cup\ P\_f$, where $P\_t = \Pi$ and $P\_f = \{\pi_1, \pi\_2, \ldots, \pi\_|\Pi|\}$. The sets P_t and P_f refer to the same regions of interest, but the elements of P_t indicate the regions that must be visited throughout the execution of the trajectory, and the elements of P_f indicate the regions that must be visited in the last execution status. The specifications are interpreted as finite words over the set $2^\wedge\ \Pi$.

In general, the composition of set P is evaluated on the word generated by the execution $r = m\_0[\models t\_j1\rangle m\_1[\models t\_j2\rangle m\_2[\models t\_j3 \ldots t\_(j\_|r|)\rangle m\_|r|$ considering the following conditions: i) $\Pi\_i \in P\_t$ is true when evaluating it on the word $h(r)$ if and only if $\exists j \in \{0, 1, \ldots, |r|\}$ such that $\Pi\_i \in ||V \cdot m\_j||$; ii) $\Pi\_i \in P\_f$ is true when evaluating it on the word $h(r)$ if and only if $\Pi\_i \in ||V \cdot m\_j||$. Furthermore, all Boolean-based φ requirements must be expressed in Conjunctive Normal Form (FNC), and such requirements represent the task that the entire robot team must fulfill and do not specify the functions of each robot at an individual level. All logical expressions can be expressed in FNC (Brown, 2012), and, when expressing φ in FNC, we have a conjunction of π terms $\varphi = \varphi\_1 \wedge \varphi\_2 \wedge \ldots \wedge \varphi\_n$. Each of the terms $\varphi\_i|i = 1, 2, \ldots, n$ are a disjunction of n_i variables of set P with the form $[\pi\_2|\neg\pi\_2] \vee \ldots \vee [\Pi\_(jn\_t)|\neg\Pi\_(jn\_t)] \vee [\pi\_(jn\_t)|\neg\pi\_(jn\_t)]$. As any Boolean formula in FNC form can be converted to a set of linear inequalities using various techniques (Smaus, 2007), a binary vector $x = [x\_(\Pi\_1), x\_(\Pi\_2), \ldots, x\_(\Pi\_|\Pi|), x\_(\pi\_1), x\_(\pi\_2), \ldots, x\_(\pi\_|\Pi|)]\hat{\ }T \in \{0, 1\}\hat{\ }(2 \cdot \Pi)$ with $2 \cdot \Pi$ variables evaluating for each component of the vector the following conditions: i) $x\_(Pi\_i) = 1$ if the proposition Π_i is evaluated true, that is, if the region labeled Π_i is visited at any time during the execution of the trajectory and $x\_(\Pi\_i) = 0$ if the region tagged as Π_i is NOT visited. ii) $x\_(\pi\_i) = 1$ if the proposition π_i evaluates to be true, that is, if a robot stops within the region labeled π_i and $x\_(\pi\_i) = 0$ if a robot does NOT stop within the labeled region as π_i, $\forall i = 1, 2, \ldots, |\Pi|$. Based on the previous for each φ_i, a function $\alpha\_i : P \to \{-1, 0, 1\}$ is defined which shows which variables of P appear in the disjunction φ_i and which of these are negated.

$$\alpha_i(\gamma) = \begin{cases} -1\ If\ \neg\gamma\ appears\ in\ \varphi_i \\ 0\ If\ \gamma\ does\ not\ appears\ in\ \varphi_i\ \forall\gamma \in \mathcal{P} \\ 1\ If\ \gamma\ appears\ in\ \varphi_i \end{cases} \tag{2}$$

Formally, the linear inequality corresponding to the disjunction φ_i is given by $\sum_{\gamma \in P}(\alpha\_i(\gamma) \cdot x\_\gamma) \geq 1 + + \sum_{\gamma \in P} \min(\alpha_i(\gamma), 0)$, where $\min(\alpha_i(\gamma), 0)$ is the minimum value between α_i and 0. Equations (1) and (2) start from the following assumptions: if the region corresponding to the symbol $\gamma \in P$ is not visited according to φ_i, then its corresponding binary variable has a coefficient $\alpha\_i(\gamma) = 0$. Out of all the regions that appear as not negated in the disjunction φ_i, at least one must be visited, and, therefore, the sum of all its corresponding binary variables must be greater than or equal to 1. A negated symbol γ means the avoidance of a region, either along a path or in the final state, which implies that its corresponding binary variable x_γ must be zero. In this way, a specification of the FNC form is algorithmically convertible, through Equation (2), into a system of n linear inequalities, one for each disjunctive term. For each of the observations of Π_i, a binary variable $x\_(\pi\_i) = 1$ is set if π_i is evaluated as true in a final state of execution. In Equation (2), a set of linear inequalities is proposed which can be used to define the value of the binary variable $x\_(\pi\_i)$ in a final marking m where N is the number of robots and v_{Π_i} is the vector characteristic of observations of Π_i

$$\begin{cases} N \cdot x_{\pi_i} \geq v_{\pi_i} \cdot m \\ x_{\pi_i} < v_{\pi_i} \cdot m \end{cases} \tag{3}$$

When finding a solution for the proposed problem, the goal is to minimize the number of transitions along the path. Therefore, the cost function $1\ ^\wedge T \cdot \sigma$ is chosen, and the MILP problem is formulated in Equation (3) to obtain a final markup in which the specification is met, where v_γ is the characteristic vector of $\gamma \in P$. The solution is obtained by activating the enabled transitions and storing the sequence of places visited by each brand.

$$st \begin{cases} min\ 1^T \cdot \sigma \\ m = m_0 + C \cdot \sigma \\ \sum_{\gamma \in \mathcal{P}} (\alpha_i(\gamma) \cdot x_\gamma \geq 1 + \sum_{\gamma \in \mathcal{P}} \min(\alpha_i(\gamma), 0), \quad \forall \varphi_i \\ N \cdot x_\gamma \geq v_\gamma \cdot m, \quad \forall \gamma \in \mathcal{P} \\ x_\gamma \geq v_\gamma \cdot m, \quad \forall \gamma \in \mathcal{P} \\ m \in \mathcal{N}_{\geq 0}^{|P|}, \sigma \in \mathcal{N}_{\geq 0}^{|T|}, x \in \{0,1\}^{\mathcal{P}} \end{cases} \tag{4}$$

To include compliance with the constraints on the trajectory, a sequence of k marks $m\_1, m\_2, \ldots, m\_k$ is considered so that $m\_1 = m\_0 + C \cdot \sigma\_1, m\_0 - Pre \cdot \sigma\_1 \geq 0; m\_2 = m\_1 + C \cdot \sigma\_2, m\_1 - Pre \cdot \sigma\_2 \geq 0 \ldots$ This implies that, between the states of the RdP $m\_(i-1)$ and m_i, each mark moves at most through one transition, and thus the triggering of transitions for empty places is avoided.

For each of the specifications Π_i that belong to the path constraint, a binary variable $x_{\Pi_i} = 1$ is introduced as long as it is evaluated as true along the path y. As the path is given by thesequence of the k intermediate marks, Equation (4) is defined as the set of linear inequalities that consider all intermediate marks and not only the final mark as in Equation (3).

$$\begin{cases} N \cdot (k+1) \cdot x_{\pi_i} \geq v_{\pi_i} \cdot (\sum_{j=0}^{k} m_j) \\ x_{\pi_i} \leq v_{\pi_i} \cdot (\sum_{j=0}^{k} m_j) \end{cases} \tag{5}$$

Finally, the solution to this case involves choosing a sequence of observations that satisfies the LTL formula and then generating the appropriate sequence of activations in NMR that produce that sequence. This solution is based on three main steps: i) a good finite prefix r (called run) is chosen from the Büchi automaton which corresponds to the LTL formula; ii) for each transition of run r, a sequence of activations is searched for the NMR model so that the observations generated produce the chosen transition; iii) the movement strategies of the robots are obtained by concatenating the firing sequences of step 2 and imposing synchronization moments between them.

Step i: to find a set of paths from B, for example, using a k-shortest path algorithm (Yen, 1971) on the adjacency plot corresponding to the transitions of B.

Step ii: to enable the transition $s\_j \rightarrow s\_(j+1)$ in B, $j = 0, \ldots, L\_r-1$, the following two conditions must be valid: a) the RMPN system must reach a final mark m that generates any observation of the set $\rho\ (s\_j, s\_(j+1)) \subseteq 2^\wedge\Pi$; b) intermediate NMRN marks must generate only observations in the set $\rho\,(s\_j, s\_j) \subseteq 2^\wedge\Pi$, so that s_j is not left in states other than $s\_(j+1)$. To verify an observation at a given achievable mark m, for each observation $\pi\_i \in \Pi$, a binary variable x_i is defined in such a way that: $x\_i = 1$, IF $v\_i \cdot m > 0$, and $x\_i = 0$ if otherwise. The following two conditions assign the correct value to x_i:

$$\begin{cases} N \cdot x_i \geq v_i \cdot m \\ x_i < v_i \cdot m \end{cases} \tag{6}$$

It is highlighted that, if $v\_i \cdot m > 0$, the first restriction of Equation (5) is $x\_i = 1$, while the second restriction ensures that $x\_i = 0$ if $v\_i \cdot m = 0$.

Step iii: To derive appropriate formal descriptions equivalent to the conditions expressed in Equations (4) and (5), a generic subset $S \subseteq 2^\wedge\ \Pi$ is considered. It is desired that the set of active observations in a mark m is included in S. The set S can be seen as a disjunction of conjunctions of propositions of Π to convert it into a Conjunctive Normal Form (FNC) by double negation, that is, the observations in m should not belong to $2\Pi/S$. By already having the FNC set, it can be used to write a set of inequalities that hold simultaneously so that the observations in m belong to S (Martínez *et al.,* 2018).

Steps ii and iii must be iterated, taking, at each iteration, another run r from the constructed set of possible runs of B. Once a run can be followed due to the RMPN observations (step ii was successful), the process can be considered as concluded, and the solution returned is given by the currently chosen execution of B, that is, by $r = s\_0 s\_1 \ldots s\_(L\_r)$, where L_r is the length of r.

These steps are implemented through Algorithm 2, in which the CPLEX software provided by IBM is used to solve the MILP problem that arises.

Experiments and results

The experiment is configured for the implementation of the algorithms proposed, using the Matlab programming software installed on a Windows 7 operating system on an ASUS X555L laptop with an Intel Core i7 processor (4510U, 3.1 GHz), 8 GB RAM, and a toolbox under development proposed by the authors for robot movement that was used as support. For the problem posed above, the displacement specification is given by the LTL formula $\varphi = \diamond\, a\_2 \wedge \diamond\, a\_15$. The trajectory obtained when executing Algorithm 1 to solve this problem can be seen in the upper left part of Figure **4**, and the respective data associated with the execution in column "Route 1" of Table 2. It should be noted that, in this case, the longest processing time is associated with the generation of the diagram of states and transitions for the robot, and that this diagram is directly linked to the number of regions into which the space is divided, as well as to the relation of adjacency between them. It can also be noted that the trajectory obtained does not evade the obstacles present in the workspace (regions 1,3,. . ., 14,16),

Algorithm 2. Continuous synthesis of control policies for case 2

Require: Environment, Regionsofinterest, specificationLTL, CPLEX

Ensure: sequence [sequence of activations per robot]

```
P ← GetPartTriang (Environment, Regionsofinterest)
Q ← GetModeloRMPN(P)
If Q = false then
    return Error in defining Q
end if
AutBachi ← GetAutBachi(specificationLTL)
if AutBachi = false then
    return Error formula LTL
end if
trajectory ← findRunAcep(AutGeneral)
while trajectory ≠ 0 do
    createπ()
    createΠ()
    X ← GetXvector(π, Π)
    for j = 0, 1, . . . , Lr − 1 do
      MILP ← formulaMILP(X)
      resolveMILP(CPLEX)
      if σ applies then
          upgrade (sequence[])
      end if
    end for
    if all the states of the trajectory are visited then
      return sequence
    else
      trajectory ← another(trajectory)
    end if
end while
```

so the LTL specification cannot be considered as fulfilled. The problem is then solved through the execution of Algorithm 1, and an obstacle avoidance condition is included in the specification, such as the formula $\varphi = \diamond\, a\_2 \wedge \diamond\, a\_15 \wedge \Box\neg(a\_1 \vee a\_3 \vee a\_4 \vee \ldots \vee a\_14 \vee a\_16)$. Thus, a new set of results is obtained consisting of the path in the upper right part of Figure 4 and the column "Path 2" of Table 2. The resulting trajectory complies with the given specification since it only enters regions 2 and 15, always avoiding the other regions of interest to the system. When comparing the results of Route 1.ªnd Route 2ïn Table 2, a noticeable difference is identified in the time associated with the generation of the diagram of states and transitions of the robot, which directly affects the time associated with calculating acceptable routes that meet the specification. This indicates that the more robust the

LTL formula in terms of delimiting the behavior of the workspace, the less time it takes to calculate a solution path. The possibility of including more robust LTL formulas implies the possibility of executing different types of tasks in the same environment, which is subject to the same complexity in the generation of the robot's transition system. Talking about various types of tasks directly refers to the possibilities of expression of logical tasks that the LTL formulas provide, mainly, security, coverage, or sequencing. The trajectory in the upper right part of Figure 4 refers to a co-safe specification and corresponds to the trajectory with the fewest number of transitions in the automaton of the complete system. However, if more regions of interest are included, this will remain the only criterion, that is, the system delivers the shortest route that covers the three regions, regardless of the order in which it covers them. An example of the above is the case of the route shown in the lower left part of Figure 4 and column "Route 3" of the Table 2, which expresses the trajectory and the resulting data for the LTL formula $\varphi = \diamond a\_2 \wedge \diamond a\_15 \wedge \diamond a\_12 \wedge \square\neg(a\_1 \vee a\_3 \vee a\_4 \vee \ldots \vee a\_11 \vee a\_13 \vee a\_14 \vee a\_16)$, which in turn includes region 12 as a region of interest.

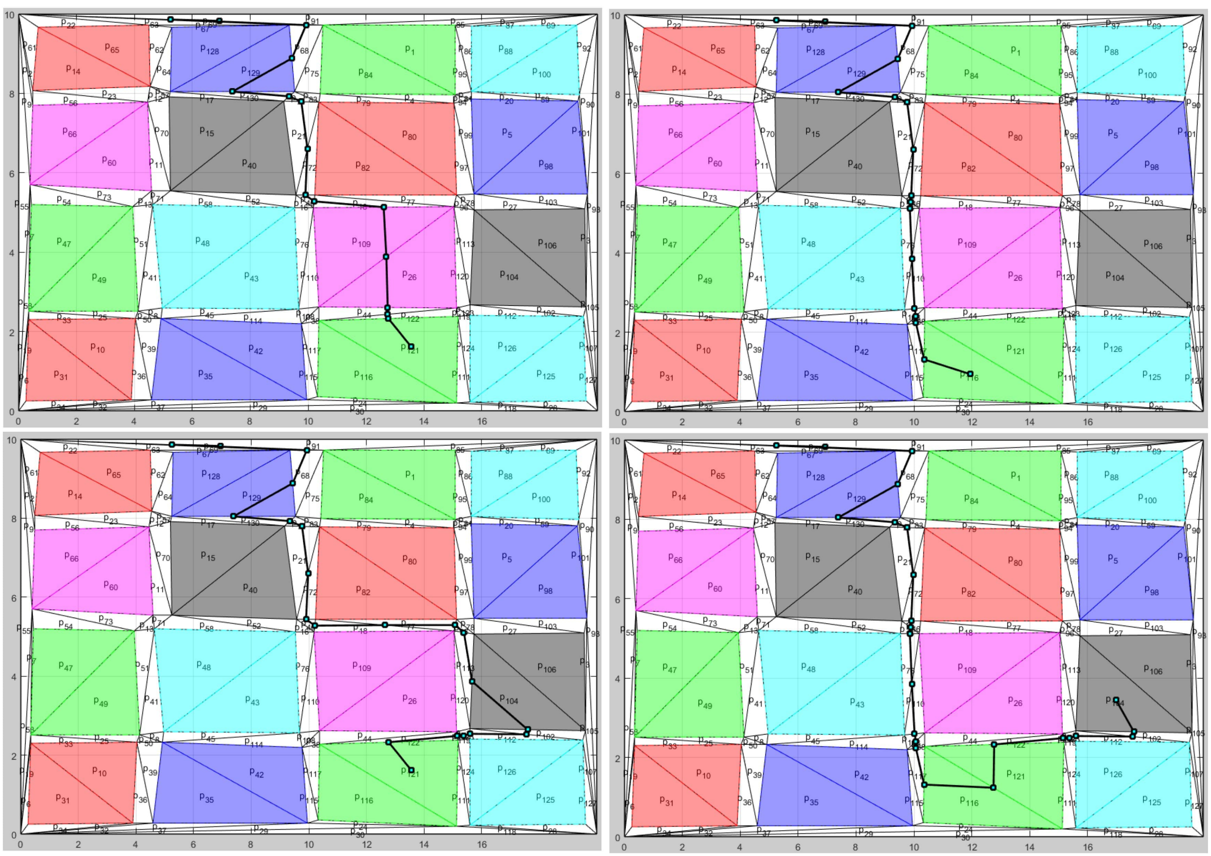

Figure 4. Trajectories obtained with Algorithm 1

Source: Authors.

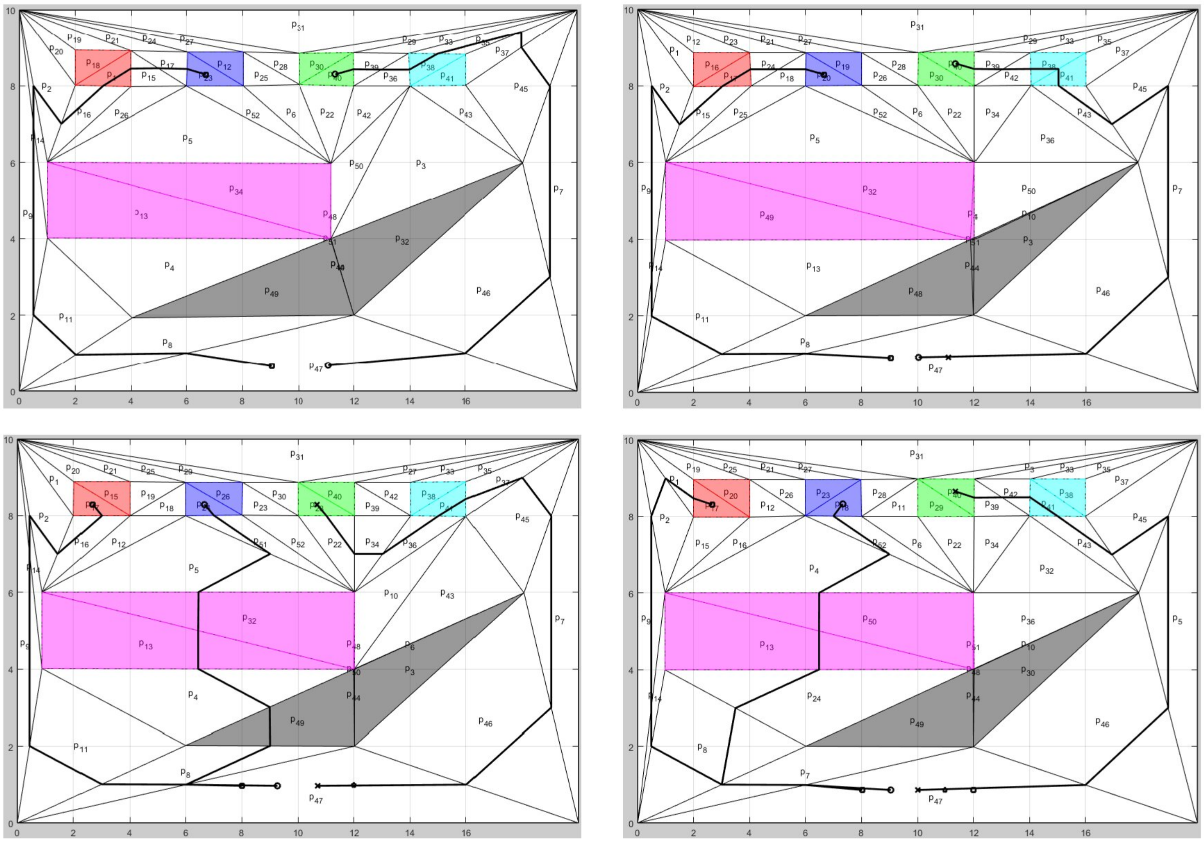

Figure 5. Trajectories obtained with Algorithm 2

Source: Authors.

However, the order in which the regions are reached is not specified, and the new expressiveness of Algorithm 1 makes it possible to do so by changing the coverage structure of the LTL formula to a sequencing structure, leaving the formula as $\varphi = \diamond\,(a_2 \wedge \diamond\,(a_{15} \wedge \diamond\,(a_{12} \wedge (\neg a_{12}) \cup a_{15}))) \wedge \Box\neg(a_1 \vee a_3 \vee a_4 \vee \ldots \vee a_{11} \vee a_{13} \vee a_{14} \vee a_{16})$. This last LTL formula expresses, in addition to the need to reach regions 2, 15, and 12 at some time in the future, the need to reach them in that order. The trajectory and the data corresponding to the solution found through Algorithm 1 in Matlab can be seen in the lower right part of Figure 4 and in the column "Path 4" of Table 2. To demonstrate that, in Algorithm 2, the time to find the solution does not depend on the number of robots that are added to the system, an environment with six regions of interest is proposed, and the results are obtained for two, three, four, and five robots cooperatively reaching the specification $\varphi = A \wedge B \wedge C \wedge D$. The formula delivered in FNC form expresses that the robot team must jointly reach the regions A, B, C, D, corresponding to the red, violet, green, and blue regions in the workspace of the Figure 5.

Table 2. Data resulting from Algorithm 1 in the calculation of the trajectories of Figure 4

Criterion	Path 1	Path 2	Path 3	Path 4
Transition system for a single robot (states)	130	130	130	130
Time to generate diagram (seconds)	2,328	0,247	0,201	0,146
Buchi automaton for solution LTL (states)	4	4	8	6
Complete system automation (states)	520	520	1040	780
Time to generate complete system automation (seconds)	0,157	0,062	0,167	0,114
Time to find an acceptable path in automation (seconds)	0,395	0,156	0,390	0,334

Source: Authors.

Table 3. Resulting data for the calculation of trajectories in Figure 5

Criterion	2 robots	3 robots	4 robots	5 robots
P	52	52	52	52
T	152	152	152	152
t_p	0,287	0,306	0,296	0,298
VMILP	2053	2053	2053	2053
=	520	520	520	520
$\neq$	600	600	600	600
$t_{c(MILP)}$	0,287	0,306	0,296	0,298
$T_{r(MILP)}$	0,265	0,185	0,252	0,248
TR1	47, 8, 11, 9, 14, 2, 16, 1, 15, 17, 23	47, 8, 11, 14, 9, 2, 15, 17, 24, 18, 20	47, 8, 11, 9, 14, 2, 16, 17	47, 7, 8, 14, 9, 2, 1, 17
TR2	47, 46, 7, 45, 37, 35, 38, 36, 39, 40	47, 46, 7, 45, 43, 41, 38, 42, 39, 40	47, 8, 49, 4, 13, 32, 5, 51, 24	47, 7, 8, 24, 13, 50, 4, 52, 18
TR3		47	47, 46, 7, 45, 37, 41, 36, 34, 22, 28	47, 46, 5, 45, 43, 41, 42, 39, 40
TR4			47	47
TR5				47

Source: Authors.

It is evident that the specification is met in all cases. However, it is also noted that not in all cases do all the robots move. That is, in some cases, a few robots move to reach the specification while the others remain static. This is because the algorithm is optimal from the point of view of the number of transitions that must be activated to reach the specification, which implies, in this case, that moving all the robots generates more shots in the transitions than they are needed. Table 3 shows the compilation of the data obtained for each of the algorithm executions in the calculation of the trajectories deposited in Figure **5**. In this case, the rows represent the measurement criteria, where P represents the size of places that the resulting RdP contains; T represents the number of transitions of the RdP; t_p represents the time it takes the system to build the RdP; VMILP represents the number of variables that are generated for the MILP problem; = represents the number of equality restrictions; $\neq$ represents the number of inequality restrictions; $t_{c(MILP)}$ represents the time needed to build the MILP problem; $T_{r(MILP)}$ represents the time required to solve the MILP problem; and $T_{R1}, T_{R2}, T_{R3}, T_{R4}$, and T_{R5} represent the sets of activations corresponding to the trajectories of each robot.

CONCLUSIONS

The proposed methodology solves the problem of synthesis of automata for the high-level control of agents (robots), where the planning of movements or the change of tasks during execution is a constant.

It was shown that, with the proposed method to change the global task of a robot team, it is only necessary to change the task given as an LTL or FNC formula.

It was also shown that, under certain criteria, the combinational state explosion problem associated with multi-agent systems can be mitigated.

It was demonstrated that many complex behaviors of robotic systems can be expressed in temporal logic, and therefore their solution can be calculated using the proposed methodology.

The presented method automatically schedules the tasks to be executed by a team of cooperating mobile robots to achieve a given task as a co-secure LTL formula or a Boolean formula in FNC form.

The solution found is optimal with regard to the number of transitions followed by the team members.

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INVESTIGACIÓN

A Framework for the Resilience of LV Electrical Networks with Photovoltaic Power Injection

Marco de referencia para la resiliencia de las redes eléctricas de BT con inyección de potencia fotovoltaica

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Abstract

Context: Electrical distribution networks have undergone several changes in the last decade. Some of these changes include incorporating distributed energy sources such as solar photovoltaic (PV) generation systems. This could modify the performance of electrical networks and lead to new challenges such as evaluating the impacts of the PV integration, the response to electrical and climatic disturbances, and the planning and restructuring of networks. Electrical network behavior with respect to PV integration could be evaluated by quantifying the variation in operation and including network resilience.

Objective: To propose a reference framework to evaluate the resilience of LV electrical networks with PV power injection.

Methodology: This paper addresses the framework for evaluating the performance of a low- voltage (LV) electrical network in the face of the integration of PV systems. It collects research related to evaluating the resilience of electrical networks on severe climate changes, natural disasters, and typical maneuvers, and then, it proposes a guideline to evaluate the performance of LV electrical networks with the integration of PV generation sources while including resilience. To this effect, the determination of resilience evaluation indices is proposed. These indices are obtained from a normalized transformation of the networks' measurable electrical parameters that are the most affected by PV integration or are significant in the performance of the networks. Finally, the evaluation of a proposed resilience index for a university building's LV network is presented as a case study.

Results: The resilience assessment proposal is applied to a case study. When evaluating the resilience of the voltage at the

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common coupling point of the PV, an index of 0,84 is obtained, which is equivalent to 59,8 hours of overvoltage.
Conclusions: It is possible to improve the resilience of a LV network through management strategies. In the case study, a 29 % reduction in overvoltage hours was obtained by applying a curtailment strategy to the PV system.
Financing: ECOS-Nord, Minciencias, and Universidad Industrial de Santander.

Keywords: distribution networks, low voltage, photovoltaic systems, performance, resilience, impacts

Resumen

Contexto: Las redes eléctricas de distribución han sufrido varios cambios en la última década. Algunos cambios incluyen la incorporación de fuentes de energía distribuidas como los sistemas de generación solar fotovoltaica (PV). Esto podría modificar el rendimiento de la red eléctrica y generar nuevos desafíos como la evaluación de los impactos de la integración fotovoltaica, la respuesta a las perturbaciones eléctricas y climáticas y la planificación y reestructuración de las redes. El comportamiento de la red eléctrica frente a la integración fotovoltaica podría evaluarse cuantificando la variación en la operación e incluyendo la resiliencia de la red.
Objetivo: Proponer un marco de referencia para la evaluación de la resiliencia de las redes eléctricas de BT con inyección de potencia PV.
Metodología: Este artículo aborda el marco para evaluar el desempeño de una red eléctrica de baja tensión (BT) frente a la integración de sistemas PV. Recoge investigaciones relacionadas con la evaluación de la resiliencia de las redes eléctricas ante cambios climáticos severos, desastres naturales y maniobras típicas, y luego propone una guía para evaluar el desempeño de las redes eléctricas de baja tensión con la integración de las fuentes de generación fotovoltaica e incluye la resiliencia. Para ello, se propone la determinación de índices de evaluación de resiliencia, los cuales se obtienen de una transformación normalizada de los parámetros eléctricos medibles de las redes que son más afectados por la integración fotovoltaica o son significativos en el rendimiento de las redes. Finalmente se presenta la evaluación de un índice de resiliencia propuesto para una red de BT de un edificio universitario como caso de estudio.
Resultados: La propuesta de evaluación de resiliencia se aplica a un caso de estudio. Al evaluar la resiliencia de la tensión en el punto de acoplamiento común del PV, se obtiene un índice de 0,84, equivalente a 59,8 horas de sobretensión.
Conclusiones: Es posible mejorar la resiliencia de la red de BT mediante estrategias de gestión. En el caso de estudio, se obtuvo una reducción del 29 % de las horas con sobretensión aplicando una estrategia de reducción al sistema PV.
Financiamiento: ECOS-Nord, Minciencias y la Universidad Industrial de Santander.

Palabras clave: redes de distribución, baja tensión, sistemas fotovoltaicos, rendimiento, resiliencia, impactos

Table of Contents

INTRODUCTION

Electrical networks transport electrical energy from generation points to consumption points. Therefore, their design must guarantee the quality conditions for the operation of the electrical system and loads. These conditions are generally voltage regulation, energy losses, chargeability, power balance, and harmonic distortion (Deboever *et al.,* 2018,Haque & Wolfs, 2016).

An electrical network design guarantees the operation within a functional and regulatory range under normal and non-normal operation conditions. The latter may include equipment or line disconnections, atmospheric discharges, or short circuit failures (Bajaj *et al.,* 2020). Additionally, severe weather conditions, malicious damage caused by humans, natural disasters, non-linear loads, equipment maneuvers, and equipment in poor condition produce non-normal operating conditions.

