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Journal Industrial Engineering

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Content Presentation

In the first article we present *Study to obtain Activated Carbon at the laboratory level of the bagasse of the Maguey Pitzometl (Agave marmorata) of Zapotitlán Salinas, Puebla* by López-Vigil Miriam Silvia, Gómez-Flores Nidia Esther, Santos-Alvarado Héctor and Islas-Torres Héctor, with adscription in the Instituto Tecnológico de Tehuacán, as the next article we present *Methodology for the Proposal of a Technological Package Development in Hydrocarbon Production Facilities* by Mendoza-Espinoza, Héctor Eduardo, Escorza-Sánchez, Yolanda Marysol and Marquez-López, Ángel de Jesús, with adscription in the Universidad Politécnica de Tulancingo and Universidad Tecnológica del Valle del Mezquital, as the next article we present *Modeling of the supply and consumption of the Huatusco Veracruz wáter network using SIMIO software* by Rosas-Ramón, Alejandro, Saavedra-Trujillo, Rigoberto, Solís-Jiménez, Miguel Ángel and González-Sóbal, Martín by with adscription in the Instituto Tecnológico Superior de Huatusco, as the next article we present *Artificial Intelligence in the Field of Ergonomics and Occupational Health for Risk Assessment* by Muñoz-Hernandez, Raquel & Rangel-Lara, Saúl, with adscription in the Universidad Politécnica del Valle de México, as the next article we present *Aluminum casting furnace filling: A case study on operational efficiency improvement* by Pérez-García, Alejandro, Muñoz-Hernández, Raquel and Rangel-Lara, Saúl, with adscription in the Universidad Politécnica del Valle de México, as the next article we present *Proposal of a marketing model to promote the acceptance of electric vehicles in Ocuiltzapotlán, Tabasco* by Vidal-Reyes, Laura, Javier-Gerónimo, Zinath, Reyes-Osorio, Yaitla Aitza, Villanueva-Guzman, Jorge Cein, with adscription in the Instituto Tecnológico de Villahermosa, as the last article we present *Enhancing stem learning through augmented reality: Applications in CAD and Mechanical systems* by Meraz-Mendez, Manuel, Corral- Ramirez, Guadalupe, Muñoz-Lopez, Luis Enrique and Duarte-Loera, Jorge, with adscription in the Universidad Tecnológica de Chihuahua.

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Article

Study to obtain Activated Carbon at the laboratory level of the bagasse of the Maguey Pitzometl (*Agave marmorata*) of Zapotitlán Salinas, Puebla

Estudio para obtención de Carbón Activado a nivel Laboratorio del bagazo del Maguey Pitzometl (*Agave marmorata*) de Zapotitlán Salinas, Puebla

López-Vigil Miriam Silvia*[a], Gómez-Flores Nidia Esther[b], Santos-Alvarado Héctor[c] and Islas-Torres Héctor[d]

[a] ROR Tecnológico Nacional de México/ Instituto Tecnológico de Tehuacán • AIE-6933-2022 • 0000-002-7424-0109 • 300532
[b] ROR Tecnológico Nacional de México/ Instituto Tecnológico de Tehuacán • NSU-9258-2025 • 0009-0004-6289-7180 • 2144387
[c] ROR Tecnológico Nacional de México/ Instituto Tecnológico de Tehuacán • LNR-3679-2024 • 0000-0001-6504-7190 • 621174
[d] ROR Tecnológico Nacional de México/ Instituto Tecnológico de Tehuacán • LNR-4392-2024 • 0000-0003-2884-868X • 625375

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* ✉ [miriamsilvia.lv@tehuacan.tecnm.mx]

Abstract

The Agave genus has a wide presence in Mexico, where approximately 75% of its total species are located, many of them endemic, as is the case of the Agave marmorata or Maguey Pitzometl, which is present in the Zapotitlán Salinas Puebla Region, which belongs to the Tehuacán-Cuicatlán Biosphere Reserve. Since pre-Hispanic times they have been used as a source of food, drink, construction, ornaments being part of the regional identity, history and culture. Currently, the growing demand for products distilled from Agave such as mezcal and tequila, have led to practices that threaten its natural regeneration. This activity generates large volumes of by-products such as bagasse, both from the maguey leaves that are removed to work only with the pineapple or center of the plant, and from the solid residue of said pineapple itself after subjecting it to the extraction process. The present work shows the results of the study to obtain Activated Carbon at the laboratory level of the bagasse of the Maguey Pitzometl (Agave marmorata) of Zapotitlán Salinas, Puebla as an alternative for the management and sustainable use of this by-product.

Study to obtain Activated Carbon at the laboratory level of the bagasse of the Maguey Pitzometl (Agave marmorata) of Zapotitlán Salinas, Puebla		
Objective	**Methodology**	**Conclusions**
To obtain Activated Charcoal from Maguey Pitzometl Bagasse from Zapotitlan Salinas Puebla at laboratory level 	Collection and cleaning of the maguey leaves of the Region under study, obtaining the bagasse, drying, carbonization, activation, washing, drying, grinding, characterization, packaging.	The bagasse of Maguey Pitzometl, which was previously characterized, is a good organic material for the production of activated carbon. Physical and chemical activation was applied using anhydrous potassium carbonate at two concentrations: 40% and 60%.

Bagasse, Activated Carbon, Endemic, By-product, Use

Resumen

El género *Agave* tiene una amplia presencia en México, donde se albergan aproximadamente el 75% del total de sus especies, muchas de ellas endémicas, como es el caso del *Agave marmorata* o Maguey Pitzometl, que se encuentra presente en la Región de Zapotitlán Salinas Puebla, la cual pertenece a la Reserva de la Biosfera Tehuacán-Cuicatlán. Desde tiempos prehispánicos han sido utilizados como fuente de alimento, bebida, construcción, ornamentos siendo parte de la identidad, historia y cultura regional. Actualmente, la creciente demanda de productos destilados a partir del *Agave* como el mezcal y el tequila, han llevado a prácticas que amenazan su regeneración natural. Esta actividad genera grandes volúmenes de subproductos como el bagazo, tanto de las pencas del maguey que son retiradas para trabajar solo con la piña o centro de la planta, como del residuo sólido mismo de dicha piña después de someterla al proceso de extracción. El presente trabajo muestra los resultados del estudio para obtención de Carbón Activado a nivel Laboratorio del bagazo del Maguey Pitzometl (*Agave marmorata*) de Zapotitlán Salinas, Puebla como una alternativa para la gestión y aprovechamiento sustentable de este subproducto.