Likewise, distributed generation (DG) systems could modify the operation of the network, which sometimes leads to violations of the operating conditions (Bajaj *et al.,* 2020,Cadini *et al.,* 2017,Correa-Flórez *et al.,* 2016). However, the impact on the electrical network due to variations in operating conditions, unexpected events, and permanent modifications could be characterized by evaluating *system resilience* (Borghei & Ghassemi, 2021,Mousavizadeh *et al.,* 2020).

There is no proper or unified concept to define resilience applied to low voltage (LV) electrical networks. Nevertheless, the resilience of an electrical system is conceived to a greater extent as the capacity of the network to withstand an adverse event without losing operating conditions, reducing the impact on the service quality to users, recovering after the event, and adapting to new operating conditions (Borghei & Ghassemi, 2021).

The concept of resilience in electrical systems emerged in the last decade (Cadini *et al.,* 2017, Mousavizadeh *et al.,* 2020), and lots of research are oriented to quantification in different scenarios. Resilience can be measured based on reliability, robustness, adaptability, and recoverability indices (Rocchetta *et al.,* 2018). All cases evaluate the level of impact of an adverse event on the electrical network.

In addition, the integration of photovoltaic (PV) systems in residential and commercial LV networks has increased in the last decade (Aleem *et al.,* 2020,Gandhi *et al.,* 2020). Thus, there is a need to carry out studies focused, for instance, on the performance of the networks in the face of variations of the injected power due to fluctuations in solar irradiance and the characterization of the resilience of LV networks (Brinkel *et al.,* 2020). This could favor the networks' capacity to withstand adverse conditions. Moreover, it will allow operators to establish complementary operating conditions of existing networks and define strategic plans to respond to PV integration in the medium and long term.

This paper is organized as follows: the concept sections present a review of the PV systems' significant impacts in LV and describe the concept of resilience in electrical networks along with the typical scenarios for evaluation. Then, the discussion section proposes how the concept of resilience could be applied to evaluate the performance of LV networks that integrate PV. The results section presents a case study to apply the discussion, and the final section presents the conclusions of this research.

Impacts of the integration of PV systems on LV distributions networks

The impacts of the integration of PVs in LV networks depend on the network architecture, the PV penetration, and the meteorological conditions (Haque & Wolfs, 2016). According to the architecture, the impacts are related to the impedances of the lines, the voltage regulation equipment, the protections, and the system's response times.

Typically, an increase in PV penetration implies an increase in impact levels. As for the meteorological conditions, the impacts of the PV system depend on the average, maximum, and minimum values of solar irradiation and ambient temperature, as well as on sporadic variations (Deboever *et al.,* 2018,Giral *et al.,* 2017).

Moreover, PV systems could favor the electrical network's reliability, load availability, and voltage regulation; relieve power congestion; and reduce losses and operation and billing costs. For example, Shanshan *et al.,* 2018 study the implementation of DG as a strategy to mitigate disconnection events.

However, PVs could also alter the voltage waveform, produce voltage and power unbalances, generate reverse power flows, and cause premature deterioration in regulation, control, and protection equipment (Shanshan *et al.,* 2018). Some significant impacts of PV systems on distribution networks are described below.

Impacts on the voltage profile

PV systems in LV could help keep the service voltage within acceptable limits (Aleem *et al.,* 2020). This is possible because the strategic location of the PV systems reduces currents in certain sections of the network, which improves voltage regulation and reduces losses (Montoya *et al.,* 2020). However, the unplanned and massive integration of PVs could cause overvoltage or low voltage (Deboever *et al.,* 2018, Haque & Wolfs, 2016).

Depending on the sitting of the PV system, a higher PV penetration can be achieved without violating the voltage limits. For example, some simulations have shown that a strategic sitting can achieve a penetration of 50 % of the feeder without violating the limits of voltage regulation (Tedoldi *et al.,* 2017).

Impacts on power and voltage balance

Non-linear power inverters could lead to injecting distorted currents and unevenly delivering power to the phases of the system (Borghei & Ghassemi, 2021). In addition, distribution networks typically operate with unbalanced voltages, which is a product of unbalanced load in the commercial and residential sectors. Thus, an unbalanced power injection of PV systems could lead to an unbalance in the service voltage (Emmanuel & Rayudu, 2017).

Impacts on the coordination of protections

In LV networks, the protection farthest from the supply bus must act first to isolate the section affected by a failure. The other protections act in sequence as a backup if the primary one does not do it.

Based on Ates *et al.,* 2016 and Paliwal *et al.,* 2014, this can indicate that the conventional LV protection schemes are vulnerable to PV integration. Moreover, three main technical aspects could cause malfunctions in the coordination of protections:

- The PV systems integration could cause bidirectional power flows in the network, which means that the coordination of protections based on a unidirectional way is ineffective.
- The network could present high variations in the current magnitude when connection and disconnection events occur or the power injected by the PV varies.
- The short-circuit current tends to increase with PV integration

Resilience in electrical networks

Electrical network resilience could be defined as the ability to withstand an adverse event without losing operating conditions and recover after the event (Afgan, 2010,Borghei & Ghassemi, 2021). A resilient electrical network simultaneously evaluates the behavior of the systems that face an event and the consequences (Baroud & Barker, 2018).

The behavior of the network can be represented by a parameter, $\Phi(t)$, generally called sustainability (Afgan, 2010). The probability that the network will operate in its normal mode is called reliability. When a disturbance, $e(t)$, occurs, $\Phi(t)$ decays according to the vulnerability to $e(t)$. The network's ability to withstand perturbations, $e(t)$, is called robustness (Baroud & Barker, 2018).

Once $e(t)$ has finished, the network experiences a transient state until it seeks a stable one. After a time, t_r, restoration starts until a stable normal operating mode, $\Phi(t_r)$, is reached. The final operation state, $\Phi(t_f)$, could be different from the initial $\Phi(t_0)$. This depends on the disturbance level and recovery of the network. The network's capacity to reach normal operating conditions is called recoverability (Baroud & Barker, 2018).

The literature shows mostly studies on the resilience of electrical networks to extreme weather events. However, these have a low probability of occurrence and high impacts (Haixiang *et al.,* 2017, Ouyang & Dueñas-Osorio, 2014), compared to events directly or indirectly caused by humans (Liu *et al.,* 2017,Shanshan *et al.,* 2018).

There are few studies related to the resilience of electrical networks to permanent modifications, such as Deboever *et al.,* 2018 and Blaabjerg *et al.,* 2017. These modifications have a low impact but could cause a sudden change of network components and strengthen or weaken the response to a temporary disturbance. They could integrate new elements as generation sources, voltage regulation equipment, or distribution lines, and they could also imply modifications of distribution transformers, the connection point of a load, or an increase in the nominal power of a generation source. Table 1 summarizes the analysis scenarios and the resilience evaluation indicators for the distribution networks according to the literature.

Discussion

This section integrates the bibliographic review. It proposes preliminary guidelines for evaluating the performance of an LV network through resilience. It considers PV power injection as a disturbance facing the electrical network.

There is currently little research on the resilience of electrical networks before DG integration. However, some studies are related to the use of smart grids and microgrids as a strategy to improve the response of networks to extreme events (Liu *et al.,* 2017,Shanshan *et al.,* 2018).

Table 1. Studies on the evaluation of resilience in electrical networks

Scenario	Indicator	Description
Several weather conditions	Generation cost (Shang, 2017)	It uses a dynamic isolated microgrid for supply during power outages
	Vulnerability, redundancy, and adaptability (Espinoza *et al.*, 2016)	It evaluates the adaptation of power systems to frequent natural disasters
Hurricanes	Risk probability and robustness (Ouyang & Dueñas-Osorio, 2014)	It analyzes power systems with high probability of hurricanes
Natural disasters and human attacks	Supply capacity and restoration time (Bie *et al.*, 2017)	It analyzes the infrastructure of power systems and the measures taken around the world
	Reliability, island mode (Haixiang *et al.*, 2017) (Rahimi & Davoudi, 2018)	They analyze the capacity of DG sources such as electric vehicles and microgrids to improve the resilience of a residential electrical network
Natural disasters in cascade	Reliability and supply capacity (Cadini *et al.*, 2017)	It analyzes the capacity of a transmission network to maintain service in case of climatic disasters
Extreme weather events	Operation cost and power supply capacity (Chong *et al.*, 2017)	It proposes an operation strategy to improve the resilience of power systems

Source: Authors.

Likewise, the integration of complementary components such as hybrid electric vehicles as generation and storage systems could supply the critical loads during a natural disaster or power outages (Rahimi & Davoudi, 2018,Shanshan *et al.*, 2018).

On the other hand, it is usual to evaluate the maximum DG power that could be installed at a node in the network without compromising the operating conditions. Generally, the IEEE 1547 standard (2020) is taken as a reference for operating conditions. The maximum power capacity is called Hosting Capacity (Shivashankar *et al.*, 2016). It is a way to assess the electrical network's resilience, and it ensures that the networks do not lose operating conditions due to the integration of the DG.

Although the consulted literature does not consider evaluating LV networks' resilience directly, it is possible to approach it from indexes that relate the impacts of a disturbance or modification in the network with its response. The evaluation indices are obtained from the normalization of the

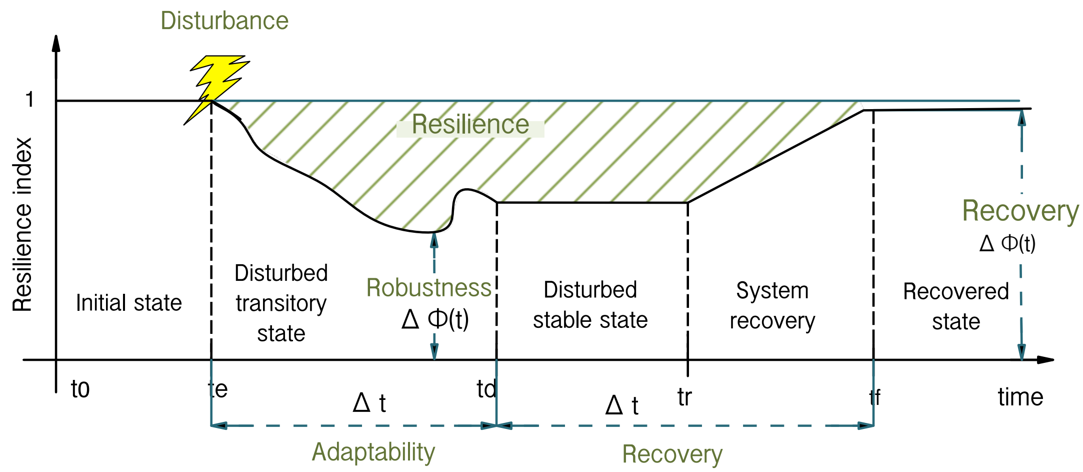

Figure 1. Evolution of a resilience index in the face of a disturbance

Source: Authors.

operating parameters affected before the disturbances and evaluation scenarios, particularly in the face of climatic and operational disturbances.

Each resilience evaluation index must be related to an operation parameter. The operating parameters are those established by the IEEE 1547 standard (2020) for DG interconnection and others determined from the review of related literature. The evolution over time of each evaluation index in the face of a disturbance is called sustainability (Afgan, 2010).

The resilience of each operation parameter can be determined from the integration of sustainability, and the total resilience of the network from a weighted parameter sum.

PV integration could be considered favorable if the evaluation indexes are kept close to 100 % and are higher than in a reference scenario, which could be the same network without PV generation or a network at a standardized level for this test.

The electrical network's operation can be quantified through a sustainability function, $\Phi_i(t)$, by an evaluation index. Before a regular operation of the system, the index must remain constant and close to 100 %. A disturbance, $e(t)$, can produce a variation and a transitory state of $\Phi_i(t)$.

It is possible to quantify the resilience of each parameter (R_i) from this variation and the transitory state, which would be the area between ideal sustainability ($\Phi_i(t) = 1$) and its evolution before the disturbance. This strategy simultaneously evaluates the definitions of robustness, adaptability, and recoverability, and it includes operation variations and response times. Figure 1 represents the evolution of a resilience evaluation index in the face of a disturbance.

The assessment of the resilience evaluation indexes can be studied in typical scenarios of distribution system disruption with PV systems. In addition, the evaluations can be made from simulations of the behavior of the PV system and the characteristics of the electrical network.

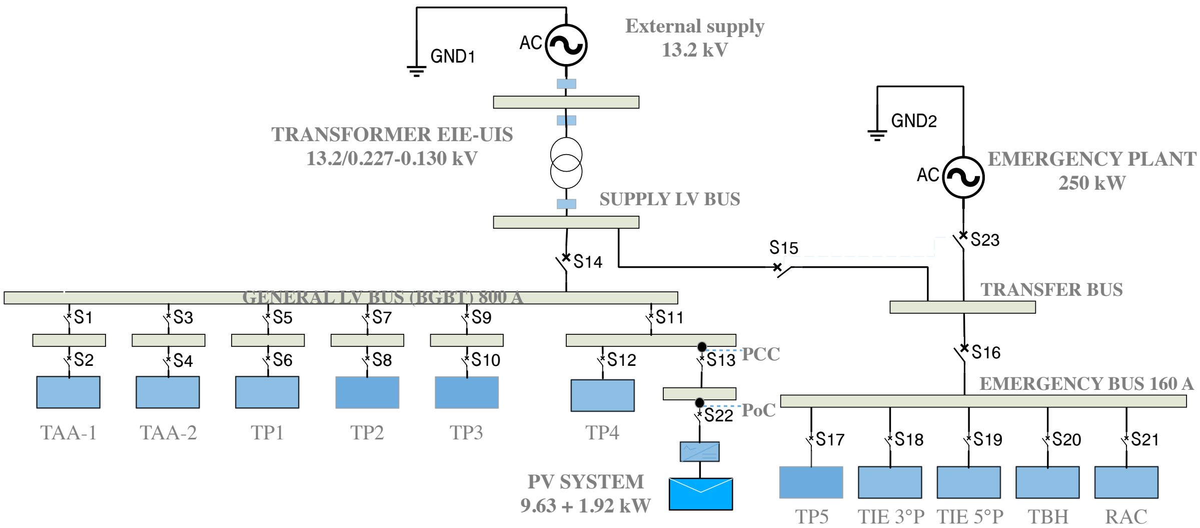

Figure 2. Electrical connection diagram of EEB, Universidad Industrial de Santander, Colombia

Source: Authors.

The evaluation scenarios must include system-specific disturbances such as voltage gaps, voltage peaks, frequency variations, and voltage unbalances. They must also consider external disturbances such as climatic variations (solar irradiation and temperature) and faults (disconnections and short circuits).

Case study

A case study is examined to apply what was exposed in the discussion section. An evaluation of the voltage regulation index is applied to estimate a resilience index at the point of common coupling (PCC). The setting of this case study is Universidad Industrial de Santander.

The electrical network of the building is appropriate for this study since it has smart meters in the primary nodes of the network. It also has an interconnected PV system through microinverters (one for each panel). Figure 2 presents the electrical connection diagram of the Electrical Engineering Building (EEB). More detailed information of the EEB can be consulted in the research by Parrado-Duque, 2020 and Téllez-Santamaría, 2020. The considerations of the case study are presented below:

Electrical network model

For the sake of simplicity, the electrical network is modeled as a single-phase equivalent. Loads are modeled as constant power, and wire conductors are modeled as constant impedance. The power output delivered by the PV system is calculated according to MPPT and the irradiance and temperature. Figure 3 presents the diagram of the single-phase equivalent Simulink model of the EEB's network.

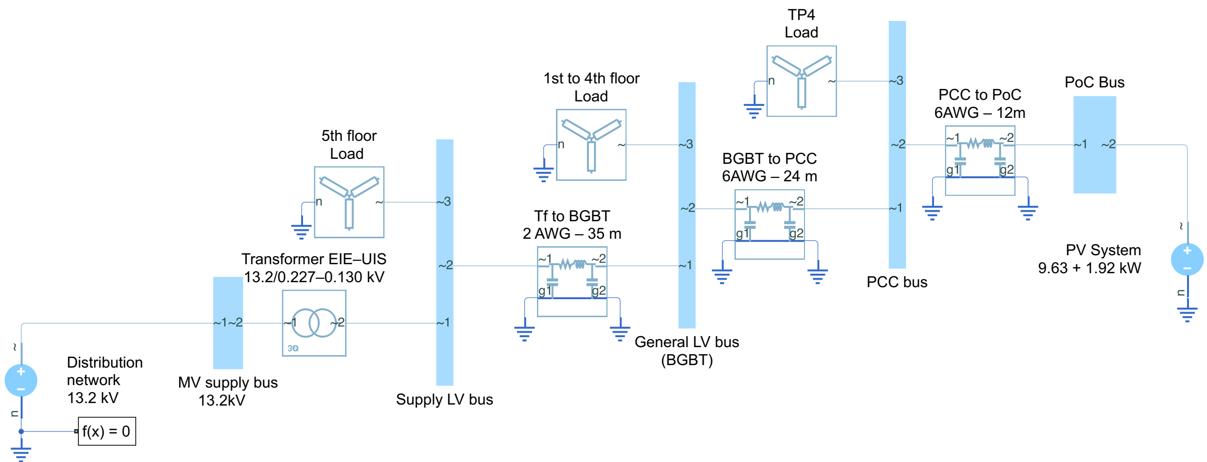

Figure 3. Simulink model of the EEB for testing

Source: Authors.

Power profiles for test

The test uses actual electrical measurements from the EEB. The electrical variables used are the voltage in the primary supply bar and the active and reactive power in the bars of each floor. The PV system uses the temperature and solar irradiance information obtained from the weather station installed on the terrace of the building.

A period with disconnection events due to high PV generation while a low load is selected for the test. The sampling period is one month (from October 17 th to November 16 th , 2019), with a time step of ten minutes. The maximum power generated by the PV system is calculated using Equations (1) and (2).

$$P_{PV}(t) = \eta_{inv} \cdot \frac{P_{PV,n} \cdot G_a(t)}{G_{a,0}} \cdot \left[1 - \frac{(T_a(t) - 25)}{200}\right] \tag{1}$$

$$Q_{PV}(t) = \frac{P_{PV}(t)}{fp} \cdot \sqrt{1 - fp^2} \tag{2}$$

where $P_{PV,n}$ is the PV system peak power [kWp], $G_{a,0}$ is the standard condition irradiance [W/m^2], $G_a(t)$ is the current solar irradiance in [W/m^2], $T_a(t)$ is the current ambient temperature in °C, η_{inv} is the inverter efficiency $P_{PV}(t)$ is the PV system active power at t [kW], fp is the oeprating power factor, and $Q_{PV}(t)$ is the PV system reactive power at t [Kvars].

Evaluation of the voltage regulation index

Equation (3) is proposed to evaluate the voltage regulation index every day. Finally, the results are averaged for the test period. The parameters of (3) are tuned according to the case study (Parrado-Duque *et al.*, 2019) expand this discussion). Figure 4 presents the transformation graphically.

$$\Phi_{\%R} = \begin{cases} 1 & \text{if} \quad V_{\%R_L} \leq V_{\%R} \leq V_{\%R_H} \\ m_L \cdot V + b_l & \text{if} \quad V_{\%R_{min}} \leq V_{\%R} < V_{\%R_L} \\ m_H \cdot V + b_h & \text{if} \quad V_{\%R_H} < V_{\%R} \leq V_{\%R_{max}} \\ 0 & \text{if} \quad V_{\%R} < V_{\%R_{min}} \\ 0 & \text{if} \quad V_{\%R} > V_{\%R_{max}} \end{cases} \tag{3}$$

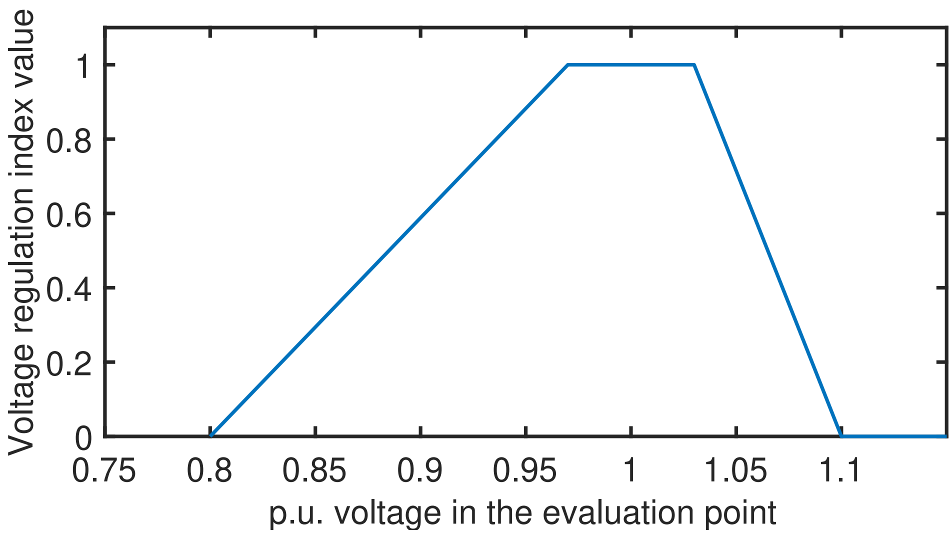

Figure 4. Voltage regulation index transformation

Source: Authors.

Here, $V_{\%R_L}$ and $V_{\%R_H}$ are the voltage regulation limits; $V_{\%R_{min}}$ and $V_{\%R_{max}}$ are the voltage regulation limits allowed for the electrical network; m_L and m_H are the slopes, which are determined according to the regulation limits; and b_L and b_H are the corresponding cut points. In the case study, an acceptable voltage value between 0,97 p.u. and 1,03 p.u. is $\Phi_{\%R} = 1$, and an unacceptable voltage of less than 0,8 p.u. and greater than 1,1 p.u. corresponds to $\Phi_{\%R} = 0$.

PV power curtailment

According to Tonkoski *et al.*, 2012, curtailment is applied to the power PV generated to reduce the overvoltage in the PCC produced by the injection of PV power. The curtailment strategy is given by

Equation (4).

$$P_{PV_{Cut}}(t) = \eta_{Cut} \cdot P_{PV}(t) \tag{4}$$

Here, $P_{PV}(t)$ is the maximum power that the PV system can deliver at time t, and it is given by Equation (4); and η_{Cut} is the curtailment index that varies between 0 and 1. It is obtainedfrom the PCC voltage. In the case there is no overvoltage in the PCC $\eta_{Cut} = 1$, if there is overvoltage, η_{Cut} decreases until a proper volateg regulation is reached or until $\eta_{Cut} = 0$.

Results and analysis

The results were obtained in MATLAB through a quasi-static power flow in Simulink. The voltage regulation index was evaluated without the curtailment strategy and then by applying it.

Figures **5** and **6** present the voltage profile for a day without the curtailment strategy and the voltage regulation index using the transformation described in Figure **4**. The voltage regulation index was evaluated for each time step.

Figures **7** and **8** present the voltage for the network at a given time during the month and when applying the curtailment strategy. Note that it considers the working hours between 6:00 and 20:00. Finally, Table 2 presents the summary of the results obtained.

This case considers overvoltage if the voltage regulation in the PCC is equal to or greater than 10 %. Note that the voltage regulation index, $\Phi_{\%R}$, indicates potential regulation problems, which is

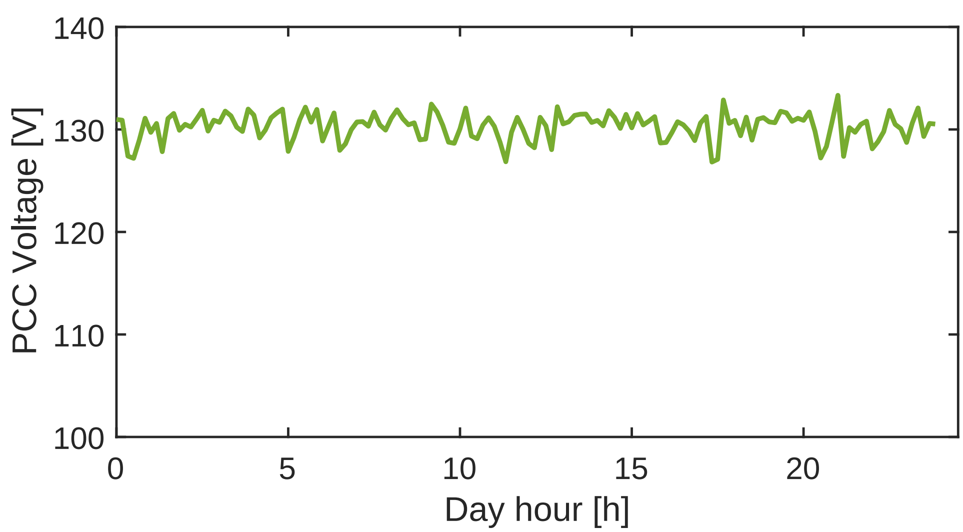

Figure 5. PCC voltage for day 1 (October 17th, 2019)

Source: Authors.

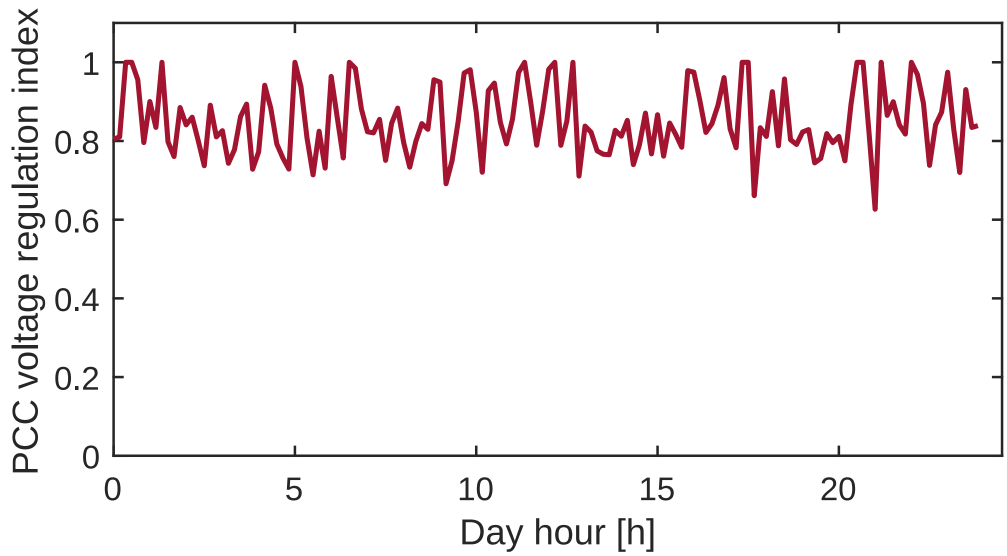

Figure 6. PCC voltage regulation index for day 1

Source: Authors.

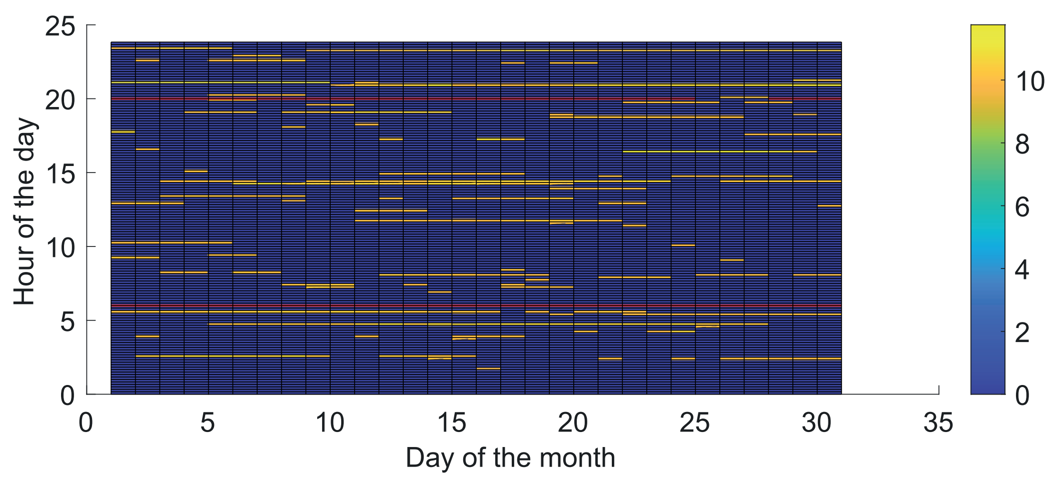

Figure 7. Voltage regulation in the PV system's PCC during the test month

Source: Authors.

consistent with the total overvoltage hours that the PV system presents. When applying the curtailment strategy, it is possible to slightly increase $\Phi_{\%R}$¨. However, a significant decrease is achieved in the total hours with overvoltage, especially in the working hours (it is reduced by 49 %). Therefore, the curtailment strategy does not affect the energy delivered by the PV system.

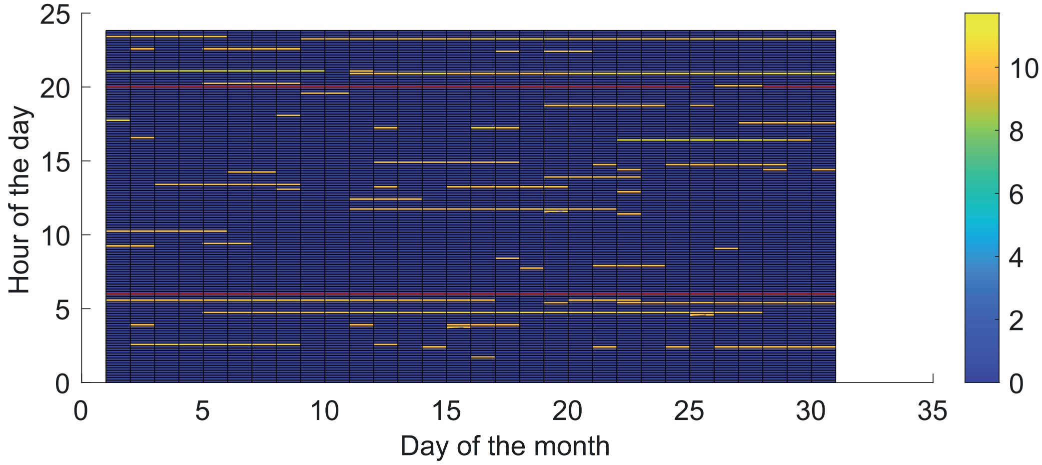

Figure 8. Voltage regulation in the PV system's PCC while applying the curtailment strategy

Source: Authors.

Table 2. Summary of results

Parameter	Non– curtailment	Curtailment
Voltage regulation index	0,84	0,845
Overvoltage total hours	59,8 h	42,0 h
Overvoltage working hours	31,0 h	15,8 h
PV generation	1,6 MWh	1,6 MWh

Source: Authors.

According to the results, applying curtailment strategies to the PV system can improve the level of resilience of the electrical network of the EEB. It is also noticed that the voltage regulation problems are typical of the network and not of the PV system. Therefore, there is an opportunity to improve applied voltage regulation strategies on the supply bar or feeder.

Conclusions

The resilience of an LV network with PV integration before disturbances has not been evaluated directly in the consulted literature. However, this can be approached from the perspective of the variation of the response in the networks to the impacts and effects that PV systems produce in the face of climatic variations and operation disturbances.

A correct evaluation of resilience must quantitatively define the normalized resilience indices from the operating parameters of the network affected by the PV integration. Parameters have been identified according to the literature and experience in the dissing of distribution networks.

It is recommended to use real operating profiles of the PV system and the network in order to obtain low error results. The case study shows congruence between the value found in the voltage regulation index and the overvoltage in the network. It also shows that the application of power management strategies can improve an electrical network's resilience level.

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INVESTIGACIÓN

Estimation of Global Solar Radiation Using NNARX Neural Networks Based on the UV Index

Estimación de la radiación solar global utilizando redes neuronales NNARX basadas en el índice UV

John Barco-Jiménez [1], Francisco Eraso-Checa [2], Andrés Pantoja [3], Eduardo Caicedo-Bravo [4]

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Abstract

Context: This work presents different models based on artificial neural networks, among them NNARX, for estimating global solar radiation from UV index measurements. The objective is to determine the efficiency of the models studied to estimate global solar radiation in terms of the coefficient of determination (R^2), the root-mean-square error (RMSE), and the mean absolute error (MAE).

Methodology: It is divided into four stages: i) conformation of the training dataset (in this case, it uses a training set of 213.019 data collected over five years in the city of Pasto, Colombia, with the Davis Vantage Pro 2.0 station); ii) preprocessing of data to remove erroneous and unusual data; iii) definition of models based on recurrent and conventional artificial neural networks according to an analysis of topologies, *e.g.* NNFIR and NNARX; iv) training of the models and evaluation of the estimation efficiency through metrics such as R^2, RMSE, and MAE. To validate the model, a new dataset collected during the last year was used, which was not included in the data training.

Results: The global solar radiation estimation models based on NNARX show the best estimation efficiency compared to conventional neural networks. The NNARX221 model has an RMSE of 54,32 and a MAE of 18,06 W/m^2.

Conclusions: NNARX models are highly efficient at estimating global solar radiation, with a coefficient of determination of 0,9697 in the best of cases. The most efficient models are characterized by using two past times and the current UV index instant, and they feed from two past times of their own estimated radiation output. Furthermore, the numerical results show that the contribution of temperature and relative humidity is not relevant to improving the efficiency of the estimation of global solar radiation. These models can be particularly important since they only use measurements made with

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UV index sensors, which are less expensive than solar radiation ones.

Keywords: recurrent neural network, Davis Vantage PRO 2.0, solar radiation model, solar radiation, UV index.

Resumen

Contexto: Este trabajo presenta diferentes modelos basados en redes neuronales artificiales, entre ellas las NNARX, para la estimación de la radiación solar global a partir de mediciones del índice UV. El objetivo es determinar la eficiencia de los modelos estudiados para estimar la radiación solar global en términos del coeficiente de determinación (R^2), la raíz del error medio cuadrático (RMSE) y el error absoluto medio (MAE).
Metodología: Se divide en cuatro etapas: i) conformación del set de datos de entrenamiento (en este caso se utiliza un set de entrenamiento de 213.019 datos recolectados durante 5 años en la ciudad de Pasto, Colombia, con la estación Davis Vantage Pro 2.0); ii) pre-procesamiento de los datos para remover datos erróneos e inusuales; iii) definición de modelos basados en redes neuronales artificiales recurrentes y convencionales basándose en un análisis de topologías, *e.g.* NNFIR y NNARX; iv) entrenamiento de los modelos y evaluación de la eficiencia de la estimación por medio de métricas como R^2, RMSE y MAE. Para validar el modelo se utilizaron datos recolectados durante el último año, los cuales no se incluyeron en el entrenamiento.
Resultados: Los modelos de estimación de radiación solar global basados en NNARX presentan la mejor eficiencia en la estimación en comparación con redes neuronales convencionales. El modelo NNARX221 presenta un RMSE de 54,32 y un MAE de 18,06 W/m^2.
Conclusiones: Los modelos NNARX tienen una gran eficiencia para estimar la radiación solar global, en el mejor de los casos con un coeficiente de determinación de 0,9697. Los modelos más eficientes se caracterizan por utilizar dos instantes pasados y el instante actual de índice UV y realimentar dos instantes pasados de su propia salida de radiación estimada. Además, los resultados numéricos muestran que la contribución de la temperatura y humedad relativa no es relevante para mejorar la eficiencia de la estimación de la radiación solar global. Estos modelos pueden ser particularmente importantes dado que solamente utilizan mediciones realizadas con sensores de índice UV que son menos costosos que los sensores de radiación solar.

Palabras clave: redes neuronales recurrentes, Davis Vantage PRO 2.0, modelo de radiación solar, índice UV.

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INTRODUCTION

Solar radiation data have become important due to the increase in the use of solar energy. In general, solar radiation data are obtained from long-term monitoring stations, and they are used for photovoltaic applications or thermal heating, cooling, or drying systems.

To design an accurate photovoltaic system according to a specific zone, it is necessary to perform an irradiance study using radiation sensors such as pyranometers, pyrheliometers, or sunphotometers. However, this kind of sensors are usually expensive, especially in cases where a large number of them is necessary.

The literature has several models and studies used to detect radiation at lower costs (Cruz-Colón *et al.,* 2012). Chacón *et al.,* 2008 and Ortiz & Peng 2005 developed a low cost irradiance sensor that describes the electric behavior of a photovoltaic module using an exponential model applied to a solar cell. The maximum error between the estimated and measured irradiance was 1,11 %. Abe *et al.,* 2020 proposed a sensor based on a phototransistor. They used the arithmetic mean for the ungrouping data method (Viljoen & Merwe, 2000). The results of the simulation showed a determination coefficient (R^2) of 0,99099 with respect to the pyranometer. Mancilla-David *et al.,* 2014 introduced a solar irradiance sensor using a photovoltaic cell, a temperature detector, and a low-cost microcontroller programmed with an artificial neural network to determine the irradiance. Under ordinary operating conditions, simulation and experimental results showed that these methods can obtain an accurate estimation. However, it is difficult to collect complete data to train these soft sensors. In addition, as time passes, a solar cell will change its electrical characteristics.

Sayago *et al.,* 2011,Ruiz-Cárdenas *et al.,* 2016, and Moreno *et al.,* 2012 used neural network models capable of estimating solar radiation through meteorological variables such as temperature, relative humidity, wind speed, and rainfall. The results show determination coefficients between 0,80 and 0,86 and root mean square errors values (RMSE) between 25 % and 48 %. Khan *et al.,* 2013, Capizzi *et al.,* 2012, and Aliberti *et al.,* 2021 explored models to estimate global solar radiation based on artificial neural networks (ANN), e.g. second-generation Wavelets with ANN, Long Short-Term Memory (LSTM), Feed-Forward Neural Networks (FFNN). The results show that the best models reached a correlation coefficient of 0,98 for Wavelet and ANN. The model based on LSTM obtained an RMSE equal to 113 Wh/m^2 and a determination coefficient of 0,9744. Hernández-Mora *et al.,* 2013 developed a statistical methodology to determine solar irradiance and the ambient temperature from real measurement data, collected every hour from six in the morning to six in the afternoon. The Anderson-Darling test (Anderson & Darling, 1952, Torres, 2002) was applied to these data, thus achieving a correlation coefficient higher than 0,96 for each hour. Despite being a reliable model, it is necessary to have a database of at least five years. Obando *et al.,* 2019 presented a literature review of ANN models for solar radiation estimation. It analyses different ANN structures under several performance criteria, providing a decision methodology to evaluate ANN models for solar radiation prediction.

Korachagaon *et al.,* 2015 proposed several polynomial models to estimate global solar radiation using variables such as, ratio of duration of sunshine to maximum sunshine hours, mean temperature, and mean relative humidity. The models allow estimating radiation at any location of the earth's surface. Some results showed that the least RMSE is within 0,185, and a correlation coefficient of the measured and estimated global solar radiation was found to be 0,52494. Likewise, Eraso-Checa *et al.,* 2018 proposed a polynomial to estimate global radiation from the UV index, which is valid for Pasto, Colombia. The results showed a correlation factor of 0,9642, and the RMSE is 30,90, which is acceptable for mid-range and low-end measurement devices.

The main contribution of this paper is that it explores the relationship between the UV index and solar radiation. The responses of these variables have a similar behavior, and the spectral response curves denote similar characteristics. This work uses an ANN trained with radiation and UV index data, and it determines the radiation based on UV index measurement and time. This estimation model becomes relevant because UV sensors are cheaper than radiation sensors, and generally they occupy less space.

This paper is organized as follows: first, it presents the theoretical aspects related to the UV index and irradiance; second, the methodology is presented and described; third, all recurrent neural networks based on NNARX models are presented; and finally, the results and conclusions are presented.

METHODOLOGY

Solar radiation

The Sun is the Earth's main energy source. This star emits electromagnetic radiation of different frequency and wavelength in the electromagnetic spectrum. Solar radiation in the atmosphere has a wavelength between 150 nm and 4.000 nm, where 7 % corresponds to ultraviolet radiation, 47 % to visible radiation, and 46 % to infrared radiation (Eraso-Checa *et al.,* 2017, Würfel, 2009). However, the wavelength that reaches the Earth's surface is attenuated to a range between 380 nm and 780 nm (Narváez & Hernández, 2013) due to absorption, reflection, and scattering phenomena. This also means that the global radiation on the surface is composed of beam, diffuse, and reflected radiation (Jäguer *et al.,* 2014). Another parameter that attenuates solar radiation is the optical air mass, which is the path length that sunlight follows through the atmosphere (Jäguer *et al.,* 2014).

Figure **1** shows the power received per unit surface exposed to radiation for each wavelength at the outer side of the Earth's atmosphere. It shows that the visible part of the spectrum has the large area between 400 nm and 700 nm, with a spectral irradiance peak around 2.000 W/m^2.nm. Ultraviolet (UV) light occupies the high energetic part of the spectrum.

The integration of spectral irradiance over wavelength corresponds to the irradiance, which is a power per unit area (W/m^2 or joules/m^{2}sec). This is a magnitude scale that includes the complete wavelength information. Radiation measuring equipment gives the solar radiation response as irradiance (W/m^2).

UV index

UV radiation is just a part of the solar spectrum at high frequencies (>10^{16} Hz). This means that it is very energetic and can ionize atoms by electrically charging them (Casal, 2010). Photon energy ranges from 3,2 eV up to 1,2x10^3 eV (Bohorquez-Ballén & Pérez-Mogollón, 2007). UV radiation allows human beings to assimilate vitamin D and, in plants, it makes photosynthesis possible. However, it also has negative effects if there is prolonged exposure, especially in human health (it breaks biological molecules, damages the eyes and skin, it causes cancer, etc.) (Bohorquez-Ballén & Pérez-Mogollón, 2007).

UV radiation is divided into three regions (Ryer, 1988):

- *UV-A: (315-400 nm):* It is the least harmful to human beings, and its intensity reaches the terrestrial surface.
- *UV-B (280-315 nm):* It is toxic to life and can destroy it. Ozone absorbs this energy (approximately 90 %) and prevents it from reaching the Earth (Casal, 2010).
- *UV-C (100-280 nm):* Its collision with oxygen atoms causes ozone generation, and it does not reach the Earth. This radiation would destroy life.

According to Lucas *et al.,* 2006, ambient UV radiation can be measured using a representation of the wavelength variation in the production of skin erythema. The UV index is an instance of this representation (the other are SED and MED). It is defined as the time-weighted average effective UV irradiance multiplied by 40, and it is expressed as power per unit area (W/m^2).

Figure **2** shows the behavior of both spectral irradiance and the erythemal action spectrum in the UV region.

The UV index is categorized as shown in Table 1, and the values range from 0 on. The higher the index value, the greater potential damage to the skin in the less time.

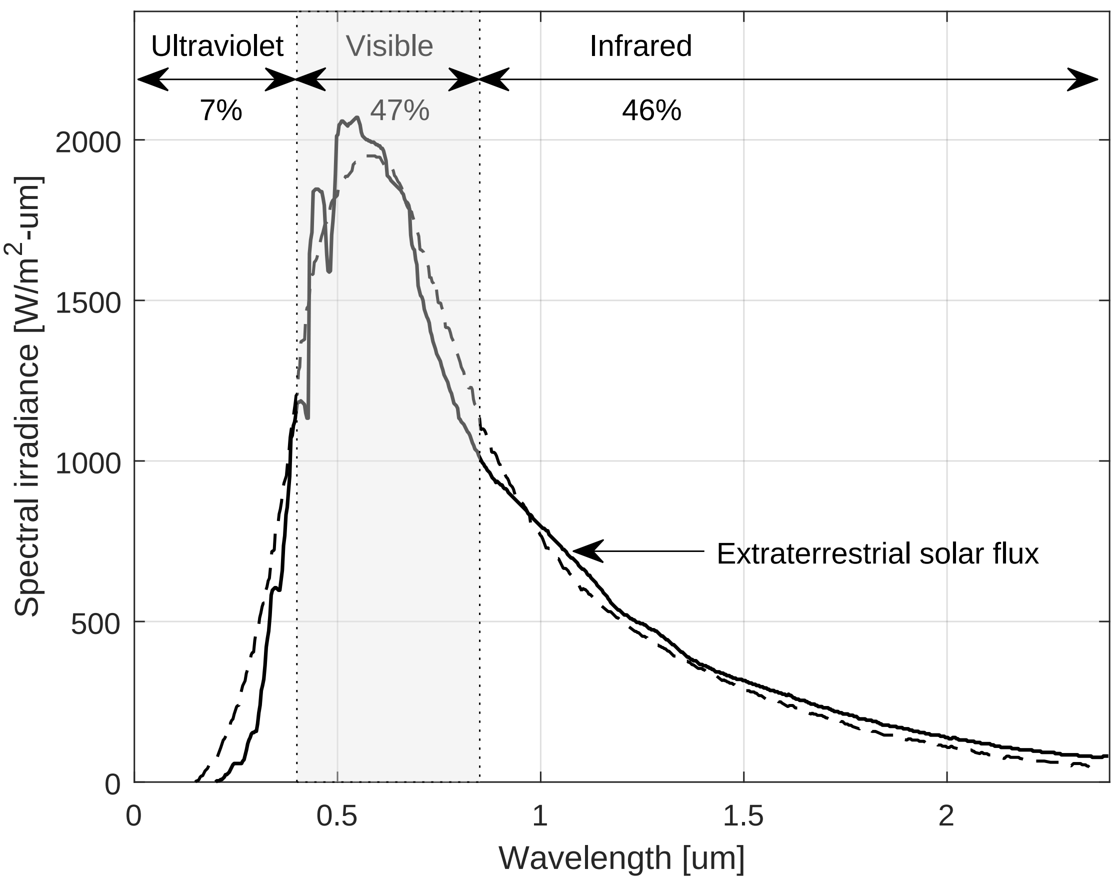

Figure 1. Extra-terrestrial solar spectrum

Source: (Würfel, 2009).

Methodological process

To develop and validate the estimation model, a methodological process was carried out, which was adapted from Eraso-Checa *et al.,* 2018. In this case, the methodology used is composed of a typical process that increases estimation reliability. In Figure 3, the methodological process is shown.

A set of climatic variables (UV index, temperature, humidity, and solar radiation) was extracted from the Davis Vantage PRO station. In this case, the dataset is made up of approximately 305.000 data for each variable from 2013 to 2018. Since the first data are raw, it was necessary to remove spurious and erroneous data using an inspection algorithm. This process removes not-a-number data, data equal to infinity, and unusual data such as out-of-range values that are physically impossible to reach. Finally, a training dataset of 213.019 data and a validation dataset of 91.696 were obtained.

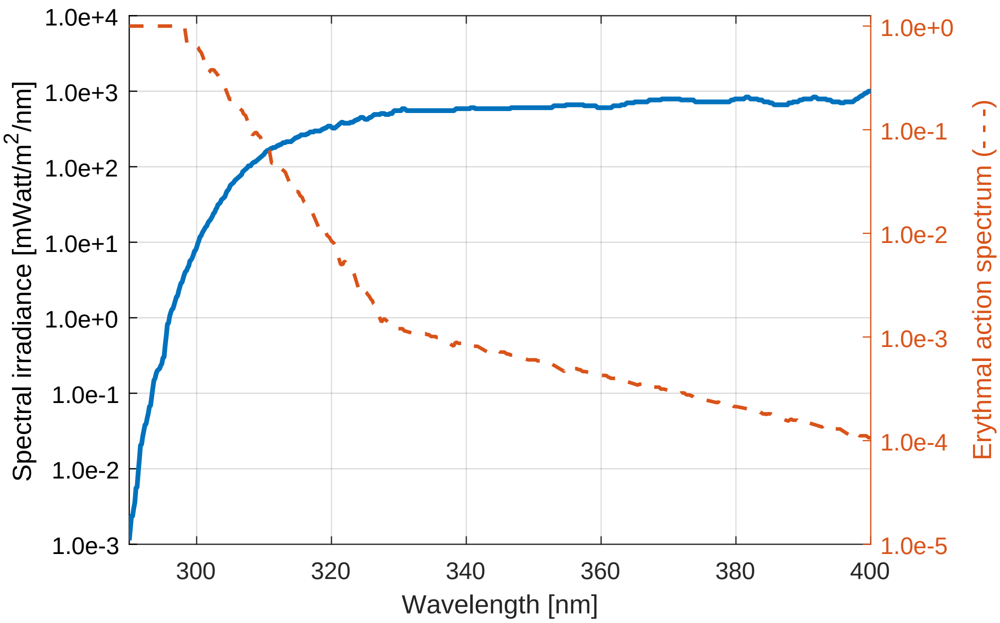

Figure 2. UV spectral irradiance and erythemal action spectrum

Source: National Services Centre (n.d.).

Table 1. UV index categorization

UV Index	Danger Category
0-2	Low
3-5	Moderate
6-7	High
8-10	Very High
11+	Extreme

Source: National Services Centre (n.d.).

After that, solar radiation was estimated with following steps: first, the estimation model based on neural networks (NN) was defined, considering estimation structures and inputs; secondly, the structure was trained using the dataset; then, there was an evaluation process using the validation dataset, which calculated some predefined metrics such as mean absolute error (MAE), root mean square error (RMSE), and the coefficient of determination (R^2).

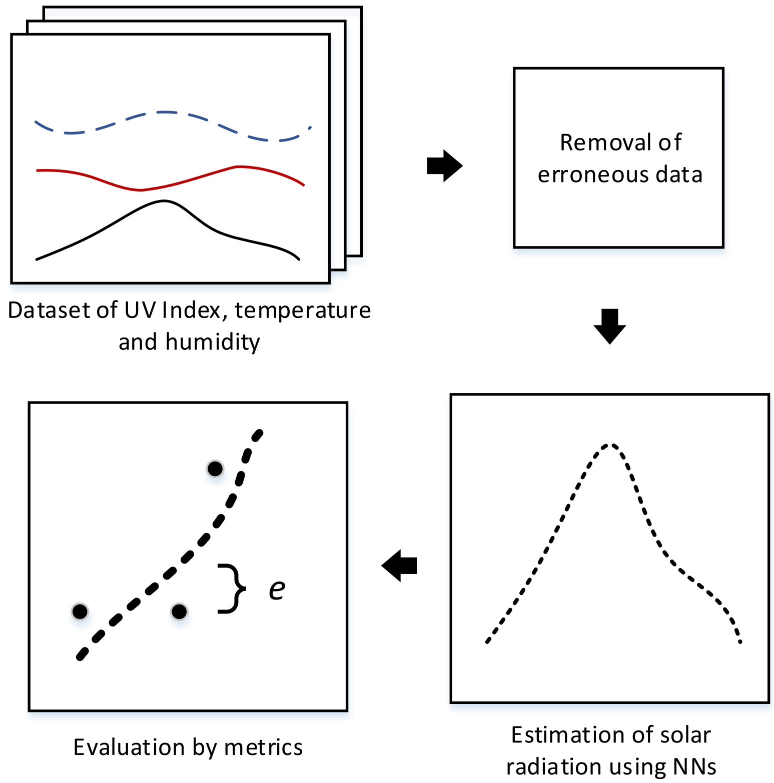

Figure 3. Methodological process

Source: Authors.

Estimation models based on ANNs

Different nonlinear models based on ANNs were used to estimate solar radiation. Mainly, two different ANN structures were used to model the estimators: Neural Network Finite Impulse Response (NNFIR) structure and Neural Network Autoregressive with Exogenous Input (NNARX).

NNFIR is a simple model estimator fed with external excitations to make a prediction. Figure 4 shows, on the left side, a NNFIR that does not have feedback. NNARX is a recurrent neural network. On the right side of Figure 4, the network uses external excitations and past instants to make a prediction.

As shown in Figure 4, the NNFIR and NNARX models are fed with past instants of one or more inputs $\left(u_1(\cdot), \ldots, u_j(\cdot)\right)$, and past instants of the estimated output $\left(\hat{y}(\cdot)\right)$ in case of the NNARX structure. For more details on NNARX and NNFIR structures, see their description in the referenced literature (Norgaard *et al.*, 2000).

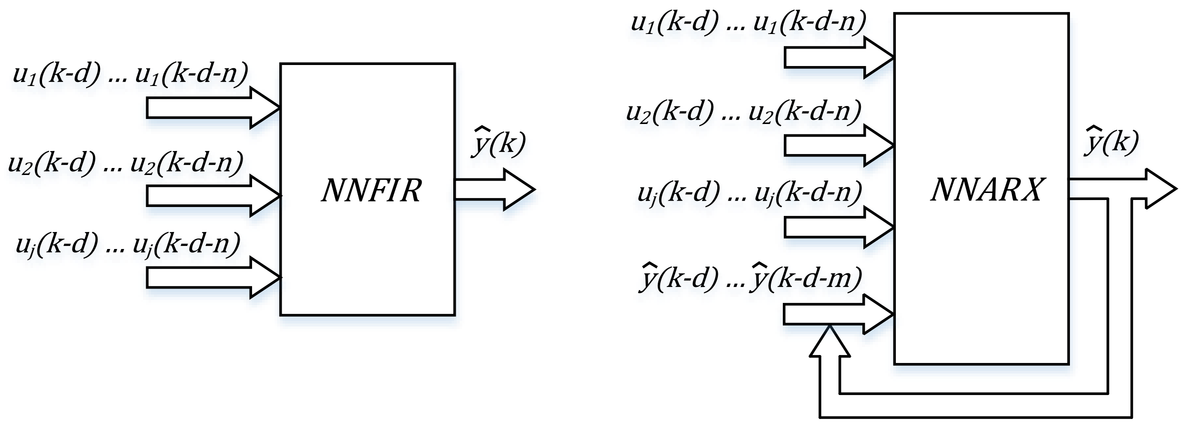

Figure 4. NNFIR and NNARX structures

Source: Authors.

In addition, this paper proposes to use the temperature as part of the estimator, aiming to compensate the lack of information of the reduced band in the UV index sensor. In that way, it is possible to quantify the contribution of the temperature in the estimation of solar radiation. To differentiate the models, models that use UV index and/or estimated radiation are denoted with a at the end, and the estimation models that use temperature in addition to the UV index and/or estimated radiation are denoted with b at the end. The definitions of these models are shown below, and they are summarized in Table 2.

Table 2. Mathematical definition of the NNFIR and NNARX models

Model	Mathematical definition
NNFIRa	R(k)=f(UV(k))
NNFIRb	R(k)=f(UV(k),T(k))
NNARX111a	R(k)=f(R(k-1), UV(k), UV(k-1))
NNARX111b	R(k)=f(R(k-1), UV(k), UV(k-1), T(k), T(k-1))
NNARX211a	R(k)=f(R(k-1), R(k-2), UV(k), UV(k-1))
NNARX211b	R(k)=f(R(k-1), R(k-2), UV(k), UV(k-1), T(k), T(k-1))
NNARX221a	R(k)=f(R(k-1), R(k-2), UV(k), UV(k-1), UV(k-2))
NNARX221b	R(k)=f(R(k-1), R(k-2), UV(k), UV(k-1), UV(k-2), T(k), T(k-1), T(k-2))

Source: Authors.

$R(\cdot)$ is the global solar radiation, $UV(\cdot)$ is the UV index, $T(\cdot)$ is the ambient temperature, and k is the time instant. NNFIR and NNARX structures are configured as follows: one hidden layer with 20 neurons, sigmoidal activation function, and Bayesian Regularization as the training algorithm.

RESULTS

In this section, the first part describes the station that collected the raw data. The second one describes the training and validation processes, and then the estimation results are presented by figures and tables with the evaluation metrics.

Meteorological station and data set

Solar radiation, the UV index, temperature, and humidity data were collected from November 2013 to December 2018 using the DAVIS Vantage Pro 2.0 meteorological station. This equipment uses the 6450 solar radiation sensor (Davis Instruments, 2014a) and the 6490 UV sensor that measures the global solar UV index (Davis Instruments, 2014b).

After applying the methodological process to 305.172 data, a training dataset of 213.019 elements and a validation set of 91.696 data for each variable (30 % of total data) were obtained. There were 457 spurious and erroneous data, as shown in Figure 5.

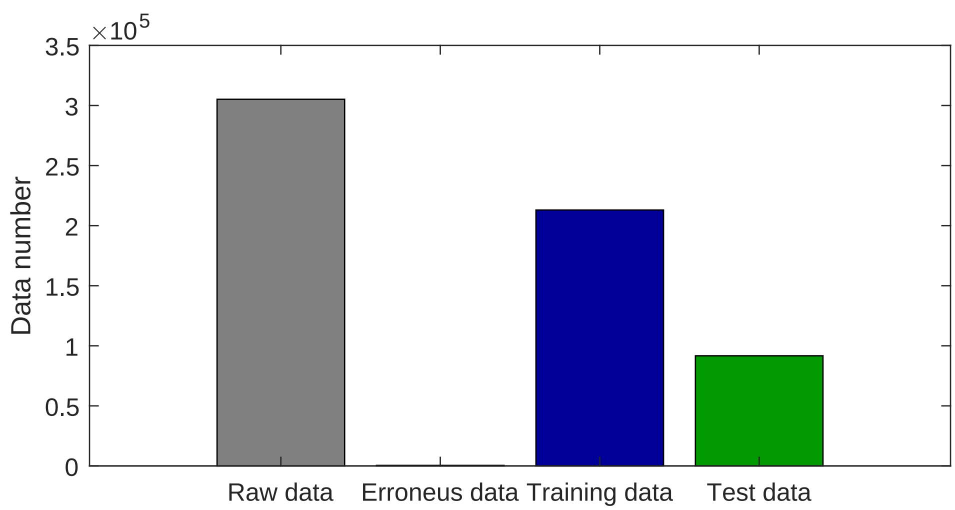

Figure 5. Use of data in the solar radiation estimation process

Source: Authors.

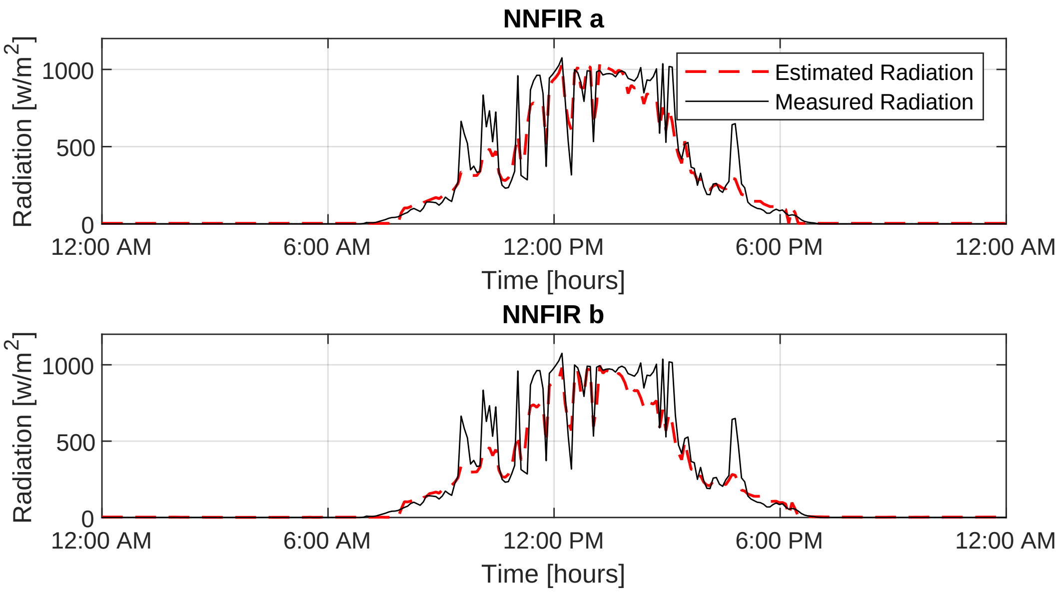

Figure 6. Solar radiation estimation using NNFIR1 and NNFIR2 structures

Source: Authors.

Numerical results

The NN MATLAB toolbox was used to train the eight proposed estimation models. Each model was trained using its corresponding dataset (inputs, outputs, and validation dataset).

The following Figures show the solar radiation estimation results using a random day from the validation data set.

As shown in Figure 6, the radiation estimation with the NNFIRa and NNFIRb structures was able to follow the general behavior of the measured radiation. However, the error increases due to instant radiation changes. These models have an estimation error of ±38.80 $\frac{W}{m^2}$ and ±42.71 $\frac{W}{m^2}$ respectively.