Estudio para obtención de Carbón Activado a nivel Laboratorio del bagazo del Maguey Pitzometl (*Agave marmorata*) de Zapotitlán Salinas, Puebla		
Objetivo	**Metodología**	**Conclusiones**
Obtener Carbón Activado a partir de Bagazo de Maguey Pitzometl de Zapotitlan Salinas Puebla a nivel laboratorio. 	Recolección y limpieza de las pencas de maguey de la Región en estudio, obtención del bagazo, secado, carbonización, activación, lavado, secado, molienda, caracterización, empacado.	El bagazo de Maguey Pitzometl, el cual se caracterizó previamente, es un buen material orgánico para la producción de carbón activado. Se aplicó activación física y química utilizando carbonato de potasio anhidro a dos concentraciones 40% y 60%.

Bagazo, Carbón Activado, Subproducto, Aprovechamiento

Area: Advocacy and attention to national problems

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Article

Introduction

Plants of the genus *Agave* are widely distributed throughout Mexico, where approximately 75% of all species are found, many of which are endemic, such as *Agave marmorata* or Maguey Pitzometl, native to the Zapotitlán Salinas Puebla region, which belongs to the Tehuacán-Cuicatlán Biosphere Reserve.

Agaves are important components of arid and semi-arid ecosystems (Delgado-Lemus, *et al*, 2014). In the Tehuacán-Cuicatlán Biosphere Reserve, the survival of this genus is related to various ecological processes of mutualism, where a host plant is required for germination and establishment (Estocapan, 2017), In addition, the flowering of agaves provides food for bats, birds, and insects throughout the year (Rojas Martínez, *et al*., 1999). The agaves of the Tehuacán Valley have been called a nectar oasis due to the high nutritional quality of their nectar (Ornelas, *et al*., 200). This characteristic allows nectarivorous bats (Phyllostomidae) to remain permanently in the region (Rojas-Martínez *et al*., 1999), which in turn play an important role as pollinators and seed dispersers for the columnar cacti of the region, which can be seen on the horizon of the valley.

Agave is a renewable natural resource with multiple applications that has the ability to adapt and grow in arid and semi-arid environments, with important ecological functions such as being a living barrier, soil improver and erosion reducer. The applications of agave and its by-products are receiving both national and international attention in nutrition, biofuels and composite materials.

All components of these plants have attracted interest in researching their potential: leaves, bagasse, fibres, thorns, cuticle, flower and stem, mainly due to their high cellulose content and some bioactive compounds. Álvarez-Chávez, J. *et al*. (2021) present an overview of agave by-products, their nutraceutical value, current applications and processing methods. Among the applications described by these authors, it is noteworthy that agave fibres are used for reinforcement and the production of polymer-based composites due to their thermomechanical properties.

Agave bagasse is considered a promising raw material for biofuels, attributed to its high water efficiency and biomass productivity, as well as its high carbohydrate content. The optimisation of physical and chemical pretreatments, enzymatic saccharification and fermentation are key to biofuel production. Emerging technologies, such as ultrasound, may provide an alternative to current pretreatment processes.

Box 1

Figure 1
Maguey Pitzometl from Zapotitlán Salinas, Puebla

Traditional uses include the production of pulque, mezcal, and tequila from agaves such as *Agave marmorata*. Currently, there is growing demand (CRM, 2020) for both mezcal and tequila, putting strong pressure on the natural resources needed for their preparation and generating a large amount of waste from the respective production processes.

According to Sierra, E. *et al*. (2021), after extracting all the compounds required for the manufacture of spirits from the agave, around 360,000 tonnes of plant waste known as bagasse are obtained each year.

This study addresses the study of an application for obtaining activated carbon from bagasse for its sustainable use in the region of Zapotitlán Salinas Puebla, with the collaboration of the Sembradores de Maguey Pitzometl de Zapotitlán Cooperative Society, Salinas Puebla, S. C. de P. de R. L. de C. V.

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It should be noted that activated carbon is a material of great interest due to its important uses, such as those described by Oblitas-Alcarraz (2025) for the removal of the heavy metal cadmium (Cd^{2+}) from aqueous solutions using activated carbon made from eucalyptus ($Eucalyptus\ globulus$). This study focuses on the use of activated carbon as an absorbent material to remove cadmium from contaminated water, a common problem due to mining and other industrial activities. Similarly, from the thesis by Peña-Cajan J. (2025), it can be concluded that the design of an activated carbon production plant using rice husks is a project that meets the commercial, technological, and economic viability requirements for a city in Peru.

Activated carbon obtained from coconut shells proved to be an efficient alternative in laboratory tests in the thesis by Maldonado-Vila, K. and Urquiaga-Casahuaman, J. (2025), as a low-cost and environmentally sustainable alternative for reducing lead in contaminated water bodies, such as the Rímac River in Peru, contributing to the mitigation of health risks and the fulfillment of SDG 6: Clean water and sanitation.

Undoubtedly, the use of a by-product such as maguey bagasse to obtain activated carbon supports the availability of alternative adsorbent agents to eliminate contaminants, odors, and harmful chemicals in industrial, commercial, and domestic applications within a circular economy.

Methodology to be developed

Collection and cleaning of maguey leaves from the region under study in coordination with the members of the Sembradores de Maguey Pitzometl de Zapotitlán Cooperative Society, Salinas Puebla, S. C. de P. de R. L. de C. V.

Obtaining bagasse for the study, with recovery of the extract for use and exploitation by members of the Sembradores de Maguey Pitzometl de Zapotitlán Cooperative Society, Salinas Puebla, S. C. de P. de R. L. de C. V.

Air drying under aseptic conditions in the Environmental Engineering Laboratory of the National Technological Institute of Mexico/Tehuacán Technological Institute, where the study was continued.

To obtain activated carbon, the tests were carried out in triplicate, where the initial weight of each dry bagasse sample was recorded on an analytical balance, subjected to carbonisation in a muffle furnace at 400°C for 20 minutes, left to cool in a desiccator, and its final weight recorded on an analytical balance. The yield per sample was calculated.

The carbonised samples were pulverised with a mortar and pestle to obtain a homogeneous particle size.