The NNARX111a and NNARX111b structures improve the estimation of solar radiation reducing the error to ±26.60 $\frac{W}{m^2}$ and ±28.61$\frac{W}{m^2}$, respectively (Figure 7). This optimization occurs because these structures make a prediction using past and present data. Therefore, they have a measurement radiation rate that is used to predict the next radiation value.

Figures 8 and 9 show the NNARX211a, NNARX211b, NNARX221a, and NNARX221b structures. These kind of structures reduce the error between ±26.27 $\frac{W}{m^2}$ and ±24.53 $\frac{W}{m^2}$. This is posssible because the network makes a prediction from two past instants. In the same way, predictions with structures that include more than two past instants were developed. Nevertheless, the error does not reduce its value significantly.

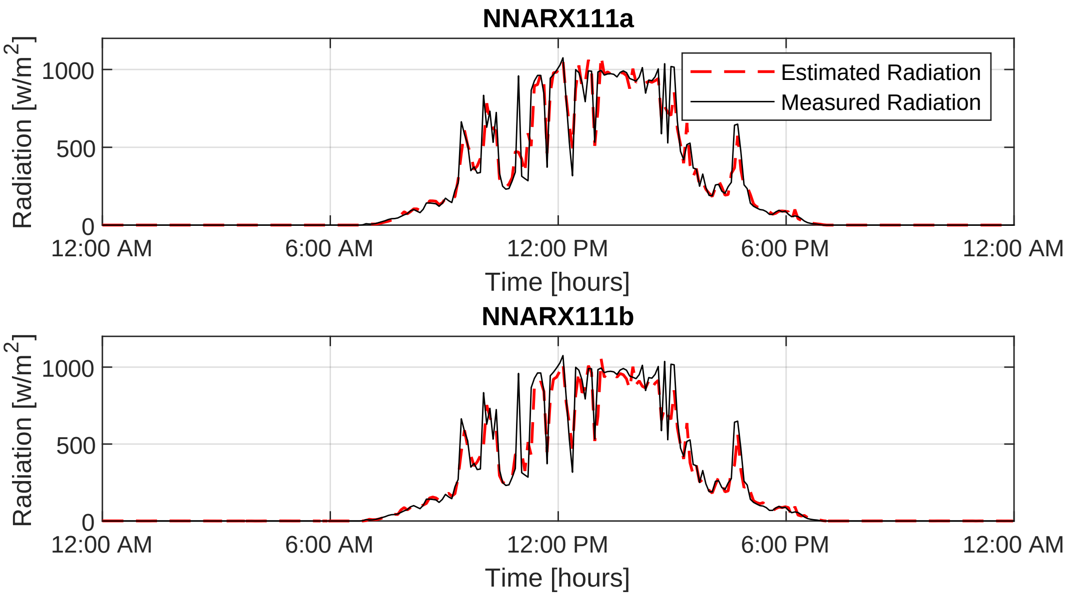

Figure 7. Solar radiation estimation using NNARX111a and NNARX111b structures

Source: Authors.

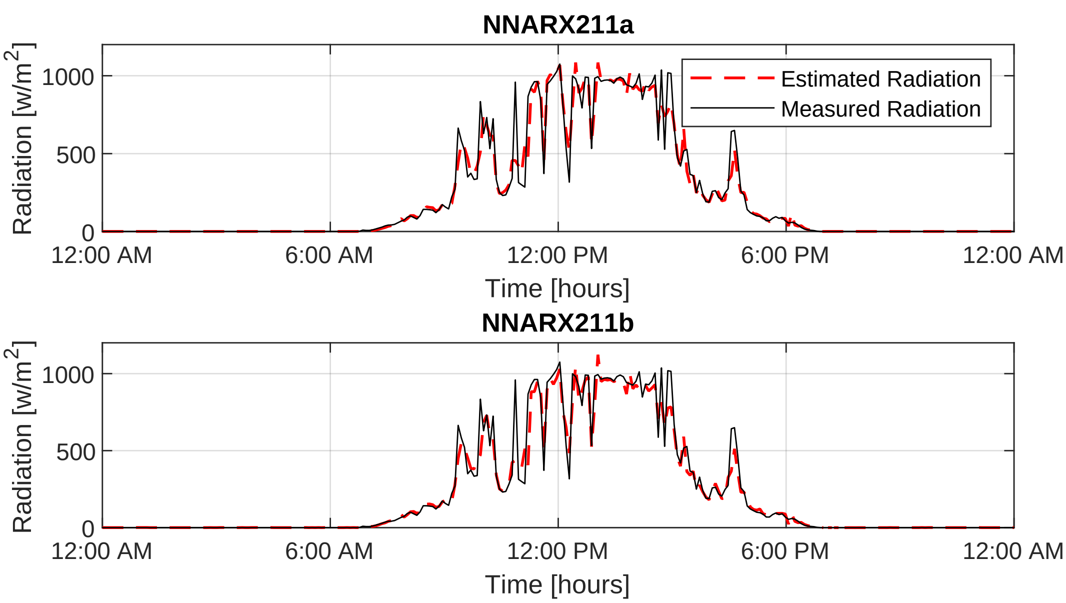

Figure 8. Solar radiation estimation using NNARX211a and NNARX211b structures

Source: Authors.

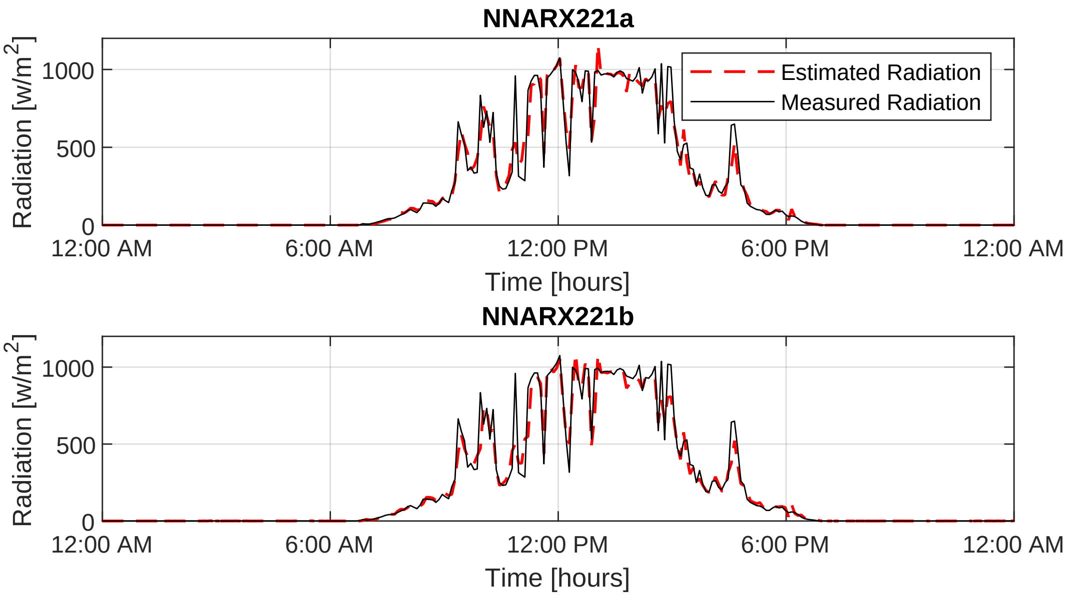

Figure 9. Solar radiation estimation using NNARX221a and NNARX221b structures

Source: Authors.

From Figures 7-9, it can be noticed that the differences between type a and b models are not significant. Despite this, type b models use other variables (temperature, humidity) to complement the estimation in contrast with type a models, which only use the input variable and the past instants. These additional variables do not significantly reduce the error. In contrast, the error increases in some cases.

According to the numerical results presented in Table 3, considering the validation data set (91.696 elements), type a models have a similar behavior to type b ones. Type b models have a smaller RMSE and a bigger R^2 coeficient in comparison with type a models. In contrast, type a models have a smaller MAE than type b models. However, the differences between models a and b are not significant.

Also, NNARX221a and NNARX221b have the best performance in terms of RMSE, MAE, and R^2 compared to other estimation models.

As seen in the Figure 10 and Table 3, the differences between estimation structures NNARX221a and NNARX221b are not significant. Hence, the contribution of the auxiliary variables (temperature and humidity) in the estimation of solar radiation is not relevant. In this sense, the NNARX221a model has the best performance (based on R^2) only using past and present instants of solar radiation and the UV index.

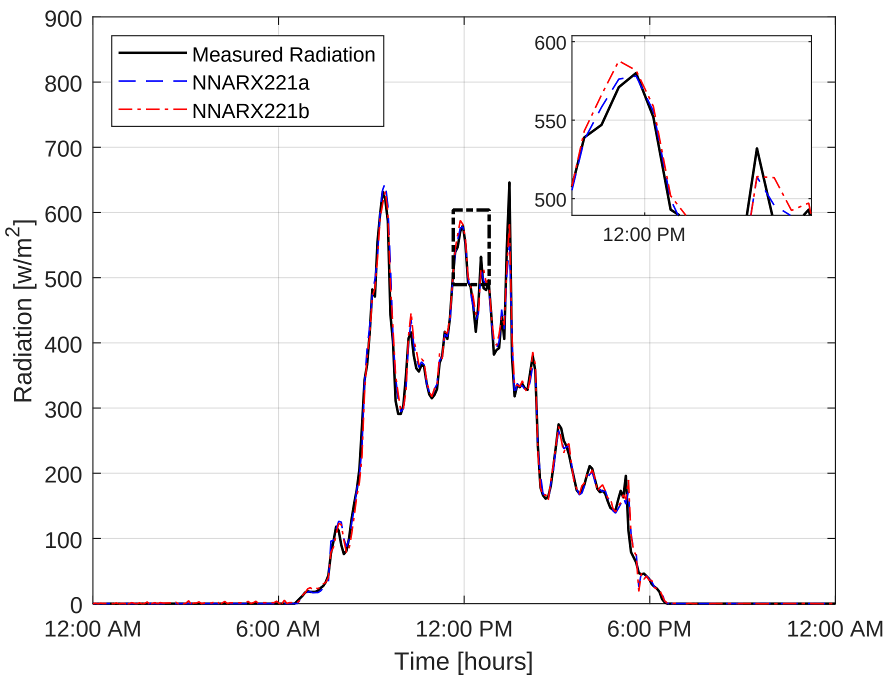

Figure 10. Comparison between estimation structures NNARX221a and NNARX221b for a random day

Source: Authors.

Table 3. Numerical results of estimation models for the validation dataset

Structure/Metric	RMSE	MAE	R^2
NNFIRa	87,855	42,526	0,92294
NNFIRb	86,863	41,301	0,92489
NNARX111a	55,835	18,624	0,96805
NNARX111b	55,532	18,643	0,96838
NNARX211a	55,066	18,314	0,96895
NNARX211b	54,809	18,347	0,96925
NNARX221a	54,710	17,905	0,96927
NNARX221b	54,321	18,069	0,96971

Source: Authors.

CONCLUSIONS

This similarity in graphical patterns between the UV index information recorded with the 6490 Davis sensor and the solar radiation data recorded with the 6450 Davis sensor allow estimating solar radiation based on UV index. For this process, there were two NNFIR and eight NNARX-trained structures. The best performance corresponds to a NNARX221 structure that makes a prediction using two past instants that include the UV index and its own outputs. It shows a determination coefficient of 0,9697, a RMSE equal to 54,32, and a MAE of 18,06 W/m^2. Because of that, the use of this structure allows the determination of solar radiation in an accurate way using the UV index.

The numerical results show that the contribution of the auxiliary variables (temperature and humidity) in the estimation of solar radiation is not relevant. The best estimations are made only using past and present instants of solar radiation and the UV index. This is particularly important since UV index measurement equipment usually has a lower cost than global radiation ones.

For future work, it could be interesting to test other prediction techniques based on artificial intelligence, such as random forests, decision trees, and short-term memories, among others. This methodology and models can be generalized to be used with other variables or time series.

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INVESTIGACIÓN

Review of Charging Load Modeling Strategies for Electric Vehicles: a Comparison of Grid-to-Vehicle Probabilistic Approaches

Revisión de estrategias de modelado de la demanda de carga para vehículos eléctricos: una comparación de enfoques *grid-to-vehicle* probabilísticos

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Abstract

Objective: In this paper, different approaches to how the penetration of electric vehicles (EV) can be modeled in power networks are reviewed. The performance of three probabilistic electric vehicle charging load approaches considering four levels of penetration of EV is also evaluated and compared.

Methodology: A detailed search of the state-of-the-art in charging load modeling strategies for electric vehicles is carried out, where the most representative works on this subject were compiled. A probabilistic model based on Monte Carlo Simulation is proposed, and two more methods are implemented. These models consider the departure time of electric vehicles, the arrival time, and the plug-in time, which were conceived as random variables.

Results: Histograms of the demand for charging of electric vehicles were obtained for the three models contemplated. Additionally, a similarity metric was calculated to determine the distribution that best fits the data of each model. The above was done considering 20, 200, 2.000, and 20.000 electric vehicles on average. The results show that, if there is a low penetration of electric vehicles, it is possible to model the EV charging demand using a gamma distribution. Otherwise, it is recommended to use a Gaussian or lognormal distribution if there is a high EV penetration.

Conclusions: A review of the state of the art of the modeling of electric vehicles under a G2V approach is presented, where three groups are identified: deterministic approaches, methods that deal with uncertainty and variability, and data-driven

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methods. Additionally, it was observed that EVCP model 3 and gamma distribution could be appropriate for modeling the penetration of electric vehicles in probabilistic load flow analysis or for stochastic planning studies for active distribution networks.
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Keywords: electric vehicle charging demand, Monte Carlo simulation, probabilistic modeling

Resumen

Objetivo: En este artículo se revisan diferentes enfoques sobre cómo modelar la penetración de los vehículos eléctricos (EV) en los sistemas eléctricos de potencia. También se evalúa y compara experimentalmente el desempeño de tres enfoques probabilísticos de demanda de carga de vehículos eléctrico considerando cuatro niveles de penetración de EV.
Metodología: Se realiza una búsqueda detallada del estado del arte de estrategias de modelado de carga de carga para vehículos eléctricos, donde se recopilaron los trabajos más representativos sobre este tema. Se propone un modelo probabilístico basado en la simulación de Monte Carlo y se implementan dos métodos más. Estos modelos tienen en cuenta la hora de salida de los vehículos eléctricos, la hora de llegada y la hora que se conectan a la red, las cuales fueron concebidas como variables aleatorias.
Resultados: Se obtuvieron histogramas de la demanda de carga de los vehículos eléctricos para los tres modelos contemplados. Adicionalmente, se calculó una métrica de similitud para conocer la distribución que mejor se ajusta a los datos de cada modelo. Lo anterior se realizó considerando 20, 200, 2.000 y 20.000 vehículos eléctricos en promedio. Si se tiene una baja penetración de vehículos eléctricos, es posible modelar la demanda de estos usando una distribución gamma. De lo contrario, se recomienda usar una distribución Gaussiana o lognormal si se tiene una alta penetración de EV.
Conclusiones: Se presenta una revisión del estado del arte en el modelado de vehículos eléctricos bajo un enfoque G2V, donde se identificaron tres grupos: los enfoques deterministas, los métodos que tratan la incertidumbre y la variabilidad y los métodos basados en datos. Adicionalmente, se observó que el modelo EVCP 3 y la distribución gamma pueden ser apropiados para modelar la penetración de vehículos eléctricos en análisis de flujo de carga probabilístico o para estudios de planeamiento estocástico en redes de distribución activas.
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Palabras clave: demanda de carga de vehículos eléctricos, simulación de Monte Carlo, modelado probabilístico

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INTRODUCTION

Due to the current debate around global warming, many countries have created numerous strategies to combat this issue. One of these strategies is the inclusion or penetration of electric vehicles (EVs) to the power grid (Alahyari *et al.,* 2019). Nevertheless, the inclusion of this technology to the power grid is not only to fight against global warming; this penetration can also achieve an efficient operation of the power grid (Alahyari *et al.,* 2019). All of this brings benefits to combat the aforementioned issue. However, this technology introduces new challenges that must be addressed. For example, with the penetration of EVs, it is not only evident that there is an increased electricity consumption in the power grid, along with the introduction of new load variations, but impacts have also been identified on transportation, manufacturing, and the economy (Li *et al.,* 2019). These impacts depend on when EVs are connected for charging, where they are connected, and at which charging power (Grahn *et al.,* 2011). Therefore, these factors must be considered in the operation, planning, and analysis of modern power grids such as active distribution networks or grid-connected microgrids (Alahyari *et al.,* 2019). The penetration of EVs in studies on power network analysis has been widely addressed (Alahyari *et al.,* 2019, Li *et al.,* 2019, Kongjeen *et al.,* 2019), and it can be supported by following several charging opportunities:
unidirectional charging, bidirectional charging, uncontrolled charging, external charging strategies, and individual charging strategies (Grahn *et al.,* 2011). Uncontrolled charging (UCC) means that EV users travel and park as they choose and connect their EVs when there is a need to recharge the battery. External charging strategies imply that the charging may somehow be controlled externally, based on the information of the power grid. Finally, individual charging strategies indicate that the individual can be seen within an UCC approach, but also that individuals may adjust their charging behavior based on economic incentives. For example, in the literature, it is commonly assumed that the penetration of EVs is modeled as a UCC unidirectional charging approach, which only considers the power flow in the grid-to-vehicle (G2V) direction. External charging strategies could be based

on either unidirectional or bidirectional charging, which can consider a power flow in the vehicle-to-grid (V2G) direction. From the literature, one comes across reviews that organize their analysis about of EV charging technologies, EVs standards, charging infrastructure, or the impacts on power grid integration. However, there are few studies that focus on analyzing the different methodologies that have emerged using the G2V philosophy. In this article, we review different G2V approaches. Additionally, we perform an experimental comparison with three probabilistic models and evaluate their performance considering four levels of EV penetration.

EV CHARGING LOAD MODELING

Several approaches for modeling EV load have been proposed in the past. According to Yi & Scoffield, 2018, we can find, for example, deterministic EV load modeling techniques (Kongjeen *et al.*, 2019), Monte Carlo simulation approaches (MCS) (Li & Zhang, 2012), fuzzy methods (Shahidinejad *et al.*, 2012), hybrid Fuzzy-MCS methods (Ahmadian *et al.*, 2017) and many other techniques (Stiasny *et al.*, 2021,Frendo *et al.*, 2020) to model the EV load. In this paper, we intend to classify these methods into three groups: deterministic, data-driven, and uncertainty/variability approaches.

Deterministic approaches

In deterministic EV load modeling, several methods assume that EV parameters are known (Yi & Scoffield, 2018). For example, the available period, the arrival or departure times of vehicles, and the travelling distance are already known or fixed by the power grid operator, that is, EVs can be seen as stationary energy storage (Yi & Scoffield, 2018). On the other hand, it is possible to find studies that have used measurement-based load modeling approaches to estimate the load model for electric vehicle fast-charging stations (Gil-Aguirre *et al.*, 2019). Basically, the authors estimate the parameters of the ZIP or polynomial load models, minimizing the discrepancy between the real measurement load and the simulated load responses (Gil-Aguirre *et al.*, 2019). Kongjeen *et al.*, 2019 implemented a modified backward and forward sweep method for analyzing the impact levels from EV load models on the grid based on constant current load and voltage-dependent loads. These deterministic EV load modeling approaches are also known as traditional methods.

Data-driven approaches

Due to the large amount of real-time driving data, by using these deterministic models, it is difficult to accurately capture the driving patterns (Li *et al.*, 2019). These patterns show the usage behaviors of drivers and directly affect the energy consumption of EVs. Data-driven models are constructed from large historical data to model the underlying realistic EV charging behaviors. Based on these data-driven models, residential EV charging load profiles can be generated with regard to different numbers of households and charging rates. According to Li *et al.,* 2019, these methods should be scalable and flexible frameworks.

Some data-driven methods have been proposed to describe EV charging patterns and analyze EV driving data. For example, data mining methods such as clustering (Yi & Scoffield, 2018,Li *et al.,* 2019), correlation analysis (Xydas *et al.,* 2016), stochastic prediction (Ashtari *et al.,* 2012), and time-series clustering (Zhou *et al.,* 2017) are commonly employed to examine EV driving data. Specifically, Zhou *et al.,* 2017 developed a time-series clustering with variable weights to analyze the driving cycle of hybrid-electric vehicles. On the other hand, Yi & Scoffield, 2018 used historical residential charging behavior data to construct probability density functions for modeling the charging duration; and then they employed clustering based on the k-nearest neighbors (KNN) algorithm for charging decision-making. (Li *et al.,* 2019) proposed a two-level clustering model to determine the driving patterns of EVs. They identified five daily driving patterns and four multifaceted driving patterns that affect the daily load curve. However, the authors considered vehicle static parking patterns and did not take weather conditions into account. Crozier *et al.,* 2019 introduced a probabilistic model based on K-means clustering for UCC of EVs to identify three distinct vehicle usage modes in the United Kingdom. However, the cluster number was included as a model parameter. To summarize, data-driven methods have a great potential for nonlinear system prediction, and the EV charging load can be computed considering different numbers of households and charging rates (Yi & Scoffield, 2018). However, these data-driven approaches have a weak performance against real-time driving data in low dimension. Although many studies mention differences between data-driven and machine learning techniques, we consider that both can be included into data-based approaches. We have found several approaches that use machine learning theory or concepts to model the EV load, charging behaviors, or driving patterns (Gerossier *et al.,* 2019,Godde *et al.,* 2015,Stiasny *et al.,* 2021). Specifically, Gerossier *et al.,* 2019 modeled the consumption profile of EVs from raw power measurements. From these measurements, the authors detected five kinds of plugs and EV batteries in order to determine the power drawn from the grid and the battery capacity using the random forest algorithm. On the other hand, Godde *et al.,* 2015 proposed an approach for modeling the charging probability of electric vehicles as a Gaussian mixture model (GMM). This GMM comprehensively captures the charging profiles, assuming underlying assumptions about battery capacity, consumption, charging infrastructure, week day, and settlement structure. Stiasny *et al.,* 2021 also used a GMM to distinguish seven aspects with respect to EV load modeling that influence the variables as flows and voltages in the grid. Frendo *et al.,* 2020 proposed a data-driven regression model for predicting the EV charging demand from a large historical dataset of charging processes. (Arias& Bae, 2017) presented a forecasting model to estimate the EV charging demand using big data technologies. Specifically, the authors performed a cluster analysis to classify traffic patterns, a relational analysis to identify influential factors affecting the traffic patterns, and a decision tree to establish classification criteria, which determines the charging speed and power of an EV.

Uncertainty/variability approaches

After having discussed several deterministic, data-driven, and machine learning approaches, we would like to present the probabilistic, possibilistic, and stochastic methods that have been used to model the EV charging demand. We have decided to name them uncertainty/variability approaches due to the fact that these techniques deal with these two properties (uncertainty and variability) in the EV charging demand modeling process. In many research areas, these two fields are confused about their meaning and use.

In probabilistic methods, it is possible to find many studies that have used individual probabilistic distribution to model the EV charging demand. For example, these studies have employed Gaussian (Sun *et al.,* 2015), Weibull (Li & Zhang, 2012), lognormal (Khoo *et al.,* 2014), exponential distributions (Khoo *et al.,* 2014), mixed probability distributions (i.e, a mixture of Gaussian distributions) (Flammini *et al.,* 2019), or non-parametric methods (Chung *et al.,* 2018, Chen *et al.,* 2020) to determine the EV charging demand. However, the most common and used technique is Monte Carlo Simulation (MCS), which is conducted for a large number of samples generated using the probability density functions from several input variables (Li & Zhang, 2012, Su *et al.,* 2019). These input variables can be home arrival/departure time, daily travelling distance/EV initial battery SoC, EV type, EV battery capacity, or EV recharge probability (Su *et al.,* 2019). Many MCS applications can be found in the literature. For example, Grahn *et al.,* 2011 analyzed the impact caused by the EV charging demand based on uncontrolled and controlled charging scenarios on the distribution transformer hot-spot temperature and loss of life by using a thermal model. Similarly, Tekdemir *et al.,* 2017 also evaluated the effects of EVs on distribution grids. The authors used the MCS and Weibull probability distribution to model the EV charging demand, and they also assumed correlated loads on the grid. Under different conditions, Ul-Haq *et al.,* 2018 employed MCS to develop an EV charging pattern model that considers the vehicle class, battery capacity, SoC, driving habit/need, plug-in time, mileage, recharging frequency per day, charging power rate, and dynamic EV charging price. In Ahmadian *et al.,* 2015, a probabilistic approach is proposed to model the EV load demand considering home arrival time, home departure time, deriving distance, nonlinear characteristics of the battery charge, and different vehicle types. The authors used historical information from the National Household Travel Survey to obtain the probability distributions. On the other hand, in possibilistic approaches, we can find that authors such as Tan & Wang, 2014 have proposed a load profile for EVs, which considers the arrival time, departure time, daily distance travelled, and vehicle parameters in order to obtain a stochastic model of driving patterns based on fuzzy logic theory. Hussain *et al.,* 2019 introduced a fuzzy inference mechanism to determine an appropriate charging, discharging, or withholding decision for EVs. This scheme also considers the available power from the smart grid, arrival time, departure time, SoC, and the required stay time of EVs. Ali *et al.* (2017) proposed a hybrid fuzzy-MCS method where the parameters are modeled according to either probabilistic or possibilistic approaches. For example, the travelling distance is modeled using a fuzzy triangular membership function, while the

Table 1. EV charging load modeling summary

Approach	Method		Advantage	Disadvantage
Deterministic	Voltage-Dependent model (Kongjeen *et al.*, 2019)		Low computational time.	Uncertainty and driving patterns are not considered.
	ZIP models (Gil-Aguirre *et al.*, 2019)			
Uncertainty/Variability	Probabilistic	Gaussian (Sun *et al.*, 2015), Weibull (Li & Zhang, 2012), and lognormal (Khoo *et al.*, 2014) distributions	Uncertainty is appropriately modeled.	They require computational effort, experience, and many input data samples to determine the demand for EVs.
		Beta (Flammini *et al.*, 2019) and Gaussian (Stiasny *et al.*, 2021) mixture models		
		A non-parametric kernel density estimation method (Chen *et al.*, 2020)		
	Stochastic	Markov chain (Sokorai *et al.*, 2018) and		
		ARIMA (Amini *et al.*, 2016) and Poisson (Jiang *et al.*, 2017) processes		
		Queue theory (García-Valle & Vlachogiannis, 2009)		
	Possibilistic	Fuzzy logic method (Shahidinejad *et al.*, 2012)		
		Fuzzy logic method with MCS (Ahmadian *et al.*, 2017)		
Data-driven	K-nearest neighbors (Li *et al.*, 2019)		They concentrate many of patterns associated with the dynamics of the EVs.	They need large amounts of data to generalize the behavior of the demand for EVs.
	Linear regression (Frendo *et al.*, 2020)			
	Random forest (Gerossier *et al.*, 2019)			

Source: Authors.

arrival and departure times are modeled by Weibull probability distributions using MCS.

Finally, in uncertainty and variability approaches, different stochastic methods have been applied to model the EV charging demand. In these stochastic methods, we found approaches such as autoregressive integrated moving average (ARIMA) processes (Amini *et al.*, 2016), Markov chains (Sokorai *et al.*, 2018), Poisson processes (Jiang *et al.*, 2017), and queue theory-based Poisson processes (García-Valle & Vlachogiannis, 2009). A summary of these approaches can be seen in Table 1.

Electric vehicle charging probabilistic (EVCP) modeling

In cases where the output variables are requested and the system is complex and includes uncertainty, probabilistic models of the system are advantageous to use in order to determine the behavior of some random variables. In our context, probabilistic modeling can be defined as a way of modeling a phenomenon that uses presumed probability distributions of certain input assumptions or variables to compute the involved probability distribution for chosen output variables (Pergler & Freeman, 2010). One way to achieve this probabilistic modeling is using MCS, which is the most commonly used technique for probabilistic modeling. This section presents three MCS-based EVCP models.

EVCP model 1

For model 1, we have considered the model presented by Su *et al.,* 2019, where the authors assumed that the daily travel distance d and the plug-in time t_p of an EV are Gaussian and lognormal random variables. The authors also assumed that the state of charge SOC_{ij} after a daily travel distance (D), can be computed from Equation (1) using the efficiency of battery power in driving cycles in EVs (η), as follows:

$$SOC_{ij} = 1 - \frac{d}{D\eta} \tag{1}$$

For each EV, the authors calculated the charging duration (t_d) to compute the total EV power using Equation (2), which is given by

$$P_{EV} = \sum_{i=1}^{5}\sum_{j=1}^{N} P_{EV_{ij}} \tag{2}$$

where,

$$P_{EV_{ij}} = \begin{cases} P_c & t_p \leq t \leq t_d \\ 0 & \text{other time} \end{cases} \tag{3}$$

where P_c in Equation (3) is the rated charging power, j is the MCS iteration, and i represents the i-th EV in the specific predefined EV fleet, that is, where $i = \{1, 2, 3, 4, 5\}$, which represents private EVs, utility EVs, commercial EVs (taxies), electric goods trucks, and electric buses, respectively.