Two activation processes were carried out, obtaining three types of carbon according to the activation method: physical activation and chemical activation with anhydrous potassium carbonate as the activating agent at two levels of 40% and 60% concentration by volume. In this case, the carbon samples were placed in saturation conditions with a contact time of 16 hours, the activating agent was separated by filtration, and the samples were subjected to a second carbonisation in a muffle furnace at 500°C for one hour. Once weighed and cooled, the product obtained is washed with distilled water at 70°C until a pH of 7 (± 0.5) is obtained in the final product, as evaluated with a potentiometer. The product is then dried in an oven at a temperature of 100°C (± 10°C) for 48 hours, the final weight is recorded, and the yield is calculated. The samples are then crushed in a mortar with a pestle, and the particle size of the three types of charcoal obtained is determined using 70, 100 and 200 mesh sieves, placed in series from largest to smallest mesh size.

The weight of each sieve is recorded on a grain scale, the weighed sample is placed on the analytical balance in the upper sieve and sifted for 20 minutes, and then the carbon sample residues retained in each sieve are weighed on the analytical balance.

The percentages of carbon retained by each sieve were calculated using the following formula:

$$A_n = \left(\frac{W_1 - W_0}{M}\right) \times 100$$

A_n = Percentage of carbon retained
W_1 = Weight (g) of sieve plus retained carbon sample
W_0 = Weight in grams of the sieve
M = Weight of sample in grams $[\sum(W_1 - W_0)]$
n = Number of sieve used

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Results

The Maguey Pitzometl leaves were harvested from plantations belonging to members of the Sociedad Cooperativa Sembradores de Maguey Pitzometl de Zapotitlán, Salinas Puebla, S. C. de P. de R. L. de C. V. Cooperative Society, taking samples of leaves from mature maguey plants with five rosettes of leaves, in order to work with plants of a similar maturity index.

Figure 2 shows the cutting of the clean leaves to obtain the bagasse, work carried out at the facilities of the participating Cooperative Society.

Box 2

Figure 2
Chopping the Maguey Pitzometl

Figure 3 shows the extraction of the juice and bagasse by passing the pieces of stalk through a stainless steel juice extractor in collaboration with the members of the Cooperative Society.

Box 3

Figure 3
Obtaining bagasse from Maguey Pitzometl

The performance results of the activated carbons obtained are summarised in Table 1, reporting the average values of three samples per activation method. The values vary significantly between treatments, mainly because in chemical activation, the washing process to remove excess sodium carbonate and lower the final pH causes a loss of fines.

Box 4

Table 1
Percentage yield of activated carbon production (average values of three determinations by activation method)

Activation	Sample (g)	Carbon obtained (g)	Performance (%)
Physical Activation	30.0077	8.0073	26.6841
Chemical Activation (K_2CO_3) at 40%	35.0001	3.6335	10.3813
Chemical Activation (K_2CO_3) at 60%	35.0005	3.6340	10.3827

The production yield of activated carbon varies greatly depending on process factors, as well as the raw material used and the activation conditions, but values such as 15.43% have been reported in an optimised study based on date palm seeds (Bamerdhah, S., *et al.*, 2025), with a higher yield for physical activation compared to this value, but a decrease with chemical activation. Figure 4 shows the weighing of the carbons obtained to monitor the yield calculation.

Box 5

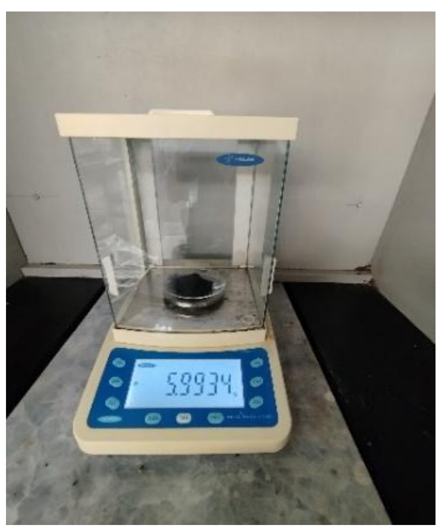

Figure 4
Weighting on an analytical balance of the activated carbons obtained

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Tables 2, 3 and 4 show, respectively, the results obtained from the determination of particle size in the samples of the three types of coal obtained.

Box 6

Table 2
Particle size distribution of activated carbon obtained by physical activation.

N° Tamiz	Retained weight (g)	Percentage retained (%)
70	0.4550	6.4534
100	0.9691	13.7451
200	0.9716	13.7805

The results of particle size tests on activated carbon indicate the percentage by weight of material that is retained or passes through different mesh screens, defining its particle size range.

Box 7

Table 3
Particle size distribution of activated carbon obtained by chemical activation with 40% K_2CO_3

N° sieve	Retained weight (g)	Percentage retained (%)
70	0.2103	3.0010
100	0.6318	9.0159
200	0.7988	11.3990

Generally, a smaller particle size improves the adsorption rate of carbon.

Box 8

Table 4
Particle size distribution of activated carbon obtained by chemical activation with 60% K_2CO_3

N° sieve	Retained weight (g)	Percentage retained (%)
70	0.1008	1.4373
100	0.4012	5.7208
200	0.6038	8.6097

Disclosures

Conflict of interest

The authors declare that they have no conflicts of interest. They have no known competing financial interests or personal relationships that could have appeared to influence the article reported in this paper.

Contribution of authors

López.Vigil, Miriam Silvia: Contributes with the idea of the project, development and organisation of the research.

Gomez-Flores, Nidia Esther: Contributes with collaboration in experimental activities.

Santos-Alvarado, Héctor: Contributed to the data analysis.

Islas-Torres, Héctor: Contributed to the review and editing.

Availability of data and materials

The data analysed during the current study are available from the corresponding author upon reasonable request.

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Abbreviations

CA	Activated Carbon
K_2CO_3	Potassium Carbonate
S.C. de P. de R. L. de C.V.ANN	Limited Liability Cooperative Production Company with Variable Capital

Conclusions

Agave marmorata is a species of high biocultural value, with deep ties to the communities where it grows, especially as it is an endemic species that has been present for thousands of years in specific ecosystems in Mexico, such as the Zapotitlán Salinas region in Puebla, which belongs to the Tehuacán-Cuicatlán Biosphere Reserve.

Its long maturation process, which fluctuates between 7 and 10 years, its restricted distribution and the growing demand for its exploitation create a combination of opportunity and risk, as it can be a source of local development but also places it in a vulnerable position if it is not managed sustainably.