EVCP model 2

For model 2, we propose an EVCP model that depends on the leaving time from home t_l, the time that the EV user is away from home t_a, and the charging efficiency η of EVs as random variables to compute the energy consumption of EVs. t_l and t_a are modeled by Gaussian distributions, and η is modeled as a uniform distribution. We also consider the five types of EVs, similarly to EVCP model 1. For our model, we approximate the minimum charging duration time t_{mcd} as a function of the initial SOC:

$$t^j_{mcd} = \frac{(\eta - SOC_{ij})C_{ap}}{P_c} \tag{4}$$

where C_{ap} is the battery capacity, and the connecting time t_c and the fully charging time t_{fc} are computed as

$$\begin{aligned} t_c^j &= t_l^j + t_l^j \\ t_{fc}^j &= t_c^j + t_{mcd}^j \end{aligned} \tag{5}$$

From the expressions shown in Equations (4) and (5), the total EV power is calculated from Equations (6) and (7), that is,

$$P_{EV} = \sum_{i=1}^{5} \sum_{j=1}^{N} P_{EV_{ij}} \tag{6}$$

where

$$P_{EV_{ij}} = \begin{cases} P_c & t_p \leq t_{fc}^j \leq t_d \\ 0 & \text{other time} \end{cases} \tag{7}$$

EVCP model 3

The third model was presented by Ahmadian *et al.*, 2015, which we have modified to include the specific predefined EV fleet of the EVCP model 1. For this model, the home arrival time t_a, home departure time t_d, and travelled distance d are Gaussian random variables, and battery efficiency is uniformly distributed. The SOC is initially computed as in Equation (1). The rated charging power P_c is modelled as a nonlinear function of the SOC, where the SOC is recursively calculated as follows:

$$SOC_t = SOC_{t-1} + \frac{100 P_c \eta}{C_{ap}} \tag{8}$$

where η represents the efficiency of the EV during driving. Considering the random variables mentioned above and Equation (8), the total EV power is calculated using Equations (9) and (10).

$$P_{EV} = \sum_{i=1}^{5} \sum_{j=1}^{N} P_{EV_{ij}} \tag{9}$$

where

$$P_{EV_{ij}} = \begin{cases} P_c & t_p \leq t \text{ and } SOC_t \leq 100 \\ 0 & \text{other time} \end{cases} \tag{10}$$

Experimental evaluation

In this section, we compare the three aforementioned MCS-based EVCP models following the procedure shown in Figure **1**. In the EV input data block, we use the information in Su *et al.*, 2019 as the battery capacity, EV types, charging power, and full endurance mileages. On the other hand, for the sampling process block, we use the parameters of Table 2 to generate samples for all random variables that feed the three MCS-based EVCP models, and then to compute the total EV power. We repeat $N = 5000$ times the procedure shown in Figure **1** to obtain the histogram for the EV electric energy consumption. We adopt some assumptions about how to use the different EV types employed in Su *et al.,* 2019. For example, we consider that 80 % of private EVs are plugged into the power grid from 18 to 7 h, and the remaining 20 % is recharged during working hours, that is, from 9 h to 17 h. We contemplate three penetration scenarios using 20, 200, 2.000 and 20.000 EVs. To determine the number of EVs, we use a Poisson distribution with an expected value λ. For each level of penetration, we consider over 60 % of private EVs, 20 % of utility EVs, 10 % of taxis, 5 % of electric goods trucks, and 5 % of electric buses.

Figure **2** shows the results of the MCS applied to the three EVCP models considering a penetration of 20, 200, 2.000, and 2.0000 expected EVs. Note that the EVCP models 1 and 2 present similar results. On the contrary, EVCP model 3 obtained significant differences in the energy consumption of the EVs. On one hand, we observe that the EVCP models 1 and 2 keep coherence when the number of EVs increases. However, this can only be true if we are analyzing similar EVs. On the other hand, from EVCP model 3, note that the energy consumption gradually changes as the number of vehicles

Table 2. Charging EV parameters for probabilistic modeling (Su *et al.,* 2019). $\mathcal{N}(\mu, \sigma)$ is a Gaussian distribution with parameters μ (mean) and σ (standard deviation); $\mathcal{LN}(\mu, \sigma)$ is the lognormal distribution; and $\mathcal{U}(a, b)$ is a uniform distribution with parameters a and b

EV type	**Period**	**Mode**	**Prob.**	**d**	**EVCP model 1**	**EVCP model 2**		**EVCP model 3**		
					t_p	t_l	t_a	η	t_a	t_d
Private	9h - 17h	Slow	10	$\mathcal{LN}$(3.2,0.92)	$\mathcal{N}$(9,0.9)	$\mathcal{N}$(7,2)	$\mathcal{N}$(10,2)	$\mathcal{U}$(0.88,9)	$\mathcal{N}$(9,0.9)	$\mathcal{N}$(7,2)
	18h - 1h	Slow	80		$\mathcal{N}$(18.5,0.1)				$\mathcal{N}$(18.5,0.1)	
	9h - 17h	Fast	10		$\mathcal{N}$(9,0.9)				$\mathcal{N}$(9,0.9)	
Utility	9h - 17h	Fast	30	$\mathcal{LN}$(3.2,0.92)	$\mathcal{N}$(18.5,0.1)	$\mathcal{N}$(17,2)	$\mathcal{N}$(12,2)	$\mathcal{U}$(0.88,9)	$\mathcal{N}$(18.5,0.1)	$\mathcal{N}$(17,2)
	18h - 7h	Slow	70		$\mathcal{N}$(12,0.9)	$\mathcal{N}$(6,2)			$\mathcal{N}$(12,0.9)	$\mathcal{N}$(6,2)
Commercial	0h - 9h	Fast	70	$\mathcal{N}$(195.49,49.99)	$\mathcal{N}$(4,2.5)	$\mathcal{N}$(16,2)	$\mathcal{N}$(12,2)	$\mathcal{U}$(0.73,9)	$\mathcal{N}$(4,2.5)	$\mathcal{N}$(16,2)
	9h - 16h	Fast	20		$\mathcal{N}$(12,2.5)	$\mathcal{N}$(0,2)			$\mathcal{N}$(12,2.5)	$\mathcal{N}$(0,2)
	16h - 24h	Fast	10		$\mathcal{N}$(18.5,0.1)	$\mathcal{N}$(9,0.9)			$\mathcal{N}$(18.5,0.1)	$\mathcal{N}$(9,0.9)
Goods Trucks	0h - 9h	Fast	60	$\mathcal{N}$(201.8,94.42)	$\mathcal{N}$(3,1.5)	$\mathcal{N}$(12,2)	$\mathcal{N}$(10,2)	$\mathcal{U}$(0.73,9)	$\mathcal{N}$(3,1.5)	$\mathcal{N}$(12,2)
	9h - 24h	Fast	40		$\mathcal{N}$(14.5,2.8)	$\mathcal{N}$(4,2)			$\mathcal{N}$(14.5,2.8)	$\mathcal{N}$(4,2)
Bus	22h - 7h	Fast	100	$\mathcal{N}$(155,10)	$\mathcal{N}$(22,0.5)	$\mathcal{N}$(5,2)	$\mathcal{N}$(12,2)	$\mathcal{U}$(0.73,9)	$\mathcal{N}$(22,0.5)	$\mathcal{N}$(5,2)

Source: Authors.

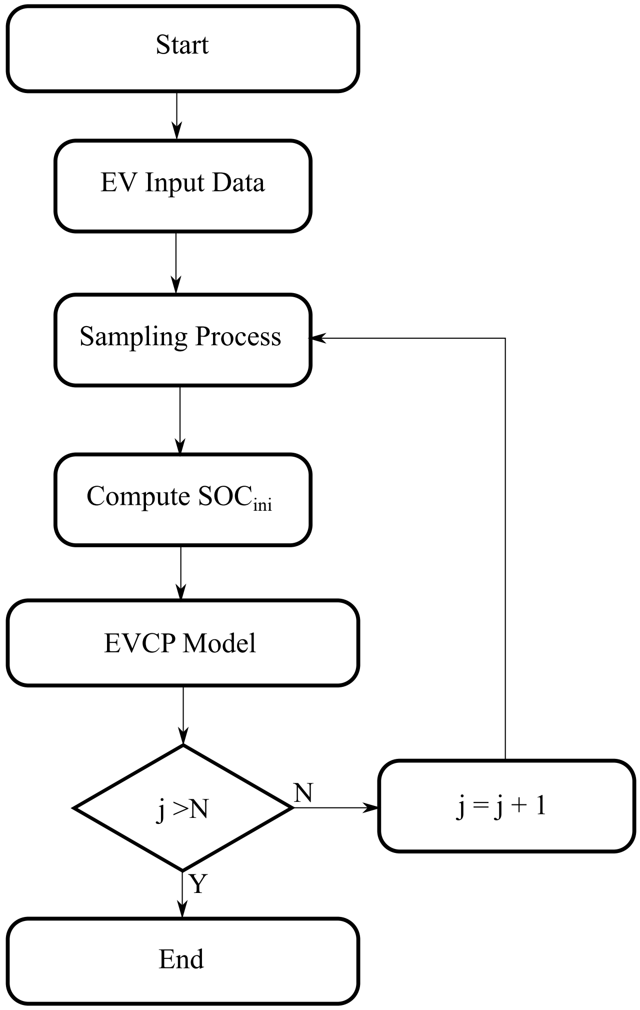
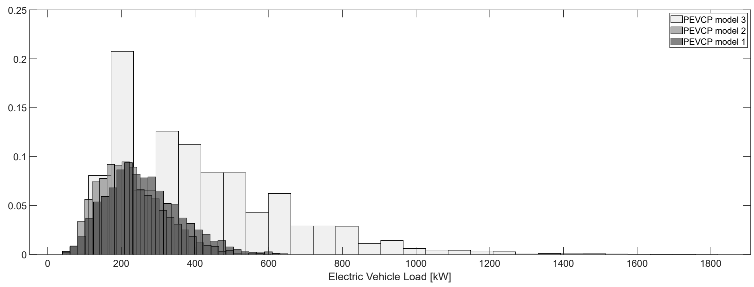


Figure 1. Flowchart for comparing the EVCP Models

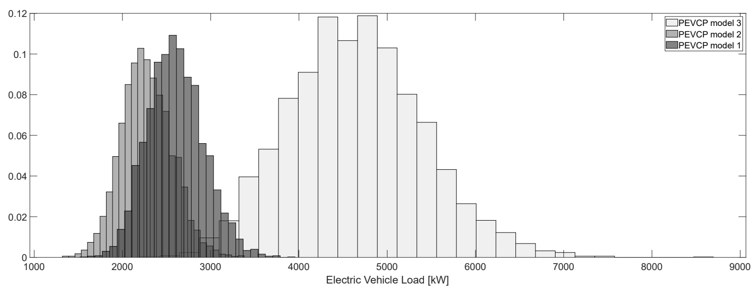
Source: Authors.

increases, but it is not consistent between one scenario and the other. From the above, it is necessary to improve EVCP models 1 and 2.

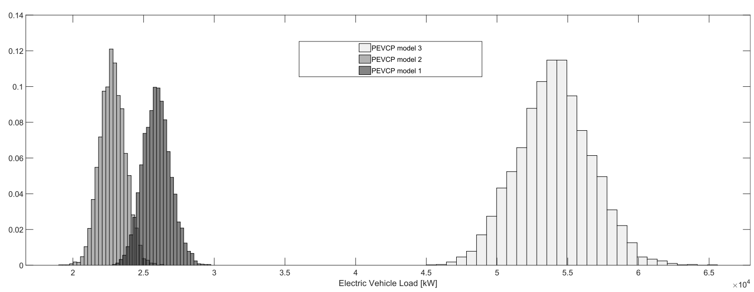
We noticed that one of the great differences of models 1 and 2 with model 3 is that the latter, in addition to considering the non-linear characteristics of the battery charge, ensures that the battery is charged once it is connected to the power grid. From Figure 2, we also noticed that, when there is



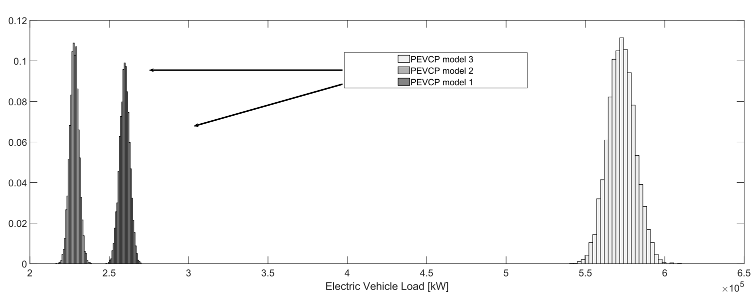
(a) $\lambda = 20$



(b) $\lambda = 200$



(c) $\lambda = 2{,}000$



(d) $\lambda = 20{,}000$

Figure 2. Histograms of the EV charging demand when we apply MCS to the three EVCP models considering a penetration of 20, 200, 2.000, and 20.000 expected EVs

Source: Authors.

Table 3. Wasserstein Distance applied between the real probability distribution and the proposed distribution of the EV demand. As proposed distribution, the gamma, lognormal, Gaussian, and Weibull distributions were analyzed

Distribution	**Wasserstein distance**			
	20	200	2,000	20,000
Gamma	17,928 ± 3,2997	18,634 ± 2,5456	58,565 ± 2,3555	235,03 ± 47,933
Lognormal	21,463 ± 1,7000	26,194 ± 10,059	60,434 ± 18,760	160,02 ± 42,010
Gaussian	49,735 ± 6,1031	48,164 ± 8,0598	69,243 ± 17,408	169,34 ± 27,718
Weibull	28,133 ± 1,5911	136,55 ± 21,603	545,91 ± 26,603	1913,2 ± 83,372

Source: Authors.

when low EV penetration, the behavior of the energy demand can be modeled using a probability distribution. However, when there is a high penetration of EVs, the probability that best adjusts to the behavior of EV demand can be a Gaussian or lognormal distribution. To this effect, we applied a similarity measure to determine how one probability distribution is different from the other, that is, we computed this distance between the real probability distribution (obtained by MCS) and a proposed distribution. Specifically, we computed the Wasserstein distance (Carrillo & Toscani, 2005) in order to measure the similarity between the true data distribution and some proposed distributions. We analyzed the Gaussian, lognormal, gamma, and Weibull distributions. To compute this distance, we repeated the experiment described above five times using only model 3, that is, we applied five times the procedure shown in Figure 1. From the obtained data, we fit the previously described distributions to the data. Then, we generated samples from these distributions and compared them, using the distance, with the data obtained by applying the MCS of each model. Table 3 shows the Wasserstein distance for modeling the EV demand considering the previous distributions. We particularly noticed that the gamma distribution can be a different modeling alternative for low EV penetration levels. On the other hand, note that the lognormal and Gaussian distributions are adequate options for modeling the demand of EVs when there is a high penetration.

CONCLUSION

A review of the state of the art of the modeling of electric vehicles under a G2V approach was presented, where three groups were identified: deterministic approaches, methods that deal with uncertainty and variability, and data-driven methods. Additionally, an experimental comparison was made with three probabilistic models based on Monte Carlo Simulation. From this comparison, we observed that EVCP model 3 and the gamma distribution can be appropriate for modeling the penetration of EVs in probabilistic load flow analysis or for stochastic planning studies for active distribution networks. As future works, it would be possible to consider smart charging strategies within these EVCP models, as well as to include more realistic scenarios.

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ESTUDIO DE CASO

A Comprehensive Review of Sustainability in Isolated Colombian Microgrids

Una revisión integral de la sostenibilidad en las microrredes aisladas colombianas

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Abstract

Context: The increase in rural electrification projects has led to the emergence of technologies that allow operating local distribution networks such as isolated microgrids. However, the successful implementation of these isolated microgrids requires that their planning, operation, monitoring, and control consider a framework that allows maintaining technical, economic, and environmental sustainability over an extended time horizon. Therefore, this paper proposes a model that allows identifying the main technical, economic, regulatory, and environmental variables that should be considered for the successful planning of Colombian rural electrification solutions.

Methodology: This paper proposes the use of System Dynamics to create a model that allows describing the causal relationships between the different variables essential for the design and operation of isolated microgrids. To this effect, the identification of the related variables and their corresponding classification are presented, together with a model of theoretical expectations about their relationships.

Results: A model that integrates and describes the behavior of the main variables involved in the operation of microgrids was formulated to analyze the possible implementation of policies that guarantee the sustainability of these solutions and enhance the use of renewable energy resources while improving the continuity of the electric energy supply.

Conclusions: It was possible to show that operation by means of isolated microgrids with the integration of Distributed Energy Resources is a sustainable solution for rural electrification in Colombia, given that it enhances the use of generation resources with a reduced carbon footprint that are present in the territories under study. These microgrids have the potential to improve the living conditions of users by reducing unsatisfied basic needs.

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Keywords: system dynamics, rural electrification, causal model, isolated microgrid operation, distributed energy resources

Resumen

Contexto: El aumento de los proyectos de electrificación rural ha propiciado la aparición de tecnologías que permiten operar redes de distribución local como microrredes aisladas. Sin embargo, la implementación exitosa de estas microrredes requiere que su planificación, operación, monitoreo y control considere un marco que permita mantener la sostenibilidad integral en un horizonte de tiempo extendido. Por ello, este trabajo propone un modelo que permite identificar las principales variables técnicas, económicas, regulatorias y ambientales que deben ser consideradas para la planificación exitosa de soluciones de electrificación rural en Colombia.
Metodología: Este artículo propone el uso de la Dinámica de Sistemas para la creación de un modelo que permita describir las relaciones causales entre las diferentes variables que deben ser consideradas en el diseño y operación de microrredes aisladas. Para ello se presentan la identificación de las variables relacionadas, su respectiva clasificación y un modelo de expectativas teóricas sobre la relación de estas variables entre sí.
Resultados: Se formuló un modelo que integra y describe el comportamiento de las principales variables involucradas en la operación de las microrredes para analizar la posible implementación de políticas que garanticen la sostenibilidad de estas soluciones y potencien el uso de recursos energéticos renovables, a la par que mejoren la continuidad del suministro de energía eléctrica.
Conclusiones: Fue posible mostrar que la operación por microrredes aisladas con integración de Recursos Energéticos Distribuidos es una solución sostenible para la electrificación rural en Colombia, pues potencia el uso de los recursos de generación con huella de carbono reducida presentes en los territorios estudiados. Estas microrredes tienen el potencial de mejorar las condiciones de vida de los usuarios al disminuir las necesidades básicas insatisfechas.
Financiamiento: Universidad Nacional de Colombia.

Palabras clave: dinámica de sistemas, electrificación rural, modelo causal, operación de microrredes aisladas, recursos energéticos distribuidos

Table of Contents

INTRODUCTION

Microgrids comprise the medium and low-voltage portion of an electrical distribution system that can operate in island mode, interconnected with other microgrids or directly connected to the main network (Bordons *et al.,* 2015,Gaona *et al.,* 2015). Microgrids adopt a variety of Distributed Energy Resources (DERs) such as non-conventional renewable energy sources (FNCER, by its Spanish initials), energy storage systems (BES), and active demand participation, which are coordinated through communication and control systems (López-García *et al.,* 2018). This kind of operation allows improving the reliability and electrical safety of the different distribution networks, and, at the same time, it can provide greater flexibility of operation over the medium and long term (Chowdhury *et al.,* 2009). The technical characteristics of microgrids make them a relevant alternative for the electrification of isolated and remote areas, which are the result of the topography and environmental conditions of each region (Chowdhury *et al.,* 2009).

The transition to a new energy model such as microgrids is subject to different political and technological barriers, due to the variety of generation sources, the characteristics of the region, the control and storage of the primary resource (given its intermittency, which is associated with climatological conditions), and changes in the operation of the distribution system (Bordons *et al.,* 2015).

This paper reviews the energy challenges in the Colombian Non-Interconnected Zone (ZNI), together with the sustainability challenges that arise during the implementation of isolated microgrids, international experiences related to these solutions, and the proposal of a solution hypothesis to the problems related to the provision of the ZNI's electric power service through isolated microgrids by using the System Dynamics (SD) methodology.

The paper is organized as follows: section 1 introduces the challenges for the provision of electric power service in the Colombian ZNI; section 2 presents some international experiences regarding the installation of isolated microgrids; section 3 provides the diagnosis of ZNI, which determines whether the use of microgrids is possible in Colombia; section 4 proposes a solution hypothesis by designing a causal diagram implemented in SD; and finally, some concluding remarks are presented about the possibility of the ZNI being the natural laboratory for isolated microgrids in Colombia.

METHODOLOGY

System thinking is the methodology used in this research. This methodology was used for the first time in the 1950s to analyze complex behaviors in different contexts (Ahmad *et al.,* 2016), and it has been implemented for more than 40 years in the field of energy due to its non-linearity, feedback, delays, and dynamic interaction between the different factors that make up a system (Gómez *et al.,* 2017).

This methodology is appropriate for dynamic-behavioral problems that can be analyzed in a time horizon where delays can be included (Gómez *et al.,* 2017). System Dynamics (SD) is a systematic thinking tool; it is a method that allows the recognition of bidirectional properties, organizes parts into systems, and takes new perspectives for decision-making (Liévano Martínez & Londoño, 2012).

The development of the methodology is divided in four stages, which are listed below (López-García, 2018):

1. **Problem structure:** In this stage, the research problem is defined, as well as the limits and the scope. Here, a state-of-the-art review is developed for identifying the problem to be addressed.

2. **Causal-relationship model:** The main objective of this stage is the creation of a conceptual diagram based on the theoretical expectations of the system's behavior, where the relationships between the independent and dependent variables of interest are analyzed.

3. **Dynamic model:** In this stage, SD is used, which is a tool that allows for scenario analysis considering the characteristics of the problem. The result is a systems diagram that shows all the problem-related variables. The evolution of variables is analyzed over a defined time horizon depending on their relationship with the different components of the system. The stability of the model is evaluated, and sensitivity tests are carried out on the main parameters to refine the system's behavior.

4. **Scenario design and model:** In this stage, different solution scenarios are tested and evaluated for the problem identified in the first stage. Therefore, the parameters or variables that can generate a potentially significant impact are identified. Then, the coherence of the model is evaluated with extreme, optimistic, and pessimistic scenarios. Finally, the performance and behavior of the variables are evaluated in each proposed scenario.

The formulation and validation of the formal model are proposed for future works, together with different solution scenarios for the identified problem.

Energy challenges of the Colombian Non-Interconnected Zones (ZNI)

The Colombian Non-Interconnected Zone (ZNI, by its Spanish initials) is defined as a "geographic area where the public electricity service is not provided through the National Interconnected System" (Law 143 of 1994), and it represents 51 % of the national territory, which is made up of 1.798 localities (IPSE, 2018). Fourteen of these localities have energy contributions from renewable energy sources: eight have energy contributions from unconventional sources, seven have photovoltaic solar installations, and one works with biomass generation. Out of these 14 locations, only three lack diesel generation support, and the remaining 11 have this energy contribution (IPSE, 2019).

The operation of the electric power supply systems in these areas is supported by some economic funds that aim to boost the expansion of service provision. The existing funds are the Financial Support Fund for the Energization of Non-Interconnected Areas (FAZNI), the Non-Conventional Energy Fund and Efficient Energy Management (FENOGE), and the General Royalty System (SGR). These funds were implemented for the improvement of energy infrastructure, the proposal of new rural energy projects, etc. The funds have become a key point for the adequation of electric power supply facilities, resulting in improvements in the efficiency, quality, and continuity of service provision in these areas.

The Colombian ZNI has energy contributions amounting to 96 % of diesel generation and 4 % of other generation sources (IPSE, 2019, Flórez-Acosta, 2009). When diesel is established as the main source of generation, the supply costs increase due to fuel purchase and transportation costs for some localities, given that these are areas with difficult access, and, thus, the means of transportation of the fuel are the air or rivers. Furthermore, due to diesel-based generation, the carbon footprint of the Colombian energy supply systems has increased, as well as the pollution and contamination of ecosystems (González-Montoya *et al.,* 2018, Garzón-Hidalgo & Saavedra-Montes, 2017).

These areas are characterized by their great distance to the main urban centers; they are areas with difficult access, and many of them are in 26 national parks and environmentally protected areas. A considerable percentage of them supply electric power to 1.448 communities in tropical forests, deserts, snow-capped mountains, and more than 544 indigenous reservations (Gaona *et al.,* 2015, López-García *et al.,* 2018). Thereupon, these areas are located where most of the country's biodiversity is found, thus making it impossible to expand the transmission lines of the National Interconnected System (SIN) to these locations (Bustos-González *et al.,* 2014).

Additionally, there are some challenges that hinder the provision of the service, such as low population density and low payment capacity. These populations are characterized by having a reduced coverage of the electricity service, and they have a low level of electric energy consumption and high service delivery costs, in addition to the lack of measurement by the generator and end users (IPSE, 2017).

When examining the different difficulties of the ZNI, such as fuel transportation, the cost of generation, and the low variability of generation sources on site, together with the challenges presented by the population residing in these environmentally protected areas, the electric power service becomes noticeably limited and with reduced quality and reliability, as well as with continuity problems. A clear example of this problem is the provision of the service for the 14 locations that have energy contributions from non-conventional renewable energy sources (FNCER) since they have an average daily supply of 15 hours and 16 minutes, as shown in Table 2. Mitú, Vaupés has a 24-hour service, thus making this town the only one with energy contributions from renewable energy sources combined with diesel generation (IPSE, 2019).

Therefore, it is evident that the Colombian ZNI presents challenges in energy sustainability, since there is no balance between energy security, social equity, and environmental impact mitigation (Grisales, 2017).

Sustainability challenges in the Colombian ZNI

The Colombian ZNI is exposed to different challenges, not only in technical matters, but also in the social, economic, and environmental fields. These challenges must be addressed according to the level of urgency and their implications according to the time scale in which they are analyzed, as shown in Table 1.

These challenges show that the energy management carried out in the ZNI must be reconsidered; it must focus on finding energy solutions that address the different technical, environmental, economic, and social issues of these areas. It is necessary to work for a reliable and continuous supply of electricity with quality standards, which decreases the negative impacts suffered by the inhabitants of these localities and takes advantage of the different energy potentials of each community given the natural wealth of the Colombian ZNI (UPME, 2015).

By overcoming of these challenges through the operation of isolated microgrids, these areas have the potential to become a natural laboratory for Colombia, which allows analyzing the effect of the inclusion of variable generation resources, as well as identifying the aspects andmost relevant considerations that must be taken into account for the coordination of DERs (López-García *et al.,* 2018).

International experiences

In general, the energy solutions for remote rural regions base their operation on small diesel generators connected at the distribution level, which entails high generation costs and irreversible environmental damage (Rodríguez *et al.,* 2017). Therefore, countries have focused on searching for alternatives to improve service provision and reduce greenhouse gas emissions to the atmosphere resulting from the burning of fossil fuels (López-García *et al.,* 2018).

Table 1. Challenges related to technical, economic, social, and environmental sustainability in the short, medium, and long term for the operation and planning of the electricity supply in the Colombian ZNI

Challenge	Time horizon		
	Short term	**Medium term**	**Long term**
Technical Sustainability	Blackouts during peak hours due to the high concentration of residential, commercial, and service constructions without bioclimatic analysis. Ignorance of the need to make rational use of energy.	Increase of electrical losses in distribution networks due to massive and uncoordinated growth in demand and the installation of appliances with reduced efficiency, as well as energy costs related to the adaptation of habitat space and lack of measurement of electricity consumption by the end user.	The need to expand conventional generation capacity from fossil fuels. The need for expansion and modernization of distribution networks.
Economic sustainability	High costs of generation and fuel transportation, as well as low profitability of the companies providing the service.	Increase in the value of electricity. Reduction of service quality.	Reduction of service availability hours due to the need to reduce operating costs. Need to increase government subsidies. Need to boost investment in projects in order to expand the provision of electric power service.
Social sustainability	Resistance to measurement and control projects.	Aversion to supply failures that have an impact on the already decreased quality of life.	Increase in the social gap and reduction of social equity due to a supply of electricity with reduced quality and high volatility.
Environmental sustainability	Ecosystem intervention with mass burning of fossil fuels.	Changes in ambient temperature. Increase in the emission of greenhouse gases due to fossil fuel generation.	Permanent modifications to protected ecosystems by fuel spills, hydrocarbon-based production, and the construction of new infrastructure. Need to promote the use of FNCER.

Source: Own elaboration based on the literature (Blasques & Pinho, 2012, IPSE, 2019, SGI&C - FNCER, 2018).

One of the alternatives proposed worldwide is energization by isolated microgrids because, given their technical characteristics, they allow improving the living conditions of end users and, above all, they benefit the local populations in remote areas of a given country, where it is difficult to provide the service either due to environmental, technical, topographic, or climatic conditions. Microgrids have the possibility of supplying uninterrupted electricity, improving reliability, reducing losses, providing greater security, and adopting distributed generation sources (Chowdhury *et al.,* 2009, Adrián *et al.,* 2016). These electrical systems are relatively new, which is why pilot projects are being developed in different educational institutions, and microgrids have been installed in different parts of the world to obtain an evaluation of these systems in order to gain knowledge and experience in the implementation of these technologies (Gaona *et al.,* 2015). Below are some international pilot projects that have been successful in implementing isolated microgrids.

The microgrid project of the Kythnos island community, located in Greece, is 4 km away from the nearest medium voltage network, and it is capable of supplying electricity to 12 houses (Dafermos *et al.,* 2015). This microgrid has become a pioneering project on issues related to the use of microgrids for energization in isolated areas of Europe. It consists of two photovoltaic plants with a rated capacity equal to 10 and 2 kW, a battery bank of 53 kWh with nominal capacity, and a diesel generator set of 5 kVA (Rese, 2012). Moreover, a load disconnection occurs when the battery charge level is too low (López-García *et al.,* 2018).

On the other hand, the village of Hartley Bay, located in British Columbia, Canada, is an isolated village of difficult access; its means of transportation are air and rivers, and it has a total population of 200 inhabitants (RCCbc, n.d.). The electric power service is provided through a microgrid with three diesel generators, which provides electricity to 20 commercial buildings and 62 residential units. Also, a demand response program has been implemented to use diesel generators as little as possible, thus optimizing diesel clearance (López-García, 2018).

In South America, there is the microgrid called Huatacondo, which is located in Chile and supplies electricity to approximately 30 families. It is made up of a 150 kW diesel generator, together with a 22 kW solar photovoltaic monitoring system, a 3 kW wind turbine, a 170 kWh battery, and an energy management system (Berkeley Lab, 2020). In addition to this, it has a social SCADA that allows monitoring, operating, controlling, and supervising the electrical system (Núñez *et al.,* 2013).

In February 2008, the island of Eigg, located in Scotland, began to generate its electricity through a microgrid that supplies energy 24 hours a day. The system allows service to 83 inhabitants who make up 38 homes and five commercial properties. The microgrid has a capacity comprising 119 kW of hydroelectric power, 24 kW of wind power, and approximately 54 kW of solar energy, together with a storage system and 160 kW of diesel generation as a backup. Thus, it has a total capacity approximately 357 kW. Users have limited service access: in the case of residential users, they cannot exceed 5 kW; and commercial users cannot exceed 10 kW each. Each resident has an energy monitoring system that helps users to not exceed the established load limits (Chmiel & Bhattacharyya, 2015).