This study presents the morphological characterisation of the Maguey Pitzometl of the Zapotitlán region, Puebla, which is one of the most important reservoirs of Agave marmorata, contributing to determining its particular morphological, physical and chemical attributes. Salinas, Puebla, which is one of the most important reservoirs of *Agave marmorata*, contributing to the determination of its particular morphological, physical and chemical attributes. In the context of sustainability and the circular economy, the production of activated carbon from agricultural waste such as Maguey Pitzometl bagasse is an alternative of great interest. The yields obtained at the laboratory level by physical activation exceed the values reported by Bamerdhah, S., *et al*., (2025) using date palm seeds as a source.

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Methodology for the Proposal of a Technological Package Development in Hydrocarbon Production Facilities

Metodología para propuesta de elaboración de paquete tecnológico en instalaciones de producción de hidrocarburos

Mendoza-Espinoza, Héctor Eduardo[a], Escorza-Sánchez, Yolanda Marysol*[b] and Marquez-López, Ángel de Jesús[c]

[a] Universidad Politécnica de Tulancingo • LJL-2442-2024 • 0000-0003-3125-6204 • 464470
[b] Universidad Tecnológica del Valle del Mezquital • LJL-2402-2024 • 0000-0001-5889-7736 • 567407
[c] Universidad Politécnica de Tulancingo • OPN-8617-2025 • 0009-0005-3873-1030 • 2186476

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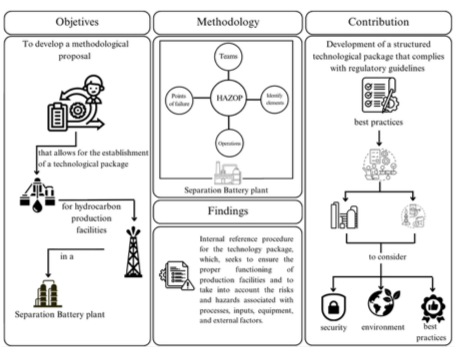
* ✉ [yescorza@utvm.edu.mx]

Abstract

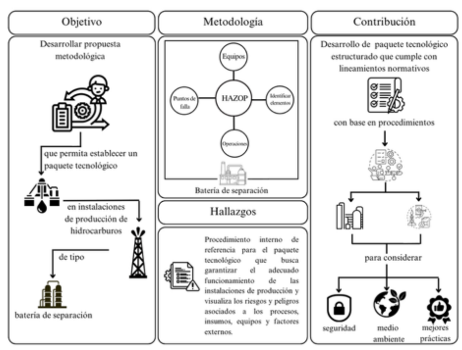
Objective: To develop a methodological proposal that allows for the establishment of a technological package for hydrocarbon production facilities in a Separation Battery plant. Method: The Hazard Analysis and Operational Methodology (HAZOP) is used in the development of the project, as it is a widely known and used methodology in the oil industry. Findings: The investigation into the operational context allows for the identification of the organization, the regulatory framework, the standards applicable to the sector, and the identification of good practices. This allows for the subsequent targeting of processes and subprocesses for information analysis and the subsequent establishment of an information matrix, allowing for the structuring of a proposal. Contributions: The proposal aims to contribute to the development of a structured technological package that complies with regulatory guidelines and guarantees proper operation in oil production facilities, providing a more complete understanding of the associated hazards and risk management.



Methodology, technology package, security

Resumen

Objetivo: Desarrollar una propuesta metodológica que permita establecer un paquete tecnológico en instalaciones de producción de hidrocarburos en una planta de tipo Batería de Separación. Método: En el desarrollo del proyecto se emplea la Metodología de Análisis de Riesgo y Operatividad (HAZOP), debido a que es una metodología ampliamente conocida y utilizada en la industria petrolera. Hallazgos: La indagación en el contexto operacional permite identificar a la organización, el marco normativo, los estándares aplicables al sector y la identificación de buenas prácticas, para posteriormente focalizar procesos y subprocesos para el análisis de información, y posteriormente establecer una matriz de información, que permitan estructurar una propuesta. Contribuciones: La propuesta pretende contribuir al desarrollo de un paquete tecnológico estructurado que cumpla con los lineamientos normativos y garantice un funcionamiento adecuado en las instalaciones petroleras de producción, comprendiendo de una forma más completa los peligros asociados y la gestión de riesgos.



Metodología, paquete tecnológico, seguridad

Area: Development of strategic leading-edge technologies and open innovation for social transformation

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Introduction

In the case of Mexico, from 1938 until the constitutional reform of 2013, oil exploration and extraction were the responsibility of the Mexican State through the parastatal Petróleos Mexicanos (PEMEX), thereby establishing a new model of organisation (Rodríguez, 2019) and regulation in supply chains, opening up to private organisations and establishing the awarding of contracts to national and international private capital companies with the aim of reactivating production in idle hydrocarbon fields (Guardado, 2024).

Article 19 of the Energy Reform sets out the basis for the creation of a national agency for industrial safety and environmental protection. In March 2015, the Agency for Safety, Energy and the Environment (ASEA) formally began operations with the aim of regulating and supervising the facilities and activities of the hydrocarbon sector in terms of safety and environmental protection. This agency aims to regulate compliance with the obligations of companies in the hydrocarbons sector through the implementation of an integrated management system that uses national and international standards and best practices as reference guidelines (Government of Mexico, 2016).

The Industrial Safety, Operational Safety and Environmental Protection Management System (SASISOPA) is considered the Mexican model for integrated management in the hydrocarbon sector and is the guiding principle under which ASEA manages the risks of regulated activities in this sector (Government of Mexico, 2017).

The SASISOPA compliance requirements establish that companies regulated in the hydrocarbons sector must integrate, preserve and keep up to date a package of information on the technology and safety of the project they are developing in the facilities under their responsibility (Márquez, 2025).

These regulatory frameworks and systems are the guidelines for the development of the proposal being developed in a private Mexican organisation.

Literature review

Hydrocarbon separation batteries are facilities designed to separate some of the components of crude oil, mainly in the liquid and gaseous phases, for which different technologies and equipment are used, including process lines, separators, pumps, tanks, flow meters, among others. Their main objective is to carry out an initial separation into phases that allows the materials to be transported to processing stations such as refineries or gas processors. The basic process in a separation battery can be described as follows: Reception of hydrocarbons from associated producing wells via discharge lines; Separation by density difference using two-phase (liquid and gas) or three-phase (water, crude oil and gas) separators; Storage in tanks; Transfer of liquid hydrocarbons using transfer pumps; Transfer of gaseous hydrocarbons using gas compressors; and Certification of transferred volumes using measuring equipment (Márquez, 2025).

This paper proposes a methodology for updating and implementing a technology package in a field operator that produces liquid and gaseous hydrocarbons in reservoirs on the northern coastal plain of the Gulf of Mexico.

In this regard, the literature review aims to clarify concepts such as technology package in accordance with the tenth element of the Mexican Government's Industrial Safety, Operational Safety and Environmental Protection Management System (SASISOPA), considering methodologies for safety analysis in oil facilities. The National Agency for Industrial Safety and Environmental Protection in the Hydrocarbons Sector (ASEA) is an administrative body of the Mexican Government's Ministry of the Environment and Natural Resources. Its main functions include regulating and supervising industrial safety, operational safety and environmental protection with regard to the activities of the hydrocarbons sector in the country, regulating oil barrels, natural gas, onshore wells, offshore platforms, petrol stations, pipelines, storage and distribution terminals, refineries, natural gas processing centres, LP gas distribution centres, among others; ASEA manages the risks of regulated activities in the sector through the implementation of an Industrial Safety, Operational Safety and Environmental Protection Management System (Safety and Environment Agency [ASEA], 2025).

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According to Mariano, technological packages for petroleum processes are guidelines that support organisations, particularly those focused on separation batteries, as each one has a specific design that depends on the number of wells it serves and the equipment used in its operation (Mariano, 2022).

According to Tarlengco, Hazard and Operability Analysis, known as HAZOP, is a systemic approach that allows for the identification of potential problems and difficulties in complex systems. It is a structured method used to analyse and discover safety risks and process inefficiencies by evaluating both new designs and existing operations. HAZOP studies are especially crucial in high-risk industries such as chemical production, nuclear energy production, oil and gas processing, and the pharmaceutical industry, among other productive areas (Tarlengco, 2025).

Methodology

Based on the HAZOP methodology, widely used in the oil industry and compatible with the objectives of this work, some stages of the HAZOP analysis were used in the development of the technological package for hydrocarbon production facilities. Complementarily, the process nodalisation methodology is used, dividing the process into parts or nodes to analyse the entire process in a structured and systematic manner. Although the methodology specifies exactly how to nodalise, it recommends doing so at each change in the process variables, such as changes in physicochemical composition, energy use, and changes in process variables, among others.

The next step in the HAZOP methodology is to apply a series of guide words to each node to determine the consequences of a deviation in the process variables. The most common guide words are: higher or lower pressure, higher or lower temperature, higher or lower flow, etc.

Based on these premises, a matrix of interactions between the nodes of the facility's process and the technical information available for the configuration of the technological package in hydrocarbon production facilities was developed.

Box 1

Table 1

Requirements matrix for the technology package in the organisation's facilities

Node	Hazardous materials and substances	Processus	Equipment	Risk management	Licences
Node 1					
Node 2					
Node 3					
Node 4					
Node 5					
Node 6					
Node 7					
Node N.					

Source: Authors

The initial phase for identifying and structuring elements in the technology package consists of identifying the nodes in the installation process where technical information about materials, equipment, and processes is required (Almanza, 2022). This phase involved a survey visit, which was documented by means of an attendance list and photographic records.

The first nodes to be defined are: Hydrocarbon reception, Separation, Well measurement, Gas utilisation, Crude oil storage, Crude oil homogenisation and pumping, Gas compression, Measurement and transfer of custody, Gas regulation and flaring, Chemical injection, Hazardous atmosphere monitoring, Drains and sumps, and Electrical supply.

The next step was to form a multidisciplinary group with personnel from the Operations, Maintenance, Infrastructure, Safety, and Quality areas to identify the technical information needed for each node, considering the area of expertise of the personnel from the various administrative units of the organisation.

During the session with the multidisciplinary group, each of the elements was defined in general terms with the aim of providing an overview of each of the elements and the type of information they should contain in accordance with best practices, international standards and the experience of the multidisciplinary team.

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The following describes the necessary information elements determined in the interactions between the sub-processes and the classification of information.

Collection Stage:

Forty-nine wells converge per discharge line, at an average distance of 1,500 metres, and two collection heads are available.

Hazardous substances and materials.
- Material and energy balance.

Equipment
- Technical specifications of the facility.
- Index of lines and services.
- Inventory of equipment, valves, and instruments.
- Criticality analysis.
- Maintenance plan.

Process
- Collection system.
- Process flow diagram.
- Piping and instrumentation diagram (PID).
- General Location Plan (GLP).
- Operating philosophy.
- Operating procedures.

Safety systems
- Hydrocarbon Sector Risk Analysis (ARSH).
- Emergency response plan (PRE).
- Drills.
- Risk atlas.
- Fire risk study.
- Permit System for Risky Work (SPTR).
- Investigation and evaluation of hazards and environmental aspects (IEPPA).

Licences
- Single Environmental Licence.

Separation stage:

The facilities have three two-phase separators, which operate by density type and enable gas-liquid separation.

Hazardous substances and materials
- Inventory of hazardous materials and substances.
- Hazardous substance safety data sheet.
- Chemical analysis of crude oil.
- Gas chromatography.

Equipment
- Separator technical data sheet.
- Safety valve calibration certificates.

Process
- Separation operating procedures.

Requirements and licences
- RSP compliance notice. Requirement to comply with NOM-020-STPS-2011 to prevent risks in the workplace and damage to facilities.

Well measurement stage:

Interconnected to the collection manifolds and the separator is the measurement ring, which was designed to enable the measurement of wells that converge in the facility without mixing sweet and sour gas streams, thus continuing to use sweet gas for engine combustion in the facility.

Equipment
- Technical data sheets for well measurement equipment.
- Calibration certificates for well measurement equipment.

Process
- Well measurement operating procedures.

Gas utilisation stage:

The separators have a gas outlet bypass for use as fuel for the operation of instruments such as: separator level controllers, installation engines, and compression module.

Equipment
- Technical data sheet for fuel gas measurement equipment.
- Calibration certificates for fuel gas measurement equipment.

Process
- Gas utilisation operating procedures.

Storage stage:

The separation battery has an installed storage capacity of 1,120 barrels with two vertical storage tanks.

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Equipment

- Technical specifications for storage tanks.
- Calibration certificates for safety valves.

Process

- Storage operating procedures.

Hazardous substances and materials

- Inventory of materials and substances (fuels, lubricants, etc.).
- Substance safety data sheet.