The Hailuoto microgrid, located in Finland, is a pilot project that aims to demonstrate the island operation mode of microgrids in a medium voltage distribution system. Hailuoto has a population of 1.000 inhabitants and 600 holiday homes. The microgrid has a capacity of 0,5 MW of wind power and 1,5 MW of diesel generation (Laaksonen *et al.*, 2014).

At the international level, projects related to microgrids have increased, as they represent a sustainable solution for rural electrification, given that they allow integrating renewable energy sources with diesel generation. Some experiences show that existing microgrids involve the community in the design, operation, and maintenance process, thus constituting an opportunity to raise awareness in the rational and efficient use of energy and ensuring the sustainability of the microgrid (Intergovernmental Panel on Climate Change, 2014).

In some African regions such as Kenya, Nigeria, and Tanzania, some microgrids to solve the rural electrification problem have been implemented. In this region, the solutions are hybrid microgrids with solar, wind, or hydraulic generation, supplemented with biomass or diesel generators (Plain *et al.*, 2019). The connected users have smart metering, and the data gathered from measuring devices can parameterize the microgrid's performance in terms of quality. This information is used to create a conceptual framework to develop microgrids for rural electrification solutions (Li *et al.*, 2020).

MICROGRIDS IN COLOMBIA

Currently in Colombia, the country's energy production in isolated areas consists of approximately 93 % of primary resources of fossil origin, approximately 4 % of hydrogeneration, and 3 % of biomass and other resources. For this reason, the Colombian government is in the process of creating and modifying some norms and laws that encourage the use of the FNCER on these regions by reducing the dependence on fossil fuels and diversifying the energy matrix. For the Colombian ZNI, these sources of generation represent sustainable environmental and social solutions over time which can complement the currently implemented conventional technologies, which constitutes an alternative to improve service delivery to the most vulnerable populations in Colombia (UPME, 2015).

The Colombian ZNI has general issues in the provision of the electric energy service, which are related to the coverage of the electric power service to the most remote populations, as well as to the little use of the primary energy resources in the different regions. The Colombian government, through the Institute for Planning and Promotion of Energy Solutions for Non-Interconnected Areas (IPSE), has installed hybrid generation projects in some isolated zones, seeking to provide a solution to the problem of electricity supply in rural areas. These different projects have been developed with the participation of conventional and unconventional generation (Gaona *et al.*, 2015). Table 2 shows the general characteristics regarding the composition of the energy matrix, the number of users, and the average daily hours of service provision of some of the projects that have energy contributions from renewable energy sources located in the ZNI.

However, the coordination and monitoring of these resources are still incipient, so it is necessary to carry out modernizations and updates of the distribution networks and the measurement and control systems, which allow these projects to become natural laboratories for the inclusion of DERs in Colombian distribution networks.

PROPOSED SOLUTION FOR THE ENERGIZATION OF THE COLOMBIAN NON-INTERDONNECTED ZONES

Considering the previously analyzed information regarding international experiences related to microgrid management and the Colombian challenges for the electrification of rural or isolated areas, some of the variables involved in the problem are analyzed, which allow identifying and describing the operation of the Colombian ZNI, integrating microgrids as a solution hypothesis for the electrification of these isolated areas. The employed methodology is System Dynamics (SD), which analyzes the cause-effect relationships between the different variables that interact in the system and allows a holistic analysis in which the response of the diverse actors is evaluated (Sterman, 2000). Figure 1 shows the variables that directly affect the model (endogenous), those that allow formulating the problem (exogenous), and those that provide an approach to the proposals (excluded), which interact in the cause-effect relationships model identified for the sustainable operation of microgrids with DG in the ZNI.

From the defined variables, the interaction between them and their impact on the problem solution is modeled. The model comprises three cycles that integrate the technical, environmental, and economic aspects that must be considered when implementing isolated microgrids as a proposal for the electrification of these areas (Figure 2). The proposed model for adopting microgrids in the Colombian ZNI will guarantee the supply of electricity to isolated regions of the country with continuity and quality indexes higher than those currently presented (López-García *et al.,* 2018).

The cycles that make up the model are: a) the technical cycle, in which it is proposed to improve the efficiency, continuity, and supply quality indexes through the use of the region's energy potentials and the coordination of the DG immersed in the microgrid, thus allowing the provision of technical support services for real-time keeping of the technical variables of the system within acceptable limits (López-García, 2018,Manrique, 2017); b) the environmental cycle, where it is shown that, although all energy use has environmental effects in its design, construction, or operation, among the variety of small-scale generation technologies existing in the country, the fossil fuel-dependent generation units stand out for their environmental impact on the ecosystems in which they are immersed (Iberdrola, 2013); c) the economic cycle, which shows the possibility of reducing the service provision costs by reducing the dependence on diesel, which is related to high transport costs and in turn reduces power losses. With the coordination of the DGs present in the region, the energy potentials in the area would be used, considering that the cost of exploiting these primary energy resources is comparatively

Table 2. General characteristics regarding the composition of the energy matrix, the number of users, and the average daily hours of service provision of some of the projects that have energy contributions from renewable energy sources located in the Colombian ZNI

Locality name - Location	Conventional generation capacity [kW]			Unconventional generation capacity [kW]				Storage systems	Daily average service provision	Number of users
	SHP	Diesel	Share [%]	Solar PV	Biomass	Wind energy	Share [%]			
Isla Fuerte - Bolívar	0	320	64,6 %	175	0	0	35,4 %	-	4,51	406
Isla Múcura - Bolívar	0	116	79,5 %	30	0	0	20,5 %	Yes	14,56	43
Santa Cruz del Islote - Bolívar	0	116	63,0 %	68	0	0	37,0 %	Yes	13,41	127
Guacamayas - Caquetá	150	0	100,0 %	0	0	0	0,0 %	-	18,8	205
Santa Bárbara - Casanare	0	23	53,5 %	0	20	0	46,5 %	-	*	17
Comunidad Indígena De Pangui - Chocó	32	0	100,0 %	0	0	0	0,0 %	-	21,35	88
Cúpica - Chocó	300	125	100,0 %	0	0	0	0,0 %	-	16,33	344
Mutis - Chocó	1875	1800	100,0 %	0	0	0	0,0 %	-	23,44	166
San Francisco - Chocó	0	224	65,1 %	120	0	0	34,9 %	Yes		266
Titumate - Chocó	0	124	54,1 %	105	0	0	45,9 %	-	1,32	105
Barranco Minas - Guainía	0	401	87,2 %	58,88	0	0	12,8 %	Yes	8	352
Nazareth - La Guajira	0	364	41,2 %	320	0	200	58,8 %	Yes	8,28	146
Palmor Ciénaga - Magdalena	373	0	100,0 %	0	0	0	0,0 %	-	23,13	436
Mitú - Vaupés	2000	4512	100,0 %	0	0	0	0,0 %	-	24	2.293

Source: Own elaboration based on the literature (Blasques & Pinho, 2012, SGI&C - FNCER, 2018).

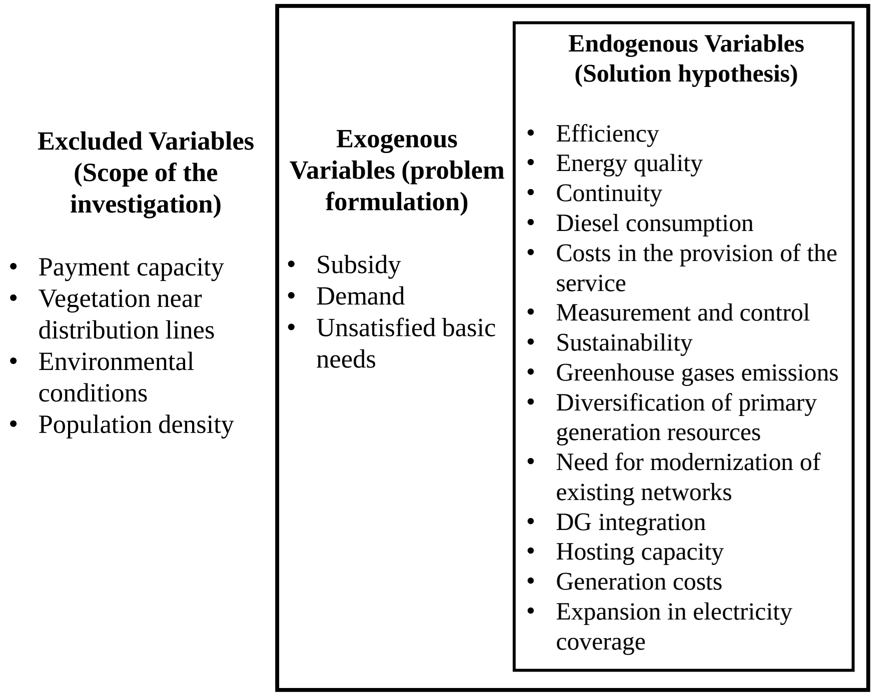

Figure 1. Defined variables of the proposed model

Source: Authors.

lower than the one incurred with the purchase of diesel (López-García, 2018, Manrique, 2017).

At the same time, the use of renewable generation sources contributes, when compared with current energy production, to have lower CO_2 emissions and greater competitiveness in the market (Departamento Nacional de Planeación, World Bank Group, & Korea Green Growth Partnership, 2017).

Technical cycle

The provision of electric power service in isolated areas depends partially on quality, continuity, and efficiency indicators to verify that the proposed solution is sustainable (Balcells *et al.*, 2010). According to international experiences, the need to modernize existing networks by adopting relatively new technologies such as storage systems, demand response programs, and unconventional energy sources is evident (Chowdhury *et al.*, 2009). Therefore, when trying to integrate non-conventional renewable generation sources in the operation of these microgrids, it is necessary to have measurement and control systems, due to the possible intermittency and variability of the primary energy resource used for generation. With the inclusion of these control technologies, it would be possible to coordinate the resources immersed in the microgrid (North American Electric Reliability Corporation, 2009).

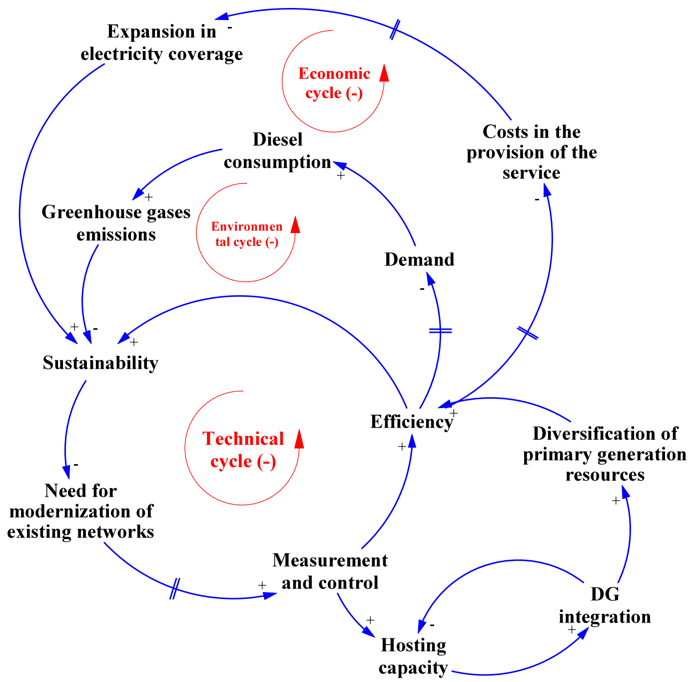

Figure 2. Proposed causal model

Source: Authors.

As there is greater sustainability in the operation of microgrids, the need for network modernization decreases, since energy security in the provision of the service is adequate, that is, it allows the service to be provided safely. If, on the contrary, the need to modernize networks grows, this leads to structural and operational changes in the system within a given time horizon (Grisales, 2017, Bueno-López *et al.*, 2020).

For its part, the hosting capacity establishes the appropriate limit for the adoption of DG in the network without affecting reliability and energy quality, thus becoming one of the main characteristics to be considered in the operation of isolated microgrids (Etherden & Bollen, 2011). A higher hosting capacity leads to greater participation of DG. Of course, since this capacity is finite, there will be a point at which it will not be possible to integrate more resources, even with proper management (Bedoya-Bedoya, 2019). With an appropriate integration of these resources, it is possible to have greater flexibility in the operation of the networks, given the different forms of generation and possibilities for managing demand, thus reducing consumption and technical losses (Bedoya-Bedoya, 2019).

Microgrids with DG inclusion have become an alternative to improve service delivery in isolated areas (López-García *et al.,* 2018). Therefore, it is necessary to increase the hosting capacity of these sources without compromising the reliability and quality of the supply or exceeding the maximum penetration limit of each source, thus ensuring the operational performance of the system (Delgado *et al.,* 2019, Valencia-López *et al.,* 2017).

Environmental cycle

Demand growth is one aspect that affects the operation of distribution networks located throughout the territory (Morales-Ramírez & Alvarado-Lagunas, 2014). In the case of the Colombian ZNI, this growth causes adverse environmental effects in the short, medium, and long term, which results from the strong dependence on diesel generation in these areas (Flórez-Acosta, 2009). Therefore, as the demand for fossil fuel burning increases, it also grows due to the need for energy supply and security (Camargo *et al.,* 2013).

The progressive replacement of diesel generation is an alternative that allows reducing the negative impact of this type of generation on the environmentally protected ecosystems and areas in which these networks are usually located, and this is the result of the adoption of renewable energy sources and the gradual decrease of the dependency on generation based on fossil fuels (Camargo *et al.,* 2013). Therefore, implementing these sources allows for environmental sustainability in the networks since it is possible to reduce the carbon footprint (Law 1715 of 2014, Giral-Ramírez, 2017).

Economic cycle

If the operation of an electrical system is efficient, the costs of providing the service are stable and may be affordable for end users (Flórez-Acosta, 2009). If, on the contrary, the system does not have efficiency and quality, the provision costs increase, affecting the final user. Given the social and economic characteristics of these regions, the costs of providing the service are too high to be fully covered by the end user (IPSE, 2017). This leads to a barrier on the expansion of the provision of the service, and it makes these systems unprofitable investments for companies in charge of generating, distributing, and commercializing electric energy, which leads to a reduction in the economic and social sustainability for the agents involved in the provision of energy.

The costs of providing services in these areas also increase as long as the participation of fossil fuel-based generation sources is predominant (González-Montoya *et al.,* 2018). When analyzing the possibility of reducing diesel consumption, the subsidies used for the purchase of fuels could be redirected and used for the adaptation and modification of networks. In this way, it will be possible to take advantage of the energy potentials of each region and increase the electricity coverage of isolated areas in the Colombian territory (López-García *et al.,* 2018).

Conclusions

With the review of some projects that integrate microgrids to the electrification of rural or isolated areas around the world, it is observed that the operation of isolated microgrids in which the DERs are integrated becomes a sustainable solution for the energization of rural or isolated areas.

International experiences show that it is necessary to make investments in the modernization and control of the distribution network in order to guarantee the use of resources and rely on the electricity supply throughout the day. Additionally, it is observed that it is necessary to include the community in these projects for the adequate use of the potential resources of the regions, as well as for the operation to be sustainable over time.

The proposed solution, implemented according to the System Dynamics methodology, models and integrates the main variables involved in the operation of microgrids, showing the cause-and-effect relationships of all participants in order to analyze the possible implementation of policies that guarantee the sustainability of these solutions and potentiate the use of energy resources in each of the regions to contribute to the reduction of the carbon footprint and other environmental conditions resulting from diesel-based generation. Also, sustainability and continuity in the service improve people's living conditions and provide coverage for unsatisfied basic needs. In this sense, continuity promotes the implementation of productive projects, such as companies whose connection to the electricity grid boosts the household economy and encourages new ventures. Therefore, these projects increase the income of end users and provide economic development to the regions.

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ESTUDIO DE CASO

A Qualitative Comparison of Distance-Based Protection Approaches for Active Distribution Networks

Comparación cualitativa de estrategias de protección con relé de distancia para redes de distribución activas

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Abstract

Objective: This paper presents a qualitative comparison of different recently proposed network protection schemes that are based on the distance function. From this comparison, possible opportunities are identified to develop strategies oriented towards protecting active distribution systems.

Methodology: This research is carried out in two parts: the first is to identify the fundamental theoretical aspects of distance protection, its main problems, and a description of the most important aspects of the relevant strategies proposed in recent years. The second part consists of selecting aspects and elaborating a qualitative comparison of the different protection schemes analyzed. This comparison makes it possible to establish the advantages and disadvantages of each of the relevant proposals used in conventional electrical networks or active distribution networks.

Results: As a result of this research, the most important aspects to consider in the protection design are identified, which therefore strongly affect its performance. These are summarized in a comparative table, which supports future research related to distance protection in active distribution networks.

Conclusions: From this research, it can be stated that the solutions analyzed, despite being relevant within the scope of distance protection applied to active distribution networks, have problems to solve. None of these strategies protects the network for all types of failures in a selective, sensitive, reliable, and cost-effective way while guaranteeing minimum supply interruption to consumers.

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Keywords: active distribution network, adaptive protection, distance relay, faults

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Resumen

Objetivo: Este artículo presenta una comparación cualitativa de diferentes esquemas de protección de redes, propuestos recientemente y basados en la función de distancia. A partir de esta comparación se identifican las posibles oportunidades para desarrollar estrategias esencialmente orientadas a la protección de sistemas de distribución activos.

Metodología: Esta investigación se realiza en dos partes: la primera se orienta a la identificación de los aspectos teóricos fundamentales sobre la protección de distancia, sus principales problemas y una descripción de los aspectos más importantes de estrategias relevantes propuestas en los últimos años. La segunda parte consiste en la selección de aspectos y la elaboración de una comparación cualitativa de los diferentes esquemas de protección analizados. Esta comparación permite establecer las ventajas e inconvenientes de cada una de las propuestas relevantes que se utilizan en redes eléctricas convencionales o en redes de distribución activas.

Resultados: Como resultado de esta investigación se identificaron los aspectos más importantes a considerar en el diseño de la protección y que, por lo tanto, afectan fuertemente su desempeño. Estos se resumen en una tabla comparativa, que sirve de apoyo a futuras investigaciones relacionadas a la aplicación de la protección de distancia en redes de distribución activas.

Conclusiones: A partir de esta investigación se puede afirmar que las soluciones analizadas, pese a ser relevantes dentro del ámbito de la protección de distancia aplicada a las redes de distribución activas, tienen problemas por resolver. Ninguna de estas estrategias permite proteger la red para todos los tipos de fallas de una manera selectiva, sensible, fiable y rentable que garantice la mínima interrupción del suministro a los consumidores.

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Palabras clave: red de distribución activa, protección adaptiva, relé de distancia, fallas

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INTRODUCTION

Motivation

In recent years, conventional distribution systems have dealt with different challenges related to energy efficiency, fast growth in demand, environmental pollution, global warming, dependence on the geographical conditions of the region, among others, which significantly affect the quality and reliability of service to the end user (Giral *et al.*, 2017). These have prompted new forms of generation at the distribution level by integrating renewable energy sources such as natural gas, biogas, wind energy, and photovoltaic plans. This type of generation is also known as distributed generation (DG), and the energy sources involved are called distributed energy resources (DER) (Rafique *et al.*, 2020), which are used to increase reliability and safety in the short, medium, and long term (Carvajal & Marín-Jiménez, 2013). However, the high penetration and integration of DER have a negative impact on distribution networks. Their impact depends on their location, sizing, and mode of operation (Buitrago-Arroyave & López-Lezama, 2013). This has resulted in increasingly complex systems with several operational problems. The main issues appear with traditional protection schemes, where challenges are noticed such as relay coordination problems due to changes in the grid structure, fault levels, and false tripping, among others (Sarangi *et al.*, 2021, Usama *et al.*, 2021).

To solve these problems, several authors have proposed protection strategies, which adapt conventional relays (overcurrent, distance, differential, undervoltage, among others) to improve their performance in these active distribution networks (ADNs) (Alam, 2019, Barra *et al.*, 2020, Li *et al.*, 2021). The proposed protection schemes focus individually on the relay function, given that each one presents specific problems when applied to ADNs, which is why this review paper presents a comparative analysis of protection schemes implemented specifically using the distance relay.

Consequently, all the analyzed factors are those that can originate malfunction in distance protection, thus affecting the safe operation of an ADN. Thus, studying the countermeasures required to eliminate or reduce these factors' impact through different protection strategy proposals is essential.

STATE OF THE ART

Distance relays are commonly used in transmission networks. However, they are also considered an essential alternative for ADNs due to their significant advantages compared to other conventional relays (Sinclair *et al.,* 2014). As an example, relay settings depend on the measured impedance, so they are not affected by changes in network topology. Distance relays also have higher sensitivity, selectivity, and accuracy, and their operation is faster than overcurrent relays (Borlase, 2017). However, the main problems with distance protection when operating in ADNs are the infeed effect, fault resistance, directional feature, among others, thus underreaching or overreaching the real impedance and resulting in an erroneous fault detection (Nikolaidis *et al.,* 2018). Another factor to consider is unbalanced faults, which can negatively affect the reliability and speed of distance protection (Sinclair *et al.,* 2014, Jia *et al.,* 2019).

Therefore, several proposals involving adaptive protection schemes based on distance relays have been published in the last years to solve these problems. These approaches aim to reduce the effects of fault resistance or infeed currents (Sinclair *et al.,* 2014). Others implement a compensation factor for zero-sequence (Tsimtsios & Nikolaidis, 2018). In addition, several strategies use different methodologies to define their approach: some are based on voltage drop (Ma *et al.,* 2015) or voltage amplitude comparisons (Liang *et al.,* 2020). Other schemes deal with more specific problems such as determining the fault direction (Chen *et al.,* 2018) or the protection challenges associated with the point of interconnection, as in El-Arroudi & Joós, 2018 and Yin *et al.,* 2021. The latter also considers the change produced by the connection of the power transformer at that point, which affects the impedance calculation seen by relay 21.

Another important aspect of distance relays is the adjustment of protection zones. Lavand & Soman, 2016 propose predictive analysis to supervise zone 1 of a distance relay using synchrophasors. Ghorbani *et al.,* 2021 provide an accurate non-pilot scheme for an accelerated trip of distance relay zone-2 faults. Regulski *et al.,* 2021 establish the adaptive reach of the 3rd zone of a distance relay with synchronized measurements.

Tsimtsios *et al.,* 2019 use a communication system to improve the performance characteristics of relay 21, such as improving the speed of digital distance protection. As examples, Jin *et al.,* 2018 employ communication systems based on the IEC 61850 standards; Liu *et al.,* 2019 implement a communication system on an field programmable gate array (FPGA) board, and it is tested using a PSCAD/EMTDC simulator and COMTRADE 99 communication protocols. Despite this, a communication system implies an increase in the operating costs of the network, which is why Tsimtsios *et* *al.,* 2019a, Tsimtsios *et al.,* 2019b introduce complete guidelines for designing economically feasible distance protection schemes for radial distribution systems with distributed generation (DG).

In addition, some strategies facilitate the estimation of voltage and current signals measured by the relay. Generally, the fast Fourier transform is the most used. Nevertheless, Zamora-Méndez *et al.,* 2016 and Vázquez *et al.,* 2020 implement the second-order Taylor-Kalman- Fourier filter for signal processing analysis, which is faster and with a smaller signal estimation error.

Paper contributions

This paper compares the odds and drawbacks of different protection strategies based on the distance relay applied to ADNs that have been proposed in recent years. It aims to identify and highlight these protection capabilities, which are useful to propose an approach to eliminate the identified gaps in future works.

Distance protection

Fundamental concepts

Protection devices have a fundamental role in electric networks. An essential device is distance protection, also known as relay 21, which contributes to ensure the continuity and quality of the service for end users (Bansal, 2019). A relay 21 is based on the positive sequence impedance, estimated between the faulted node and the relay location. Therefore, these relays use the measured current and voltage to determine the impedance in the presence of fault conditions (Borlase, 2017).

According to Ma & Wang, 2018, the measured impedance at the relay location (Z_m) is presented in Equation (1).

$$Z_m = \frac{\dot{U}_m}{\dot{I}_m} \tag{1}$$

Variables $\dot{U}_m$ and $\dot{I}_m$ are the voltage and the current phasors measured by the distance relay. When the network is in normal operating condition, $\dot{U}_m$ is, approximately, the rated voltage, $\dot{I}_m$ is the load current, and Z_m is the load impedance. However, when a fault occurs, $\dot{U}_m$ decreases, $\dot{I}_m$ increases, and Z_m becomes the impedance between the fault and the relay location. In this way, the distance relay is designed to recognize fault conditions and generate a trip order when Z_m is lower than the zone setting impedance (Z_{set}), as presented in Equation (2).

$$\text{If} \quad Z_m < Z_{set}, \qquad \text{then send trip signal to 52} \tag{2}$$

The tripping region of the 21 function can be plotted on the R–X plane, as shown in Figure 1, where the protection zone is delimited by Z_{set}, which is the diameter of the circle in the case of mho-type distance protection. Nevertheless, Mohajeri *et al.,* 2015 presents the tripping range as delimited by straight lines, considering other factors such as variations of setting distance, fault resistance, power factor, and measurement errors, thus forming a quadrilateral tripping area, as shown in Figure 2.

Main issues with distance protection for ADN

Distance relays are generally used in transmission networks. Nevertheless, these have also been considered to be an essential alternative for ADNs, due to their significant advantages in comparison with other conventional relays. As an example, the relay settings depend on the measured impedance, and these are not affected by changes in grid topology (Usama *et al.,* 2021). They also have higher sensitivity, selectivity, and accuracy, and their operation is faster compared to overcurrent relays (Borlase, 2017).

The main issues that cause a malfunction of distance relays when applied in ADNs are presented here. Short lines originate overreach errors in impedance estimation due to the low X/R ratio, since this affects the magnitude of the fault current (Hooshyar & Iravani, 2017). In the case of intermediate sources, the infeed effect is a major influencing factor for distance protection, which affects the measured impedance. This problem results in underreach phenomena because the relay 21 does not

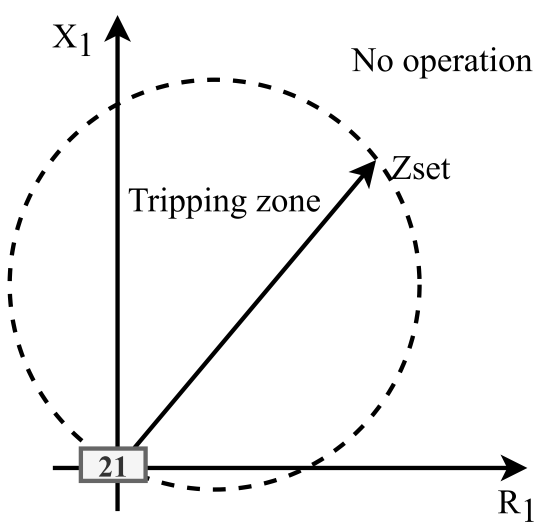

Figure 1. Mho-type operational characteristics of distance protection

Source: Sinclair *et al.,* 2014, Mohajeri *et al.,* 2015.

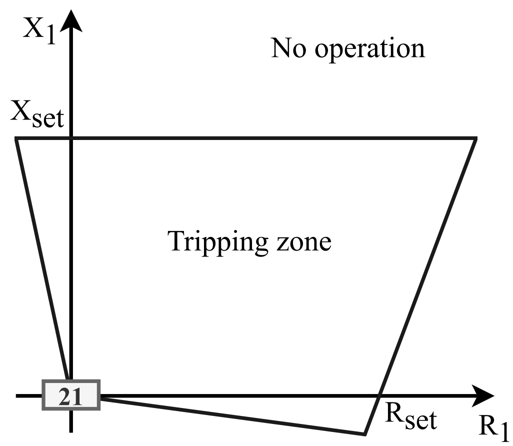

Figure 2. Quadrilateral operational characteristics of distance protection

Source: Sinclair *et al.*, 2014, Mohajeri *et al.*, 2015.

measure the total fault current. Similarly, the fault resistance also results in an additional impedance measured by the relay. However, this effect may cause not only underreach but also overreach phenomena. The latter causes the relay not to detect the fault since the impedance seen is outside the protection zone (Nikolaidis *et al.*, 2018).

Other additional problems are related to the directional function, which, in the case of using the positive or negative sequence components, is affected by the harmonic distortion caused by inverter-based DERs (Hooshyar & Iravani, 2017). Moreover, the intensity and nature of the aforementioned effects vary mainly due to the DG penetration level.

Description of some recent distance protection approaches for ADN

Several authors have focused on the advantages and issues of distance protection. Therefore, several strategies have been proposed in the last few years to improve this, especially in the case of ADN application.

A. Approach presented by (Sinclair *et al.*, 2014):

The paper by Sinclair *et al.*, 2014 describes the advantages of using distance relays for distribution protection to solve some DG integration problems. To adequately implement distance protection, it is necessary to model the operating characteristics. The paper argues that distance elements derive their

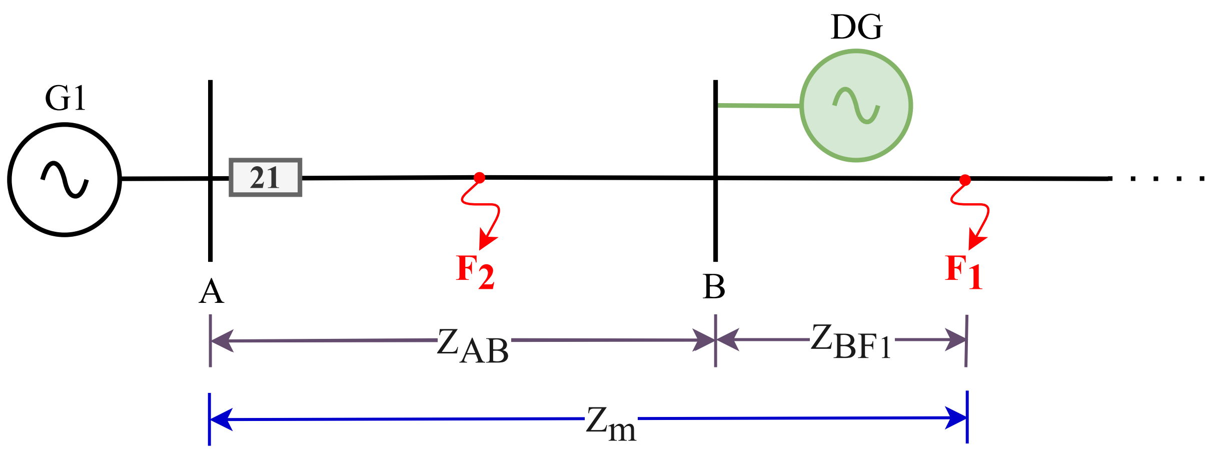

Figure 3. Distance relay in a faulted system

Source: Authors.

operating and polarizing signals from measured voltages and currents. These signals are applied either to the magnitude or angle comparator, from which a trip decision is derived.