Homogenisation and pumping stage:

The contents of the storage tanks are transferred by means of a pumping system, which is connected to a suction head where a duplex piston pump driven by a gas engine moves the liquid hydrocarbon through a pipeline.

Equipment

- Technical data sheet for pumping equipment.

Process

- Homogenisation and pumping operating procedures.

Compression stage:

The total natural gas (sweet-sour mixture) produced by the primary separation of the installation is compressed, measured and sent to the Compression Station.

Hazardous substances and materials.

- Inventory of materials and substances
- Substance safety data sheet.

Equipment

- Compression equipment technical data sheets.
- Emergency shutdown system technical data sheets.
- Control loop diagram.

Process

- Compression module operating procedures.

Measurement and transfer of custody stage:

For the quantification and certification of liquid hydrocarbons, the separation battery has a measuring skid. This system consists of a Coriolis mass meter as the primary measuring element, which in turn has a basket filter, static mixer, temperature and pressure transmitters, and a flow computer.

Equipment

- Technical data sheets for measurement systems.
- Calibration certificates for measurement and custody transfer equipment.

Process

- Operational procedures for measurement and custody transfer.

Gas regulation and flaring stage:

The separation battery has a burner for venting and flaring gas. Currently, 100% of the gas received through discharge lines is used, either for compression or fuel, so the venting and flaring system is only available in the event of a shutdown in the compression module.

Equipment

- Technical data sheet for the regulation system.
- Technical data sheet for the gas meter to burner.

Process

- Operating procedures for regulation and burner.

Chemical injection stage:

In order to minimise the concentration of hydrogen sulphide in the hydrocarbon, equipment for injecting a hydrogen sulphide sequestering chemical is installed, which, by means of a pneumatic pump, injects the product into the separator inlet. To prevent the formation of scale in the process lines, a scale inhibitor chemical is also injected.

Hazardous substances and materials.

- Inventory of chemical substances.
- Chemical safety data sheet.

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Equipment
– Injection system technical data sheets.

Process
– Chemical injection operating procedures.

Hazardous atmosphere monitoring stage:

To mitigate the risk posed by the presence of hazardous gases in the process, an audible and visible alarm system is in place, which is activated by three sensors located in the separator area, tank area and operator's cabin.

Equipment
– Technical data sheets for hazardous atmosphere detection systems.
– Calibration certificates for hazardous atmosphere detection systems

Process
– Operating procedures for monitoring hazardous atmospheres.

Drain and sump stage:

The equipment that has a drain line to the oily sump is: Separators, measuring skid and pump.

Hazardous substances and materials.
– Inventory of hazardous waste.

Equipment

– Technical data sheet for ecological station.

Process
– Operating procedures for waste management.

Power supply stage:

The facility's electrical power is supplied by the Federal Electricity Commission and, in addition, there is a natural gas-powered electric generator installed in the Compression Module, which supplies electricity to the Battery and Module. The motor generator is started up and the power supply is switched manually on the electrical panel of the Separation Battery.

Equipment
– Technical data sheet for electric motor generator. Electrical supply - Process.
– Motor generator operating procedures.
– Electrical classification plans.
– Single-line diagrams.
– Physical grounding system.

Derived from the application of interactions according to the selected methodology, a list of elements of the technology package was generated containing the information necessary to comply with SASISOPA provisions, best practices and standards in the hydrocarbons sector, defining the following structure:

The following describes the necessary information elements determined in the interactions between the sub-processes and the classification of information: Hazardous substances and materials, Equipment, Process, Safety systems, and Licences.

Box 2

Table 2
Application of the matrix in the hydrocarbon collection sub-process

Hazardous Substances and Materials	Equipment	Process	Risk management	Requirements and licences
Material and energy balance	*Installation technical specifications *Index of lines and services *Census of valves (operational, auxiliary and safety) *Census of equipment (critical, auxiliary, safety) *Census of instruments *Criticality analysis *Maintenance plan	*Collection system *Process flow diagram *Piping and instrumentation diagram *General location plan *Operating philosophy *Operating procedures	* ARSH *PRE *Drills *Risk Atlas *Fire Risk Assessment *IEPAA *SPPTR	*Single Environmental Licence

Source: Authors

Based on the application of interactions from the selected methodology, a list of elements from the technology package was generated that contain the information necessary to comply with SASISOPA provisions, best practices, and standards in the hydrocarbons sector, defining the structure presented in Table 3. At this stage of the project, the technology procedure relating to the Field Operator process was updated with regard to the Technology Related to the Process in the organisation's Integrated Management System Facilities, describing the methodology used to obtain the list of elements of the technology package, considering the flow chart of operations shown in Figure 1.

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Box 3

Table 3
List of items in the technology package

Process
Operating philosophy
Collection system
General location plan
Process flow diagram
Piping and instrumentation diagram
Electrical classification plans
Single-line diagrams
Physical grounding systems
Control loop diagrams
Separation battery operating procedure
Compression module operating procedure
Operating procedure for measurement and custody transfer
Waste management procedure
Equipment
Installation technical data sheet
Index of lines and services
Census of equipment, valves and instruments
Criticality analysis
Maintenance plan
Safety valve calibration certificates
Separator technical data sheet
Well measurement equipment technical data sheet
Well measurement equipment calibration certificates
Fuel gas measurement technical data sheet
Calibration certificates for fuel gas measurement equipment
Technical specifications for storage tanks
Technical specifications for pumping equipment
Technical specifications for compression equipment
Technical specifications for emergency shutdown systems
Technical specifications for measurement and custody transfer systems
Calibration certificates for measurement and custody transfer systems
Gas burner meter technical data sheet
Injection system technical data sheet
Hazardous atmosphere detection equipment technical data sheets
Hazardous atmosphere detector calibration certificates
Ecological station technical data sheet
Electric motor generator technical data sheet
Materials and substances
Material and energy balance
Inventory of hazardous substances and materials
Chemical analysis of crude oil
Gas chromatography
Crude oil safety data sheet
Natural gas safety data sheet
Lubricants safety data sheet
Fuels safety data sheet
Chemicals safety data sheet
Inventory of hazardous waste
Risk management
Hydrocarbon sector risk analysis ARSH
Emergency response plan PRE
Risk Atlas
Fire risk assessment
Permit system for hazardous work SPPTR
Investigation and assessment of hazards and environmental aspects IEPAA
Drill programme
Licences
Single environmental licence LAU
Notice of compliance for pressure vessels