As explained above, during normal operating conditions, Z_m equals Z_{load}. In the case of a fault, the measured impedance changes to an impedance with larger inductive and lower resistive components, which is primarily determined by the feeder impedance, from the relay node to the faulted point, as shown in Equation (3) and presented in Figure 3. This last operating condition considers fault 1 (F_1).

$$Z_m = Z_{AB} + Z_{BF1} \tag{3}$$

where, Z_{AB} and Z_{BF1} are the positive-sequence impedance from the substation to the next successive bus, as well from this node to the fault point.

However, as previously presented, it is necessary to consider the factors that affect the measured impedance. This is shown in Equation (4), where the infeed effect is included. This effect is due to the presence of DG in node B.

$$Z_{m,infeed} = Z_{AB} + \frac{I_{G1} + I_{DG}}{I_{G1}} Z_{BF1} \tag{4}$$

where, $Z_{m,infeed}$ is the measured impedance considering the infeed effect, I_{G1} is the fault current contribution from the utility source and measured by the relay, and I_{DG} is the fault current contribution from the DG on node B. If only the fault resistance (R_F) is considered, the impedance seen by the relay 21 is obtained as expressed by Equation (5).

$$Z_{m,R_F} = Z_{AB} + Z_{BF1} + R_F \tag{5}$$

B. Approach proposed in Tsimtsios and (Nikolaidis *et al.,* 2018):

The case of the zero-sequence compensation factor (K_0) for the correct operation of distance protection during single-line-to-ground faults (SLG) is considered by Tsimtsios & Nikolaidis, 2018. In this case, the impedance calculated by the ground distance element is different from the positive-sequence impedance up to the fault position due to the zero-sequence current effect. Thus, to achieve its correct operation, the zero-sequence current is compensated by the K_0 factor presented in Equation (6), which is included in the relay settings.

$$K_0 = \frac{(z_0 - z_1)}{K z_1} \tag{6}$$

where z_0 and z_1 are the per-unit zero and positive-sequence line impedances from the relay location up to the fault position, respectively, and K can be equal to 1 or 3, depending on the relay design. Therefore, the impedance calculated by the relay (Z_m), considering K_0 in case of a phase-a SLG fault is obtained as shown in Equation (7)

$$Z_m = \frac{Z_{m,nc}}{(1 + K_0)} \tag{7}$$

where, $Z_{m,nc}$ represents the non-compensated fault impedance, namely the impedance measured up to the fault point without the consideration of K_0.

C. Approach presented by (Ma *et al.,* 2015):

Ma *et al.,* 2015 presents an alternative approach that considers the voltage drop under high-resistance faults to propose an adaptive scheme for a quadrilateral-type relay. First, this strategy establishes a voltage drop equation from the relay location to the fault point. Equation (8) shows the voltage drop in a double-source system considering a fault 2 (F_2) as in Figure **3**.

$$\dot{U}_m = \dot{I}_m Z + \dot{U}_f \tag{8}$$

where Z is the real fault impedance and $\dot{U}_m$ is the voltage at the fault point, which is determined by the multiplication of the fault current ($\dot{I}_f$) and resistance (R_F).

For the case of a fault 2 (F_2), the voltage and current phasors are shown in Figure **4**. Due to the contribution of the opposite side current, I_{DG}, there is an angular difference, ψ, between $\dot{I}_m$ and $\dot{I}_f$. In addition, φ_{line} is the impedance angle of the protected line, and φ_{ui} is the angular difference between $\dot{U}_m$ and $\dot{I}_m$. Therefore, performing a phasor analysis of Figure **4** from Equation (8), the fault impedance is obtained using Z_m, as shown in Equation (9).

$$Z_{AF2} = Z_m \left| \frac{\sin(\varphi_{ui}) + \psi}{\sin(\varphi_{line}) + \psi} \right| \frac{\cos\varphi_{line} + j\sin\varphi_{line}}{\cos\varphi_{ui} + j\varphi_{ui}} \tag{9}$$

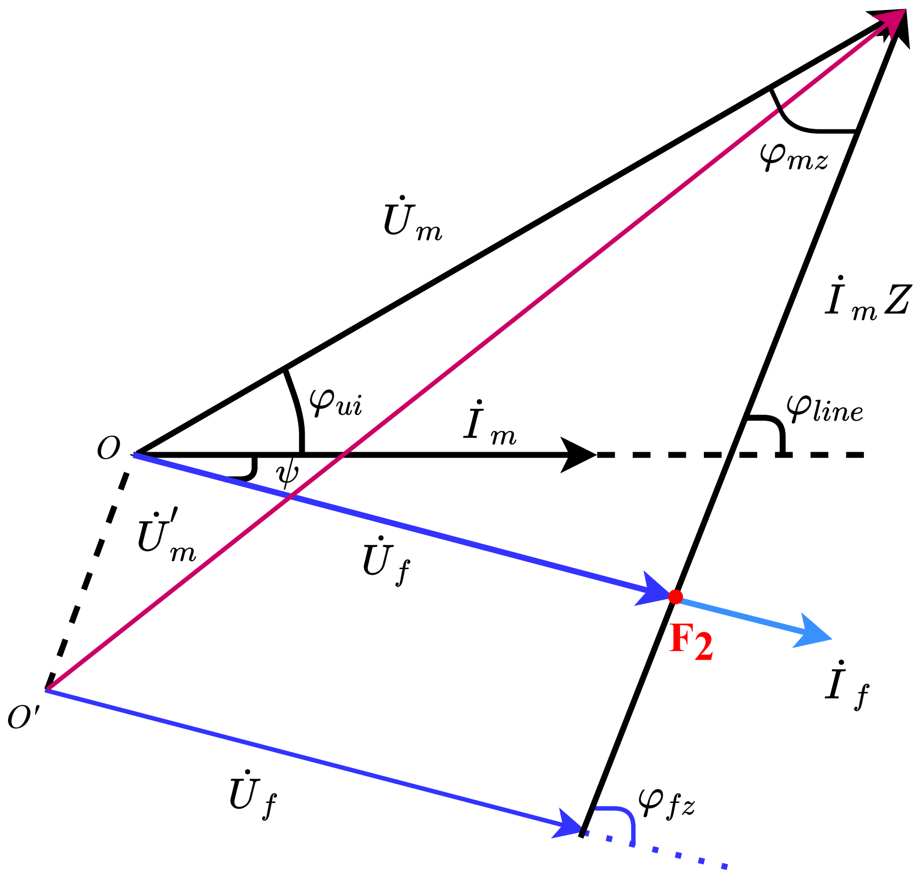

Figure 4. Phasor diagram of V and I vectors

Source: Ma *et al.*, 2015, Liang *et al.*, 2020.

The adaptive protection criterion is established from Equation (8). To this effect, it is important to define an adaptive adjustment coefficient (k_1), which is responsible for readjusting the quadrilateral characteristics (R_{set} and X_{set}) of the distance protection shown in Figure 2. The k_a factor is defined in Equation (10).

$$k_a = \left| \frac{\sin(\varphi_{line}) + \psi}{\sin(\varphi_{ui} + \psi)} \right| \tag{10}$$

D. Approach introduced by (Liang *et al.*, 2020)

The approach by Liang *et al.*, 2020 proposes a protection scheme based on voltage amplitude comparison. The main objective is to reduce fault resistance problems by using the fault-point voltage, measured current, and setting impedance to establish a virtual measured voltage. The approach is divided into two schemes: the first one identifies in-zone and out-of-zone faults from all types of faults by comparing the amplitudes of the original ($\dot{U}_m$) presented in Equation (8) and the virtual ($\dot{U}'_m$) measured voltages in Equation (11).

$$\dot{U}'_m = \dot{I}_m Z_{set} + \dot{U}_f \tag{11}$$

According to Figure **4**, a phasor analysis is performed to represent the original and virtual voltages. Consequently, a new distance protection criterion is proposed, as shown in Equation (12).

$$\begin{cases} |\dot{U}'_m| \geq |\dot{U}_m|, & \text{in zone fault} \\ |\dot{U}'_m| < |\dot{U}_m|, & \text{out of zone fault} \end{cases} \tag{12}$$

The second scheme is aimed to identify in-zone and out-of-zone faults under all fault types, based on the improved original and virtual measured voltages. It is considered essential to improve the sensitivity of distance protection because the measured fault voltage varies according to the fault resistance, which can lead to measurement and calculation errors; an in-zone fault may be misidentified as an out-of-zone fault, thus causing a distance protection malfunction.

Consequently, the sensitivity of the proposed protection scheme is then improved by introducing a special voltage phasor ($\dot{U}_{fset}$), which is expressed in Equation (13).

$$\dot{U}_{fset} = U_{set} < (\dot{U}_f) \tag{13}$$

where U_{set} is the setting voltage. Therefore, the voltages in Equations (8) and (11) are modified by replacing the fault voltage ($\dot{U}_f$) with the special voltage phasor ($\dot{U}_{fset}$), obtaining the improved original ($\dot{U}_{m\_imp}$) and improved virtual ($\dot{U}'_{m\_imp}$) voltages as a result. Thus, the proposed protection criterion shown in Equation (12) is conserved, but the compared magnitudes change with these improved measures. Equations (14) and (15) show the possible values of the $\dot{U}_{m\_imp}$ and $\dot{U}'_{m\_imp}$ magnitudes determined from Figure **4**.

If $|\dot{U}_f| < U_{set}$

$$\begin{aligned} |\dot{U}_{m\_imp}| = |\dot{U}_m|; \qquad & |\dot{U}'_{m\_imp}| = |\dot{U}'_m| \\ |\dot{U}'_m| = \sqrt{|\dot{U}_m|^2\left(\frac{\sin\varphi_{mz}}{\sin\varphi fz}\right)^2 + |\dot{I}_m Z_{set}|^2 + 2|\dot{U}_m||\dot{I}_m Z_{set}|\sin\varphi_{mz}\cot\varphi_{fz}} \end{aligned} \tag{14}$$

If $|\dot{U}_f| \geq U_{set}$

$$\begin{aligned} |\dot{U}_{m\_imp}| = \sqrt{|\dot{U}_m|^2 + (|\dot{U}_f| - U_{set})^2 - 2|\dot{U}_m|(|\dot{U}_f| - U_{set})\cos(\varphi_{fz} - \varphi_{mz})} \\ |\dot{U}'_{m\_imp}| = \sqrt{U_{set}^2 + |\dot{I}_m Z_{set}|^2 + 2U_{set}|\dot{I}_m Z_{set}|\cos\varphi_{fz}} \end{aligned} \tag{15}$$

where φ_{fz} is the angular difference between $\dot{I}_m Z$ and $\dot{U}_f$, and φ_{mz} is the angular difference between $\dot{I}_m Z$ and $\dot{U}_m$, as presented in Figure **4**

E. Approach proposed by (Yin *et al.,* 2021)

A particular case unfolds when DG units are connected at the utility side of the transformer. It is therefore interesting to analyze the problems and challenges associated with the point of interconnection (POI). In Yin *et al.,* 2021, a new distance protection method is presented, whose objective is to introduce an enhanced measured impedance calculation using residual voltage compensation to correctly and timely detect all fault types, particularly SLG faults at the POI. The protection scheme considers a previous analysis of the apparent impedance for SLG faults, aimed to find the root cause of the incorrect apparent impedance seen by the distance relay on the DG side. In this case, the distance relay on the DG integration side sees an SLG fault in the interconnection line as a phase-to-phase fault due to the commonly used delta-wye transformer configuration.

The proposal is based on a residual-voltage-compensated method for reliable POI protection. To this effect, a broken-delta high-voltage transformer (VT) is used to feed the proposed relays 21 on the DG integration side in order to provide residual voltage (V_0) for calculating the compensated impedance. This adjustment enables the measurement of the correct apparent impedance for all faults, including SLG faults by the relay. The following considerations must be made: (i) V_0 on the utility side should be converted to the DG side, and (ii) the angle of V_0 needs to be shifted based on the interconnection transformer winding connection. After considering the impedance compensations for the transformer winding connection used (YD11), the measured impedance for the phase-to-ground ($Z_{m,ag}$) can be obtained as shown in Equation (16).

$$Z_{m,ag} = \frac{V_a - V_b}{I_a - I_b} + \frac{V_0 e^{j30}}{2I_{1DG}} \tag{16}$$

where I_{1DG} is the positive sequence fault current contributions from the DG side. Considering the above, the proposed five-module distance relay is presented in Figure 5. The modules are as follows:

1. *Phasor calculation module:* it calculates the phasor values from the CTs and VTs using sampling techniques.
2. *Impedance compensation module:* it estimates the compensation factor using the residual voltage at the utility side and the positive-sequence current at the DG side.
3. *Angle shift module:* it shifts the angle of V_0 based on the interconnection transformer winding configuration.
4. *Impedance calculation module:* it calculates the measured impedance based on transformer connection.
5. *Fault detection module:* it detects the fault using typical distance relay operation characteristics.

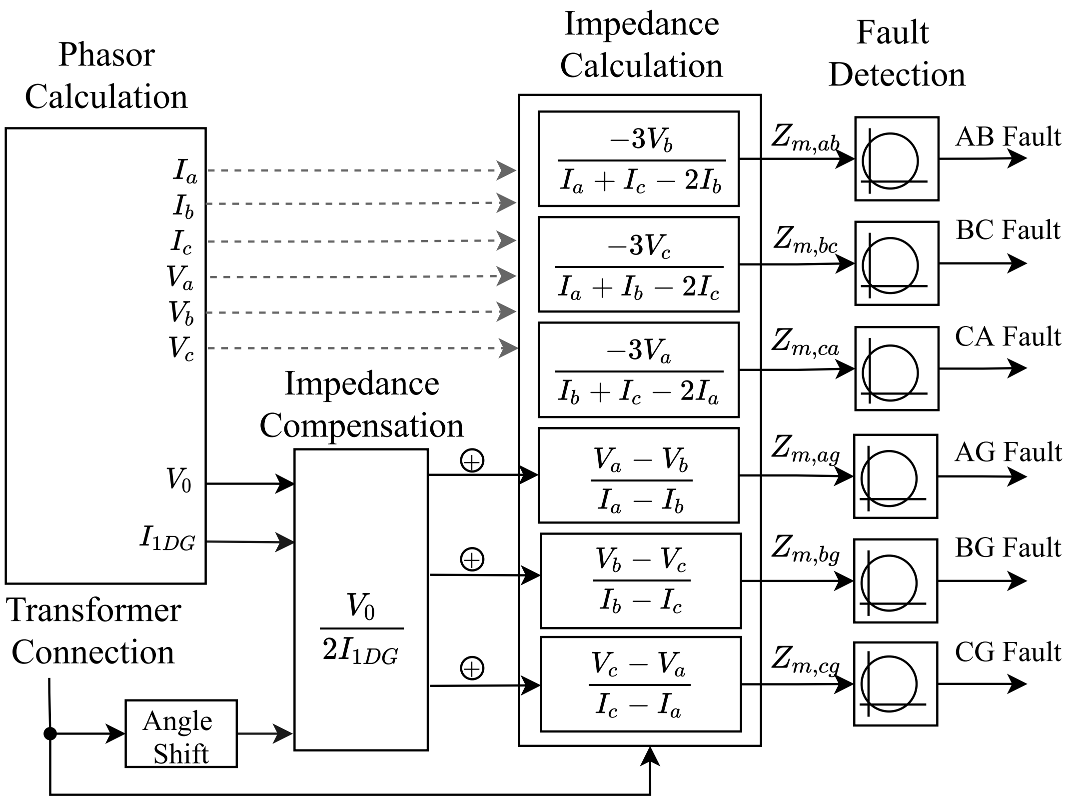

Figure 5. Block diagram of distance relay with residual voltage compensation

Source: Yin *et al.*, 2021.

F. Approach presented by (Chen *et al.*, 2018)

The detection of the active power flow direction in case of a fault is critical for the correct operation of 21 protection. Chen *et al.*, 2018 propose a distance relay in the time domain based on the R-L differential equation algorithm, which is suitable for wind power integration systems and also solves the direction identification problem mainly when zero-voltage faults occur.

The proposal considers a directional element based on the time domain and the differentiated characteristics of the memory voltage drop and the actual voltage drop, on equivalent impedance from relay location to power sources under forward and reverse fault conditions. This proposal also includes the correlation criterion to detect the fault direction. In this approach, a model of double-fed induction generator (DFIG) based wind farm with characteristics of the transient electromotive force (EMF) is established. To determine the directional feature, the memory voltages drop ($\dot{U}_1, \dot{U}_3$), and the actual voltages ($\dot{U}_2, \dot{U}_4$) are used as follows:

1. If $\dot{U}_1$ and $\dot{U}_2$ have the same variation trend after the fault, it is a forward fault.

2. If $\dot{U}_3$ and $\dot{U}_4$ have the same variation trend after the fault, it is a reverse fault.

These voltages are obtained as shown in Equation (17).

$$\dot{U}_1 = \dot{U}_{m,m} + \left(R_{GD}\dot{I}_{m,m} + L_{DG}\frac{d\dot{I}_{m,m}}{dt} \right) - \dot{U}_{m,f}$$
$$\dot{U}_2 = R_{DG}\dot{I}_{m,f} + L_{DG}\frac{d\dot{I}_{m,f}}{dt}$$
$$\dot{U}_3 = \dot{U}_{m,m} + (R_{G1} + R_l)\dot{I}_{m,m} - (L_{G1} + L_l)\frac{d\dot{I}_{m,m}}{dt} - \dot{U}_{m,f}$$
$$\dot{U}_4 = -(R_{G1} + R_l)\dot{I}_{m,f} - (L_{G1} + L_l)\frac{d\dot{I}_{m,f}}{dt} \tag{17}$$

where, $\dot{U}_{m,m}$ and $\dot{I}_{m,m}$ are the memory voltage and memory current; and $\dot{U}_{m,f}$ and $\dot{I}_{m,f}$ are the measured voltage and measured current after a fault, respectively. Next, if $\dot{U}_m$ after the fault is higher than U_{set}, a distance (l) from the relay location to the fault point is calculated based on the R-L differential-equation algorithm, as given by Equation (18). If the estimated distance l is larger than the setting value l_{set}, it is an external fault. If $0 < l < l_{set}$, it is an internal fault. If the estimated distance, l, is negative, it is an external fault. If the $\dot{U}_m$ after the fault is lower than U_{set}, the previously described method is used to detect the fault direction.

$$\dot{U}_m = \dot{U}_f + \left[L_{l1}\frac{d(\dot{I}_m - \dot{I}_{m0})}{dt} + R_{l1}(\dot{I}_m - \dot{I}_{m0}) + L_{l0}\frac{d\dot{I}_{m0}}{dt} + R_{l0}\dot{I}_{m0}l \right] \tag{18}$$

G. Approach introduced by (Tsimtsios *et al.,* 2019):

Several protection proposals use communication systems to adapt and improve the operational performance of distance protection. As an example, a pilot-based distance protection scheme for meshed distribution systems with DG is proposed by Tsimtsios *et al.,* 2019. The main contribution of this approach is proposing an efficient protection strategy for meshed grids since most of the networks that integrate DGs are radial, and this scheme provides protection with a considerable fault resistance and under the infeed conditions.

The meshed distribution system used in the test contains forward and reverse distance protection, which is essential to detecting the fault direction in its corresponding zones. The proposed logic depends on these elements, as well as the correct operation of the communication system. The approach proposes that, after the fault impedance estimation, the algorithm checks if it lies inside the forward distance zone. In that case (and after the time required for the relay to respond expires), a permission signal is sent to forward distance elements (FDE). If a permission signal is received from FDE at the same time, the circuit breaker (CB) is tripped. If the CB fails to open, a breaker-failure function is designed for the adjacent CBs.

H. Approach presented by (Tsimtsios *et al.,* 2019a, Tsimtsios *et al.,* 2019b)

A generalized distance-based protection design for DG integrated MV radial distribution networks is proposed in two parts. The former, presented in Tsimtsios *et al.,* 2019a, proposes a complete guideline for designing directly applicable and economically feasible distance protection schemes for medium-voltage (MV) radial distribution systems with distributed generation. In the second part, these guidelines are applied to a real MV radial overhead distribution line with a high DG penetration level. The proposed guidelines intend to take account of distributed generation, dealing with the issues already mentioned in the previous sections and the coordination of relays 21. The procedure is systematic and independent of specific DG conditions, while it must be performed only once for a particular distribution system. Moreover, the designed protection scheme is intended to guarantee simplicity; to this effect, it installs the minimum number of distance relays, given that the proposed guidelines are implementable using existing distance relay technology and without using communication means. This guideline is divided into the following sections: 1) basic protection scheme design, 2) distance zone time setting criteria used to determine the time delay settings and the number of relays 21, 3) distance zones reach setting criteria used to determine the zones reactive/resistive coverage to ensure dependability, 4) unintentional lateral coverage setting criteria to address overreaching of laterals by lower-step distance zones; and 5) the additional setting adjustments.

METHODOLOGY

The approaches analyzed above present several alternatives that contribute to mitigating the problems associated with distance protection applied to ADNs. However, to identify future opportunities to develop research proposals related with that protection, a comparative analysis of the proposals above is considered in this paper, which is presented in Table 1. This qualitative analysis allows identifying research gaps and associated challenges related to applying distance protection relays. As can be seen, no proposal covers all the ADN protection requirements. This represents a challenging task, and it suggests the importance of proposing and developing new strategies for adequate ADN protection.

CONCLUSIONS

This paper provides a comprehensive review of some recent adaptive protection strategies based on the implementation of distance relays in ADNs. The analysis compares the advantages, difficulties, and limitations of these approaches based on their operational characteristics. In addition, the proposals are classified according to the different issues covered in their models, thus affecting the protective device's correct performance. Therefore, it is concluded that, despite all the efforts made

Table 1. Comparison of protection approaches based on distance relays

Reference	Issues					Applied to			Observations
	Infeed Effect	Fault Resist.	Direction	Communic.	K_0 factor	Transmission	Distribution	ADN	
Sinclair *et al.*, 2014	•	•			•		•	•	This considers a perfect performance of the directional relay feature.
Tsimtsios & Nikolaidis, 2018	•				•		•	•	The effect of the fault resistance is not considered. The setting criteria for coverage and time delay in case of faults in remote relay areas is not analyzed.
Ma *et al.*, 2015		•			•	•			The proposed scheme is not affected by transition fault resistance or load current in transmission lines, or even in ADN.
Liang *et al.*, 2020		•				•			The mitigation of CT saturation and VT errors is considered to improve 21 performance.
Yin *et al.*, 2021		•	•		•		•	•	This proposal provides an economical solution as it can be implemented in the existing distance relay platform. Nonetheless, its application is limited to relays at the POI.
Chen *et al.*, 2018			•			•		•	The direction method is easy to implement within a short data window under zero-voltage faults. This is analyzed only for transmission lines that integrate DG.
Tsimtsios *et al.*, 2019	•	•	•	•	•		•	•	This approach depends on a communication system to function properly, which affects the reliability of the protection scheme.
Tsimtsios *et al.*, 2019a Tsimtsios *et al.*, 2019b	•	•			•	•	•	•	These protection schemes are economically feasible since the distance relays depend only on local measurements.

Source: Authors.

to propose solutions to mitigate ADN protection issues, there is no efficient strategy for all types of faults in a selective, sensitive, reliable, and cost-effective way, ensuring minimum supply disruption to consumers. Finally, this paper provides directions for developing more complete strategies to adequately improve the AND protection.

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About the presentation format

Submitted articles must be unpublished works written in Spanish or English, and must be typed in Microsoft Word (2003 and beyond), complying with the following indications:

- *Times New Roman* letter, 12 point (except it is required for some sections).
- One column, double-spaced.
- All the margins 3 cm.
- Paragraphs should be justified without spaces between consecutives and without cutting words.
- Do not include page breaks or section finals.
- If you want to emphasize words or phrases from the text, do not use bold letters but italic.
- Decimals should be pointed with comma (,) and not with period (.).
- Thousands and millions should be pointed with a fine space.
- Avoid footnotes.
- Arabic nomenclature must be used only until the third level.

About the article structure

The papers must have the following structure and comply with the following requirements:

Composition of an article

All the articles submitted for evaluation and possible publication by the Tecnura Journal must have at least the following components:

- Title in Spanish and English.
- Information about the authors.
- Abstract in Spanish and English.
- Key words in Spanish and English.
- Introduction.
- Conclusions.

- Future work (optional).
- Acknowledgements (optional).
- Bibliographical references.

If the article is related to scientific and technological research must have, in addition to the above, the following components:

- Methodology.
- Results.
- Financing.

Title

The title of the article must be short or divided in title and subtitle, attractive for the potential reader and written in capital letters. It should appear centered between the margins, written in *Times New Roman* letter, in bold, font size 18. The title of the article has to be in Spanish and English separated by double space. Maximum 20 words.

Authors

After the title the complete name(s) of the author(s) must be written, with their basic biographical data: undergraduate degree, graduate degree, occupation or position, institutional affiliation (institution where they work), dependency, city, country and e-mail. The above information must be immediately below the author's name.

Abstract

The scope and purpose of the work must be established giving a clear and concise description of the methodology, results presented and the conclusions obtained. Maximum of 250 words.

Keywords

Between three and ten keywords must be chosen, written in English with *Times New Roman* letter in bold and italic.

Key words must be written in alphabetic order and must be as standard as possible, for which it is suggested the use of international databases accor- ding to the area of knowledge. For example, in the area of Electrics and Electronics it is suggested to use the IEEE thesaurus and World Bank thesaurus that can be accessed at the following web pages respectively:

`http://www.ieee.org/documents/2009Taxonomy_v101.pdf` http://multites.net/mtsql/wb/site/default.asp

Abstract in Spanish

Translation to the Spanish language of the text that appears in the abstract, it must be correct and precise.

Keywords in Spanish

Translation to the English language of the keywords in Spanish, they must be correct and precise.

´ Keywords must be written in the order of the English version and must be as standard as possible, for which it is suggested the use of international databases according to the area of knowledge. For example, in the area of Electrics and Electronics it is suggested to use the UNESCO thesaurus that can be found at the following web pages:

http://databases.unesco.org/thessp

Introduction

The general idea of the work must be described, its context, backgrounds, state of the art of the topic, objectives and possible scope of the work.

Methodology

The writing of this part must allow any specialized professional in the topic to replicate the research.

Results

Explanation and interpretation of the findings. If necessary, a brief discussion focused on the interpretation of the results can be presented.

Conclusions

Implication of the results and their relation to the proposed objective.

Financing

Mention the associated research from which the article was derived and the entity that endorsed and financed the research.

Acknowledgments

They should preferably be brief and include the essential contributions for the development of the paper.

Equations

Equations must appear centered with respect to the main text. They must be referenced with consecutive numbers (written in parenthesis close to the right margin). Equations are cited in the main text employing the word equation, and followed by the number in parenthesis. Equations must be made in an appropriate equation editor and compatible with "InDesign" software, as for example the equation editor of Windows.

Tables

In the case of implementation of tables, it is recommended that these are not inserted as images, considering that in that format they cannot be modified. The title of each table must include the word table (in italic) followed by the corresponding consecutive number and a brief name of the table. The heading must be written in TNR letter, italic and font size 9.

Charts are not presented but tables and they should be automatically raised from the text processor. Tables should be named and referenced in the article, in strict order. Every table must have at the bottom the source from which it was taken, or to mention self-authorship if it is the case.

Figures

All the figures or pictures have to be sent in JPG or PNG format with a minimum resolution of 300 DPI, adapted to gray scale.

The footnote or name of each figure must include the word figure (in italic) followed by the corresponding consecutive number and a brief description of the content of the figure. The footnote of the figure must be written in Times New Roman letter, italic and font size 9. Figures must be named and referenced in the article, in strict order. Every figure must have at the bottom the source from which it was taken, or to mention self-author-ship if it is the case.

Symbols

The symbols of the constants, variables and functions in Latin or Greek letters –included in the equations- must be in italic; the mathematical symbols and the numbers do not go in italic. The symbols must be identified immediately after the equation. Units, dimensions and symbols of the international system must be used.

When using acronyms or abbreviations, the complete equivalence should be written first, followed by the corresponding acronym or abbreviation in parenthesis and from there it is only written the respective acronym or abbreviation.

Bibliographic references

The adopted reference citation style by Tecnura journal is APA sixth edition. The cites, bibliographic references and infography are included in the last part of the article. The bibliographic references must be alphabetically ordered according to the author's first surname, without numbering.

There should only appear the cited references in the main body of the work, in tables or in figures.

It means, in the list there should not appear other references although they have been consulted by the authors for the work preparation. We suggest using tools such as: Cites and bibliography from Microsoft Word (for APA sixth edition version 2013 or superior), Zotero, Mendeley, among others.

The call for a bibliographic reference is inserted in the text, at the pertinent point, under certain characteristics:

- If the sentence includes the author's surname, it should only be written the date into a parenthesis, for instance:
  Cuando Vasco (2012), analizó el problema de presentado en ....
- When the author is not included in the sentence, surname and date must be into a parenthesis. La investigación de materiales dio una visión en el área (Martínez, 2012).
- If the document or work has more than two authors, the first cite must include all the surnames. 1990. (Fernández Morales, Villa Krieg & Caro de Villa, 2008) ....
- In the following mentions, it must only be written the author's first surname, followed by "et al.". En cuanto al estudio de las aguas, Fernández Morales et al. (2008) encontraron que ...
- When the document or work has more than six authors, it must be used from the first mention "et al.".