Source: Authors

Box 4

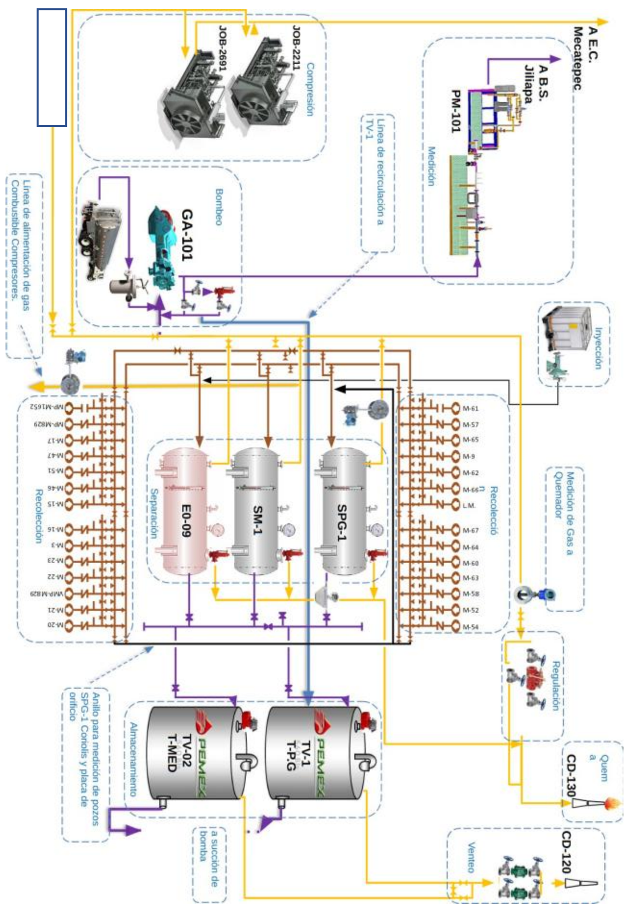

Figure 1
Operations flow chart

Source: Authors

Results

The project aimed to develop a methodology to identify, integrate, update, and manage the elements that make up the Separation Battery technology package, in order to ensure compliance with the requirements to be implemented during the project life cycle of element IX of SASISOPA 'Best Practices and Standards' defined for the oil industry in Mexico (Official Gazette of the Federation, 2020).

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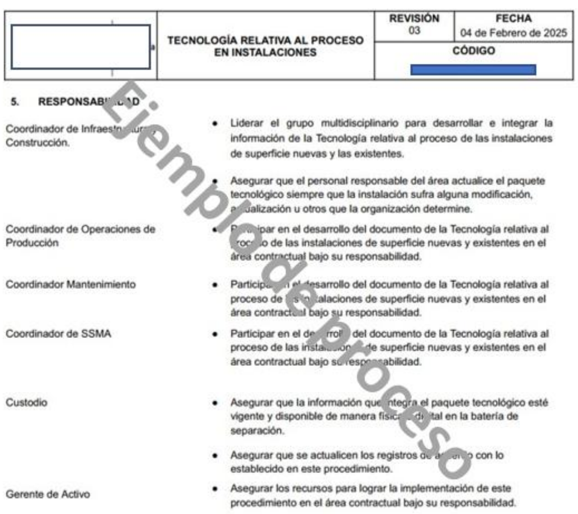
This was achieved through a review of regulations, standards and best practices in the hydrocarbons sector, which determined that the applicable regulations generally correspond to ISO 9001 - Quality (International Organisation for Standardisation, [ISO], 2025a), ISO 14001 – Environment (ISO, 2025b), ISO 45001 Standard – Health and Safety (ISO, 2025c), NOM-018-STPS-2015 – Harmonised System for the Identification and Communication of Hazards and Risks from Hazardous Chemicals in the Workplace (Official Gazette of the Federation, 2015), NOM-010-STPS-2014 Chemical agents contaminating the working environment (Official Gazette of the Federation, 2014), NOM-020-STPS-2011 Pressure vessels, cryogenic vessels, steam generators or boilers (Official Gazette of the Federation, 2011), among the main ones; Subsequently, the methodology for updating and administering the elements that make up the technology package was developed, followed by the procedure that establishes the guidelines for the development, updating, and administration of the organisation's technology packages.

Box 5



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5. RESPONSABILIDAD

Coordinador de Infraestructura y Construcción.	• Liderar el grupo multidisciplinario para desarrollar e integrar la información de la Tecnología relativa al proceso de las instalaciones de superficie nuevas y las existentes. • Asegurar que el personal responsable del área actualice el paquete tecnológico siempre que la instalación sufra alguna modificación, actualización u otros que la organización determine.
Coordinador de Operaciones de Producción	• Participar en el desarrollo del documento de la Tecnología relativa al proceso de las instalaciones de superficie nuevas y existentes en el área contractual bajo su responsabilidad.
Coordinador Mantenimiento	• Participar en el desarrollo del documento de la Tecnología relativa al proceso de las instalaciones de superficie nuevas y existentes en el área contractual bajo su responsabilidad.
Coordinador de SSMA	• Participar en el desarrollo del documento de la Tecnología relativa al proceso de las instalaciones de superficie nuevas y existentes en el área contractual bajo su responsabilidad.
Custodio	• Asegurar que la información que integra el paquete tecnológico esté vigente y disponible de manera física y digital en la batería de separación. • Asegurar que se actualicen los registros de acuerdo con lo establecido en este procedimiento.
Gerente de Activo	• Asegurar los recursos para lograr la implementación de este procedimiento en el área contractual bajo su responsabilidad.

Figure 2
Responsibilities in the process
Source: Authors

To subsequently apply the designed sequence, which summarises 16 activities, as follows:

1. Assign personnel to the multidisciplinary group to develop or update the technology package.
2. Assign a group leader.
3. Include all areas of the organisation.
4. Identification of sub-processes and nodes to consider technical information.
5. Initial overview of information gathering to validate processes and nodes.
6. Identification by sub-processes and nodes of materials, substances, equipment, among others.
7. Technical meeting to determine complementary information in accordance with applicable regulations.
8. Integration of information from the technology package requirements matrix.
9. Integration of the elements and structure of the technology package.
10. Create a checklist for the integration of the package elements to identify the degree of compliance of the facilities.
11. Assign responsible persons by area for updating information that represents an area of opportunity.
12. Ensure updating through a checklist and its validation.
13. Integration of the technology package by type of facility in accordance with its documentation.
14. Make the technology package information available in printed form and on a duly specified digital medium.
15. The facility custodian shall verify that the technology package is up to date, available, and accessible to personnel involved in each process, sub-process, or node, from management to operational levels.
16. The facility custodian shall prepare a quick reference guide, which shall be distributed to all personnel.