Next it is described a series of examples of the more used references, according to the reference style adopted by Tecnura journal:

Periodical Publications:

Basic Form

Surnames, A. A., Surnames, B. B. & Surnames, C. C. (Date). Article's title. Title of the publication, volu- me (number), pp. xx-xx. doi: xx.xxxxxxx

Basic article

Guevara López, P., Valdez Martínez, J., Agudelo González, J., & Delgado Reyes, G. (2014). Aproximación numérica del modelo epidemiológico SI para la propagación de gusanos informáticos, simulación y análisis de su error. Revista Tecnura, 18(42), 12 -23. doi:http://dx.doi.org/10.14483/udistrital.jour.tecnura.2014.4.a01

Web article

Rodríguez Páez, S., Fajardo Jaimes, A., & Páez Rueda, C. (2014). Híbrido rat-race miniaturizado para la banda ISM 2,4 GHZ. Revista Tecnura, 18(42), 38-52. Recuperado de http://revistas.udistrital.edu.co/ojs/index.php/Tecnura/article/view/8059/9675

Books:

Basic Form

Surnames, A. A. (Year). Title. City: Editorial.

Surnames, A. A. (Year). Title. Recovered from http://www.xxxxxx.xxx

Surnames, A. A. (Year). Title. doi: xx.xxxxxxxx

Surnames, A. A. (Ed.). (Year). Title. City: Editorial.

Book with author

Goleman, D. (2000). La inteligencia emocional: Por qué es más importante que el cociente intelectual. México: Ediciones B.

Book with editor:

Castillo Ortiz, A. M. (Ed.). (2000). Administración educativa: Técnicas, estrategias y prácticas gerenciales. San Juan: Publicaciones Puertorriqueñas.

Book elecronic version:

Montero, M. & Sonn, C. C. (Eds.). (2009). Psychology of Liberation: Theory and applications. [Versión de Springer]. doi: 10.1007/ 978-0-387-85784-8

Technical report:

Basic Form

Surnames, A. A. (Year). Title. (Report No. xxx). City: Editorial

Report with authors

Weaver, P. L., & Schwagerl, J. J. (2009). U. S. *Fish and Wildlife Service refuges and other nearby reserves in Southwestern Puerto Rico*. (General Technical Report IITF-40). San Juan: International Institute of Tropical Forestry.

Report from a Government agency

Federal Interagency Forum on Child and Family Statistics. America's Children: Key National Indicators of Well-Being, 2009. Washington, DC: U.S. Government Printing Office. Recuperado de http://www.childstats.gov/pubs/index.asp

Thesis

Basic form

Surnames, A. A. (Year). Title. (Unpublished master or doctorate thesis). Institution name, Location.

Unpublished thesis, printed

Muñoz Castillo, L. (2004). *Determinación del conocimiento sobre inteligencia emocional que poseen los maestros y la importancia que le adscriben al concepto en el aprovechamiento de los estudiantes*. (Tesis inédita de maestría). Universidad Metropolitana, San Juan, PR.

Commercial database thesis

Santini Rivera, M. (1998). *The effects of various types of verbal feedback on the performance of selected motor development skills of adolescent males with Down syndrome*. (Tesis doctoral). Disponible en la base de datos ProQuest Dissertations and Theses. (AAT 9832765).

Web thesis

Aquino Ríos, A. (2008). *Análisis en el desarrollo de los temas transversales en los currículos de español, matemáticas, ciencias y estudios sociales del Departamento de Educación*. (Tesis de maestría, Universidad Metropolitana). Recuperado de `http://suagm.edu/umet/biblioteca/UMTESIS/Tesis_Educacion/ARAquinoRios1512.pdf`

Standards or patents

Basic form

Surnames, A. A. Title of the patent. Country and number of the patente. Classification of the patent, date of official license. Number and date of patent request, pagination.

Hernández Suárez, C. A., Gómez Saavedra, V. A., & Peña Lote, R. A. Equipo medidor de indicadores de calidad del servicio de energía eléctrica para usuario residencial. Colombia., 655. G4F 10/0, 15 de Marzo 2013. 27 de Octubre 2011, 147

ARTICLE SUBMISSION

Authors must submit their articles through the application Open Journal System in digital format, attaching the cover letter and the article-authors format.

Cover letter

The article must be submitted with a cover letter addressed to the director and editor of the journal, Engineer Cesar Augusto Garcia Ubaque, including:

- Specific request to consider your article to be published in Tecnura journal.
- Full title of the article.
- Full names of all the authors of the paper.
- Certification of the originality and unpublished character of the paper.

- Exclusivity of submission to Tecnura journal.
- Authoring confirmation with signature of all the authors.

This letter must be signed by all the authors, scanned and sent with the remaining requested documents.

Article-authors information format

The article has to be submitted with an information format about the article and its authors which can be downloaded from the web page of Tecnura journal http://revistas.udistrital.edu.co/ojs/index.php/Tecnura/index, in the section "Forms and Documents". It is important to complete all the fields of information requested, some of them have comments to clarify better what is being requested. The format must not be scanned.

Article

Article in digital format (Word 2003 and later editions) that complies with all the presentation rules described in chapter three, "Article structure", of this guide of instructions for authors.

PUBLICATION PROCEDURE

The procedure to be followed by Tecnura journal for the evaluation and possible publication of the papers sent by the authors is the following in chronological order:

1. Delivery of the article with the cover letter and the information format by the authors.
2. Notification to the author about the reception of the article.
3. Verification of the presentation rules by the monitor of the journal.
4. Notification to the author about the evaluation of the presentation rules.
5. Submission of corrections made by the authors related to the evaluation of presentation rules.
6. Submission of the articles to the selected arbitrators.
7. Notification of the beginning of the arbitration process of the article.
8. Notification to the authors about the decision made by the editorial committee, and about the evaluations made by the arbitrators.
9. Delivery of the corrections made by the authors with respect to the evaluations made by the arbitrators.
10. Study of the final version of the article and the evaluations of the arbitrators by the editorial committee.

11. Delivery by the authors of the letter that surrenders right to the editor of the journal.
12. Submission of the version with style corrections and diagramed to the authors.
13. Verification of errors and final approval of the version with style corrections and diagrammed by the authors.
14. Publication of the article in the corresponding number of Tecnura journal.
15. Notification to the authors of the number of interest.
16. Delivery of a copy of the journal to each one of the authors of the published article.

ARTICLE ARBITARION PROCESS

Considering the quarterly periodicity of the journal, the Editorial Committee makes four calls every year for the submission of articles, approximately in the months of February, May, August and November. The articles will be received until the date established in the call.

Once received the articles, the monitor of the journal will make an initial form evaluation to verify the completion of the elements mentioned in this guide of instructions to authors. After receiving again the article with the requested corrections by the journal's monitor, the paper will be submitted to evaluation by three academic peers (through time it is expected to include more external peers to participate in the process).

Each article sent to Tecnura journal is checked by two expert academic peers external to the institution of the authors, by a process of "*Peer-review*" of double blind, guaranteeing the anonymity of authors and evaluators; every paper sent is considered confidential and so it is demanded to evaluators.

Possible conclusions of the result of the evaluation by the judges are only three: publish the article without modifications, publish the article with modifications and not publish the article.

Subsequently, the Editorial Committee takes the decision to publish or not the articles, based on the results of the evaluations made by the assigned arbitrators. In case of contradictions in the evaluations with respect to the publication of an article, the editorial committee will send the article to a third peer and will be inclined for the two evaluations that have the same concept with respect to the publication of the article.

In each call the main author must suggest at least four possible external arbitrators to his work institution evaluators, who must be specialists in the specific topic of the article sent and must have at least Masters level, and at least two must to be international. Potential evaluators can belong to a university or industry, public or private; their complete names must be provided, highest academic formation, institutional affiliation and e-mail. The editorial committee will analyze these four potential evaluators in order to enrich the database of arbitrators of Tecnura journal.

Instructions for authors

https://revistas.udistrital.edu.co/index.php/Tecnura/about/submissions

The Editorial Committee of Tecnura journal reserves the right to print, reproduce total or partially the article, as the right to accept or reject it. In the same way, it has the right to make any editorial modification that considers necessary; in this case the author will receive written recommendations from the evaluators. If accepted, authors must deliver the article with the suggested adjustments within the dates given by the journal to guarantee its publication in the programmed number.

CONTACT

For any additional information request, please send an e-mail to Tecnura journal tecnura@udistrital.edu.co, tecnura@gmail.com or by mail to Cesar Augusto Garcia Ubaque, Director and Publisher of Tecnura Journal, to the following address:

Tecnura Journal
Journals Room, Block 5, Office 305.
Faculty of Technology
Universidad Distrital Francisco José de Caldas
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tecnura.ud@correo.udistrital.edu.co, tecnura@gmail. com
Web page:
https://revistas.udistrital.edu.co/ojs/index.php/ Tecnura/index

Instrucciones para los autores

https://revistas.udistrital.edu.co/index.php/Tecnura/about/submissions

CONTENIDO

ALCANCE Y POLÍTICA EDITORIAL DE LA REVISTA

La revista Tecnura es una publicación institucional de la Facultad Tecnológica de la Universidad Francisco José de Caldas, de carácter científico-tecnológico con periodicidad trimestral, que se publica los meses de enero, abril, julio y octubre. Su primer número apareció en el segundo semestre del año 1997 y hasta la fecha ha mantenido su regularidad.

Las áreas temáticas de interés de la revista Tecnura están enfocadas a todos los campos de la ingeniería, como la electrónica, telecomunicaciones, electricidad, sistemas, industrial, mecánica, catastral, civil, ambiental, entre otras. Sin embargo, no se restringe únicamente a estas, también tienen cabida los temas de educación y salud, siempre y cuando estén relacionados con la ingeniería. La revista publica únicamente artículos de investigación científica y tecnológica, de reflexión y de revisión. En consecuencia, durante la fase de evaluación editorial inicial se rechazarán los artículos cortos y reportes de caso.

La revista Tecnura está dirigida a docentes, investigadores, estudiantes y profesionales interesados en la actualización permanente de sus conocimientos y el seguimiento de los procesos de investigación científico-tecnológica, en el campo de las ingenierías. Tiene como misión divulgar resultados de proyectos de investigación realizados en el área de las ingenierías, a través de la publicación de artículos originales e inéditos, realizados por académicos y profesionales pertenecientes a instituciones nacionales o extranjeras del orden público o privado. Los artículos presentados deben ser trabajos inéditos escritos en español o inglés; sin embargo, tendrán preferencia los artículos que muestren conceptos innovadores de gran interés, que traten sobre asuntos relacionados con el objetivo y cobertura temática de la revista.

Instrucciones para los autores

https://revistas.udistrital.edu.co/index.php/Tecnura/about/submissions

Tecnura es una publicación de carácter académico indexada en los Índices Regionales Scielo Colombia (Colombia) y Redalyc (México), además de las siguientes bases bibliográficas: INSPEC del Institution of Engineering and Technology (Inglaterra), Fuente Académica Premier de EBSCO (Estados Unidos), CABI (Inglaterra), Index Corpernicus (Polonia), Informe Académico de Gale Cengage Learning (México), Periódica de la Universidad Nacional Autónoma de México (México), Oceanet (España) y Dialnet de la Universidad de la Rioja (España). También hace parte de los siguientes directorios: Sistema Regional de Información en Línea para Revistas Científicas de América Latina, el Caribe, España y Portugal Latindex (México), Índice Bibliográfico Actualidad Iberoamericana (Chile), e-Revistas (España), DOAJ (Suecia), Ulrich de Proquest (Estados Unidos).

Tecnura es una revista arbitrada mediante un proceso de revisión entre pares de doble ciego. La periodicidad de la conformación de sus comités Científico y Editorial está sujeta a la publicación de artículos en revistas indexadas internacionalmente por parte de sus respectivos miembros.

La Universidad Distrital Francisco José de Caldas, sus directivas, el Editor, el Comité Editorial y Científico no son responsables por la opinión y criterios expresados en el contenido de los artículos y estos se publican bajo la exclusiva responsabilidad de los autores y no necesariamente reflejan el pensamiento del Comité Editorial.

Además de la versión impresa, la revista Tecnura tiene también una versión digital disponible en su página web: `http://revistas.udistrital.edu.co/ojs/index.php/Tecnura`

TIPOS DE ARTÍCULOS ACEPTADOS

De acuerdo con la clasificación del Índice Nacional de Publicaciones Científicas y Tecnológicas (Publindex-Colciencias), la revista Tecnura recibe postulaciones de artículos inéditos de los siguientes tipos:

Artículos de investigación científica y tecnológica: documento que presenta, de manera detallada, los resultados originales de proyectos de investigación. La estructura generalmente utilizada contiene cuatro apartes importantes: introducción, metodología, resultados y conclusiones.

Artículo de revisión: documento resultado de una investigación donde se analizan, sistematizan e integran los resultados de las investigaciones publicadas o no publicadas, sobre un campo en ciencia o tecnología, con el fin de dar cuenta de los avances y las tendencias de desarrollo. Se caracteriza por presentar una cuidadosa revisión bibliográfica de al menos 50 referencias.

FORMATO DEL ARTÍCULO

Del lenguaje y estilo apropiado para la redacción de artículos

- Deben emplearse estructuras de oraciones simples, evitando las que sean demasiado largas o complejas.

- El vocabulario empleado debe ser básico y común. Los términos técnicos deben explicarse brevemente; asimismo, el significado de las siglas debe presentarse la primera vez que estas aparecen en el texto.
- Los autores son responsables de que su trabajo sea conducido de una manera profesional y ética.

De la extensión de los documentos

Los artículos no deben tener una extensión de más de 25 páginas en tamaño carta y a doble espacio, con márgenes simétricas de 3 cm. Solo en el caso de los artículos de revisión las 25 páginas no inclu- yen las referencias bibliográficas.

Del formato de presentación

Los artículos presentados deben ser trabajos inédi- tos escritos en español o inglés y deben digitarse en Microsoft Word (2003 en adelante), cumplien- do con las siguientes indicaciones:

Letra *Times New Román* de 12 puntos (a excep- ción de que se requiera lo contrario para algunos apartados).

- Una columna a doble espacio.
- Todas las márgenes de 3 cm.
- Los párrafos se justifican, y no debe haber espacio entre los consecutivos.
- No incluir saltos de página o finales de sección.
- Si se desea resaltar palabras o frases del texto, no usar letra negrita sino letra cursiva.
- Los decimales se deben señalar con coma (,) y no con un punto.
- Los millares y millones se deben señalar con un espacio fino.
- Evitar las notas de pie de página.
- Se debe utilizar nomenclatura arábiga hasta el tercer nivel únicamente.

De la estructura del documento

Los trabajos deben tener la siguiente estructura y cumplir con los siguientes requisitos:

Composición de un artículo

Todos los artículos remitidos para su evaluación y posible publicación por parte de la revista Tecnura deben tener por lo menos los siguientes componentes:

- Título en español e inglés.
- Información de los autores.
- Resumen en español e inglés.
- Palabras clave en español e inglés.
- Introducción.
- Conclusiones.
- Trabajo futuro (opcional).
- Agradecimientos (opcional).
- Referencias bibliográficas.

Si el artículo es de investigación científica y tec- nológica deben tener, además de lo anterior, los siguientes componentes:

- Metodología.
- Resultados.
- Financiamiento.

Título

ítulo El título del artículo deberá ser corto o dividido en título y subtítulo, atractivo para el lector potencial y escrito en mayúscula sostenida. Este debe aparecer centrado entre las márgenes, escrito con letra *Times New Roman*, en negrita, tamaño de fuente 18. El título del artículo debe ir en español e inglés separado por un espacio doble. Máximo 20 palabras.

Autores

Después del título debe escribirse el (los) nombre(s) completo(s) del (los) autor(es), acompañado de los datos biográficos básicos: título de pregrado, título de posgrado, ocupación o cargo, afiliación institucional (institución donde labora), dependencia, ciudad, país y correo electrónico. La información anterior debe ir inmediatamente debajo del nombre del autor.

Resumen

Debe establecer el objetivo y alcance del trabajo, una descripción clara y concisa de la metodología, los resultados y las conclusiones obtenidas. Máximo 250 palabras.

Palabras clave

Debe escogerse entre tres y diez palabras clave, escritas en español con letra *Times New Roman*, en negrita y cursiva.

Las palabras clave deben estar escritas en orden alfabético y ser de uso estandarizado, para lo cual se sugiere utilizar bases de datos internacionales según el área del conocimiento. Por ejemplo, en el área de Eléctrica y Electrónica se sugiere utilizar el tesauro de la UNESCO que se pueden encontrar en la página: http://databases.unesco.org/thessp.

Abstract

Debe ser una traducción correcta y precisa al idioma inglés del texto que aparece en el resumen en español.

Keywords

Debe ser una traducción correcta y precisa al idioma inglés de la lista de palabras clave en español.

Las *keywords* deben estar escritas en el orden de las palabras clave y ser de uso estandarizado, para lo cual se sugiere utilizar bases de datos in- ternacionales según el área del conocimiento. Por ejemplo, en el área de Eléctrica y Electrónica se sugiere utilizar los Tesauros de la IEEE y/o World Bank que se pueden encontrar en las siguientes páginas respectivamente: http://www.ieee.org/documents/2009Taxonomy_v101.pdf, http://multites.net/mtsql/wb/site/default.asp

Introducción

Debe describir el planteamiento general del trabajo, así como contexto, antecedentes, estado de arte de la temática abordada, objetivo y posible alcance del trabajo.

Metodología

La redacción de este apartado debe permitir a cualquier profesional especializado en el tema replicar la investigación.

Resultados

Explicación e interpretación de los hallazgos. Si es necesario, se puede presentar una discusión breve y enfocada a la interpretación de los resultados.

Conclusiones

Implicación de los resultados y su relación con el objetivo propuesto.

Financiamiento

Mencionar la investigación asociada de la cual se derivó el artículo y la entidad que avaló y financió dicha investigación.

Agradecimientos

Preferiblemente deben ser breves y deben incluir los aportes esenciales para el desarrollo del trabajo.

Ecuaciones

Deben aparecer centradas con respecto al texto principal. Las ecuaciones deben ser referenciadas con números consecutivos (escritos entre paréntesis cerca al margen derecho). Las ecuaciones se citan en el texto principal empleando la palabra ecuación y seguida del número entre paréntesis. Las ecuaciones deben ser elaboradas en un editor de ecuaciones apropiado y compatible con el paquete de software InDesign, por ejemplo, el editor de ecuaciones de Windows.

Tablas

Para el caso de realización de tablas se recomienda que estas no sean insertadas como imágenes, considerando que en este formato no pueden ser modificadas. El encabezado de cada tabla debe incluir la palabra Tabla (en negrita) seguida del número consecutivo correspondiente y de un breve nombre de la tabla. El encabezado debe estar escrito con letra Times New Roman, en cursiva y tamaño de fuente 9.

No se presentan cuadros sino tablas y estas se deben levantar automáticamente desde el procesador de textos. Las tablas deben ir nombradas y referenciadas en el artículo, en estricto orden. Toda tabla debe tener en su parte inferior la fuente de la que fue tomada, o mencionar que es autoría de los autores si es el caso.

Figuras

Todas las figuras o fotografías deben enviarse en formato PNG o TIFF con una resolución mínima de 300 DPI, adaptadas a escala de grises.

El pie o rótulo de cada figura debe incluir la palabra Figura (en negrita) seguida del número consecutivo correspondiente y de una breve descripción del contenido de la figura. El pie de figura debe estar escrito con letra Times New Roman, en cursiva y tamaño de fuente 9. Las figuras deben ir nombradas y referenciadas en el artículo, en estricto orden. Toda figura debe tener también la fuente de la que fue tomada, o mencionar que es autoría de los autores si es el caso.

Símbolos

Los símbolos de las constantes, variables y funciones en letras latinas o griegas –incluidos en las ecuaciones– deben ir en cursiva; los símbolos matemáticos y los números no van en cursiva. Se deben identificar los símbolos inmediatamente después de la ecuación. Se deben utilizar las unidades, dimensiones y símbolos del sistema internacional.

Cuando se empleen siglas o abreviaturas, se debe anotar primero la equivalencia completa, seguida de la sigla o abreviatura correspondiente entre paréntesis y en lo subsecuente se escribe solo la sigla o abreviatura respectiva.

Referencias bibliográficas

El estilo de citación de referencias adoptado por la revista Tecnura es APA sexta edición. Las citas, referencias bibliográficas e infografía se incluyen al final del artículo. Las referencias bibliográficas deben ordenarse alfabéticamente de acuerdo con el primer apellido del primer autor, sin numeración.

Solo deben aparecer las referencias que fueron citadas en el texto principal del trabajo, en las tablas o en las figuras. Es decir, en la lista no deben aparecer otras referencias aunque hayan sido consultadas por los autores para la preparación del trabajo. Sugerimos utilizar herramientas como: *Citas y bibliografía de Microsoft Word* (para APA sexta edición versión 2013 o superior), *Zotero, Mendeley*, entre otras.

El llamado de una referencia bibliográfica se inserta en el texto, en el punto pertinente, bajo ciertas características:

- Si la oración incluye el apellido del autor, solo se debe escribir la fecha dentro de un paréntesis, ejemplo:

  Cuando Vasco (2012), analizó el problema de presentado en . . . .

- Cuando no se incluye el autor en la oración, debe ir entre el paréntesis el apellido y la fecha. La investigación de materiales dio una visión en el área (Martínez, 2012).

- Si el documento u obra tiene más de dos autores, se debe citar la primera vez con todos los apellidos. 1990. (Fernández Morales, Villa Krieg & Caro de Villa, 2008) . . . .

- En las menciones siguientes, solo se debe escribir el primer apellido del autor, seguido de un "et al". En cuanto al estudio de las aguas, Fernández Morales et al. (2008) encontraron que . . .

- Cuando el documento u obra tiene más de seis autores, se debe utilizar desde la primera mención el "et al".

A continuación se describen una serie de ejemplos de las referencias más utilizadas, según el estilo de referencias adoptado por la revista Tecnura:

Publicaciones Periódicas:

Forma Básica

Apellidos, A. A., Apellidos, B. B. & Apellidos, C. C. (Fecha). Título del artículo. Título de la publicación, volumen (número), pp. xx-xx. doi: xx.xxxxxxx

Artículo básico

Guevara López, P., Valdez Martínez, J., Agudelo González, J., & Delgado Reyes, G. (2014). Aproximación numérica del modelo epidemiológico SI para la propagación de gusanos informáticos, simulación y análisis de su error. Revista Tecnura, 18(42), 12 -23. doi: http://dx.doi.org/10.14483/udistrital.jour.tecnura.2014.4.a01

Artículo web

Rodríguez Páez, S., Fajardo Jaimes, A., & Páez Rueda, C. (2014). Híbrido rat-race miniaturizado para la banda ISM 2,4 GHZ. Revista Tecnura, 18(42), 38-52. Recuperado de http://revistas.udistrital.edu.co/ojs/index.php/Tecnura/article/view/8059/9675

Libros:

Forma Básica

Apellidos, A. A. (Año). Título. Ciudad: Editorial.

Apellidos, A. A. (Año). Título. Recuperado de http://www.xxxxxx.xxx

Apellidos, A. A. (Año). Título. doi: xx.xxxxxxxx

Apellidos, A. A. (Ed.). (Año). Título. Ciudad: Editorial.

Libro con autor

Goleman, D. (2000). La inteligencia emocional: Por qué es más importante que el cociente intelectual. México: Ediciones B.

Libro con editor

Castillo Ortiz, A. M. (Ed.). (2000). Administración educativa: Técnicas, estrategias y prácticas gerenciales. San Juan: Publicaciones Puertorriqueñas

Libro versión electrónica:

Montero, M. & Sonn, C. C. (Eds.). (2009). Psychology of Liberation: Theory and applications. [Versión de Springer]. doi: 10.1007/ 978-0-387-85784-8

Informe técnico

Forma Básica

Apellidos, A. A. (Año). Título. (Informe Núm. xxx). Ciudad: Editorial

Informe con autores

Weaver, P. L., & Schwagerl, J. J. (2009). U. S. Fish and Wildlife Service refuges and other nearby reserves in Southwestern Puerto Rico. (General Technical Report IITF-40). San Juan: International Institute of Tropical Forestry.

Informe de una agencia del gobierno

Federal Interagency Forum on Child and Family Statistics. America's Children: Key National Indicators of Well-Being, 2009. Washington, DC: U.S. Government Printing Office. Recuperado de http://www.childstats.gov/pubs/index.asp

Tesis

Forma Básica

Apellidos, A. A. (Año). Título. (Tesis inédita de maestría o doctorado). Nombre de la institución, Localización.

Tesis inédita, impresa

Muñoz Castillo, L. (2004). *Determinación del conocimiento sobre inteligencia emocional que poseen los maestros y la importancia que le adscriben al concepto en el aprovechamiento de los estudiantes*. (Tesis inédita de maestría). Universidad Metropolitana, San Juan, PR.

Tesis de base de datos comercial

Santini Rivera, M. (1998). *The effects of various types of verbal feedback on the performance of selected motor development skills of adolescent males with Down syndrome*. (Tesis doctoral). Disponible en la base de datos ProQuest Dissertations and Theses. (AAT 9832765).

Tesis web

Aquino Ríos, A. (2008). *Análisis en el desarrollo de los temas transversales en los currículos de es- pañol, matemáticas, ciencias y estudios sociales del Departamento de Educación.* (Tesis de maestría, Universidad Metropolitana). Recuperado de http://suagm.edu/umet/biblioteca/UMTESIS/Tesis_Educacion/ARAquinoRios1512.pdf

Estándares o patentes

Forma Básica

Apellidos, A. A. Título de la patente. País y número de la patente. Clasificación de la patente, fecha de concesión oficial. Número y fecha de solicitud de la patente, paginación.

Hernández Suárez, C. A., Gómez Saavedra, V. A., & Peña Lote, R. A. Equipo medidor de indicadores de calidad del servicio de energía eléctrica para usuario residencial. Colombia., 655. G4F 10/0, 15 de Marzo 2013. 27 de Octubre 2011, 147

ENVÍO DE ARTÍCULOS

Los autores deben enviar sus artículos a través de la aplicación para tal fin del Open Journal System en formato digital, adjuntando la carta de presentación y el formato de información artículo-autores.

Carta de presentación

El artículo debe ir acompañado de una carta de presentación dirigida al director y editor de la revista, Ing. Cesar Augusto García Ubaque, donde incluya:

- Solicitud expresa de considerar su artículo para publicarlo en la revista Tecnura.
- Título completo del trabajo.
- Nombres completos de todos los autores del trabajo.
- Certificación de la originalidad y el carácter inédito del trabajo.
- Exclusividad de su remisión a la revista Tecnura.
- Confirmación de la autoría con la firma de todos los autores.

Esta carta deberá estar firmada por todos los autores, escanearse y enviarse junto con los demás documentos solicitados.

Formato de información artículo-autores

El artículo además debe ir acompañado de un formato de información sobre el artículo y sus autores, el cual se puede descargar de la página web de la revista Tecnura: http://revistas.udistrital.edu.co/ojs/index.php/Tecnura, en la sección "Formatos y Documentos". Es importante completar todos los campos de información solicitados, algunos de ellos tienen comentarios para aclarar mejor lo que se está solicitando. El formato no debe escanearse.

Artículo

Artículo en formato digital (Word 2003 en adelante) que cumpla con todas las normas de presentación descritas en el capítulo 3, "Formato del artículo", de la presente en las instrucciones a los autores.

PROCEDIMIENTO PARA LA PUBLICACIÓN

El procedimiento que sigue la revista Tecnura para la evaluación y posible publicación de los trabajos enviados por los autores es el siguiente en orden cronológico:

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2. Notificación al autor de correspondencia de la recepción del artículo.
3. Verificación del tema del artículo con respecto a las áreas de interés de la revista.
4. Verificación de las normas de presentación por parte del monitor de la revista.
5. Notificación al autor de correspondencia de la evaluación de las normas de presentación.
6. Envío de las correcciones realizadas por los autores con respecto a la evaluación de las normas de presentación
7. Envío del artículo a los árbitros seleccionados.
8. Notificación del inicio del proceso de arbitraje del artículo.
9. Notificación a los autores de la decisión tomada por el Comité Editorial y de las evaluaciones hechas por los árbitros.
10. Envío de las correcciones realizadas por los autores con respecto a las evaluaciones de los árbitros.
11. Estudio de la versión final del artículo y de las evaluaciones de los árbitros por parte del Comité Editorial.
12. Envío por parte de los autores de la carta de cesión de derechos al editor de la revista.
13. Envío de la versión con corrección de estilo y diagramada a los autores.
14. Verificación de errores y aprobación final de la versión con corrección de estilo y diagramada por parte de los autores.
15. Publicación del artículo en el número correspondiente de la revista Tecnura.
16. Notificación a los autores de la publicación del número de interés.
17. Envío de un ejemplar de la revista a cada autor del artículo publicado.

PROCESO DE ARBITRAJE DE ARTÍCULOS

Considerando la periodicidad trimestral de la revista, el Comité Editorial realiza cuatro convocatorias anuales para la recepción de artículos, aproximadamente en los meses de febrero, mayo, agosto y noviembre. Los artículos serán recibidos hasta la fecha máxima establecida en cada convocatoria.

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Cada artículo remitido a la revista Tecnura es revisado por dos pares académicos externos a la institución de los autores, mediante un proceso de "revisión entre pares" (*Peer-review*) de doble-ciego, garantizando el anonimato de los autores y evaluadores; se considera confidencial todo trabajo recibido y así se le exige a sus evaluadores.

Las posibles conclusiones de los resultados de la evaluación por parte de los árbitros son únicamente tres: publicar el artículo sin modificaciones, publicar el artículo con modificaciones o no publicar el artículo.

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En cada convocatoria el autor de correspondencia debe sugerir al menos cuatro posibles evaluadores externos a su institución laboral, los cuales deben ser especialistas en el tema específico del artículo remitido, tener al menos maestría y por lo menos dos deben ser internacionales. Los posibles evaluadores pueden pertenecer a una universidad o industria, pública o privada; de estos se debe proporcionar el nombre completo, su formación académica más alta, su afiliación institucional y su correo electrónico. Estos cuatro potenciales evaluadores serán analizados por el Comité Editorial a fin de ampliar la base de datos de los árbitros de la revista Tecnura.

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Para cualquier solicitud de información adicional puede comunicarse a través del correo electrónico de la revista Tecnura: tecnura@udistrital.edu.co, tecnura@gmail.com, o por mensajería con el Ing. Cesar Augusto García Ubaque, Director y Editor de la revista Tecnura, a la dirección:

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https://revistas.udistrital.edu.co/ojs/index.php/Tecnura

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