Conclusions

This study developed the methodology for establishing the structure and elements that a Separation Battery technology package must contain in order to meet the requirements of industrial safety, operational safety, environmental protection, and best practices and standards in the hydrocarbons sector in Mexico. The work carried out enabled the development of an internal reference procedure for the technology package, which, when implemented and updated, seeks to ensure the proper functioning of production facilities and to take into account the risks and hazards associated with processes, inputs, equipment, and external factors.

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Areas of opportunity include identifying the level of compliance of the technology package through a documentary review of the facility with respect to the structure of elements established in the procedure, evidence of operation and compliance, from which areas of opportunity can be identified and analysed based on the multidisciplinary groups already established in the organisation for the development of the methodology and previous work.

Among the main limitations identified was the time required to coordinate the schedules of the people participating in the multidisciplinary groups. Therefore, establishing alternative meeting mechanisms, such as videoconferences, video calls, collaborative work in the cloud or online, are alternatives to face-to-face work that can contribute to achieving the planned results.
Future work could include evaluating the feasibility of applying the methodology developed to other separation batteries within the same company.

Identifying the most efficient mechanisms for disseminating the technology package in order to expand it.

Integrating a proposal to update the technology package based on the areas of opportunity identified by multidisciplinary groups within the organisation.

It is also relevant to evaluate the methodology in other oil facilities of the organisation to compare its operability or, where appropriate, to take actions to complement the actions for its implementation.

Declarations

Conflict of interest

The authors declare that they have no conflict of interest. They have no competing financial interests or known personal relationships that could have influenced the article presented in this article.

Author contribution

Mendoza-Espinoza Héctor Eduardo: Contributed to the project idea, analysis, research method and technique, writing.

Escorza-Sánchez Yolanda Marysol: Contributed to research method and technique, writing.

Márquez-López Ángel de Jesús: Contributed to the project idea, analysis, research method and technique, writing

Availability of data and materials

The information and data used or analysed during this study are available upon reasonable request from the corresponding author, subject to prior written authorisation from the company where the project was carried out.

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The research did not receive any funding; however, one of the authors is a collaborator with the organisation where it was carried out.

Abbreviations

ASEA	Safety, Energy and Environment Agency
ARSH	Risk Analysis of the Hydrocarbons Sector
DTI	Piping and Instrumentation Diagram
HAZOP	Hazard and Operability Study Risk and Operability Analysis Methodology
IEPPA	Investigation and evaluation of hazards and environmental aspects
LP	Liquefied Petroleum
NOM	Official Mexican Standard
PEMEX	Petróleos Mexicanos
PLG	General Location Plan
PRE	Emergency Response Plan
RSP	Pressure Vessels
SASISOPA	Industrial Safety, Operational Safety and Environmental Protection Management System
SPPTR	Permit System for High-Risk Work

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Antecedents

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Article

Modeling of the supply and consumption of the Huatusco Veracruz wáter network using SIMIO software

Modelación del abastecimiento y consumo de la red hídrica de Huatusco Veracruz con software SIMIO

Rosas-Ramón, Alejandro[a], Saavedra-Trujillo, Rigoberto[b], Solís-Jiménez, Miguel Ángel*[c] and González-Sóbal, Martín[d]

[a] ROR Tecnológico Nacional de México - Instituto Tecnológico Superior de Huatusco • ONJ-8085-2025 • 0009-0005-0605-7774 • 2064387
[b] ROR Tecnológico Nacional de México - Instituto Tecnológico Superior de Huatusco • ONJ-8276-2025 • 0009-0001-1621-1414
[c] ROR Tecnológico Nacional de México - Instituto Tecnológico Superior de Huatusco • N-6243-2018 • 0000-0002-8125-0989 • 94216
[d] ROR Tecnológico Nacional de México - Instituto Tecnológico Superior de Huatusco • S-7631-2018 • 0000-0003-0038-8319 • 463431

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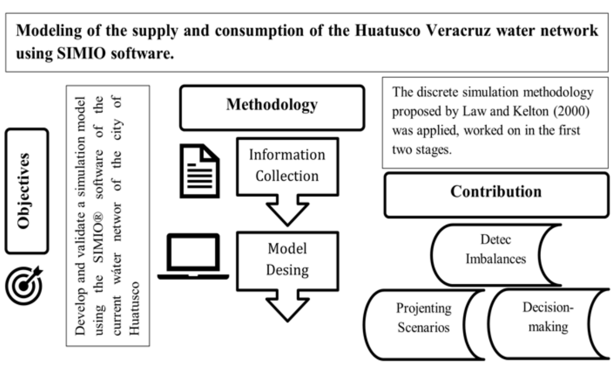
* ✉ [msolisj@huatusco.tecnm.mx]

Abstract

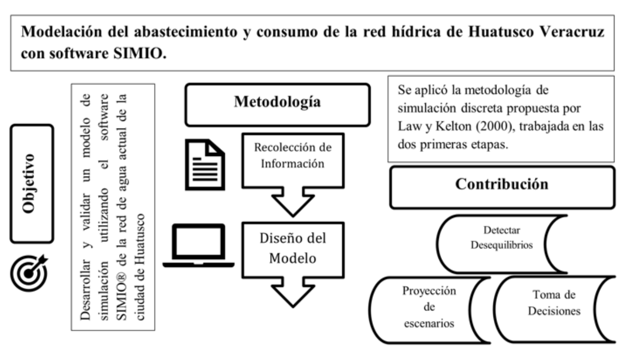
The main objective of this article is to develop and validate a simulation model using SIMIO® software for the current water network in the city of Huatusco, Veracruz, in order to analyze its consumption and distribution for different sectors: domestic, urban, commercial, industrial, residential, and social interest. To this end, the discrete simulation methodology implemented by Law and Kelton was used, which included the characterization of the infrastructure, the collection of historical consumption data, and the construction of a model representing the supply cycles, with the purpose of evaluating usage patterns. Once the model was simulated, it was validated against the real system using a paired t-test. The result of this work is a statistically validated model that can serve as a support tool for decision-making in the city's water management, facilitating the projection of future scenarios and the detection of possible imbalances in distribution.



Simulation, Water Network, Distribution

Resumen

El objetivo principal de este artículo es desarrollar y validar un modelo de simulación mediante el software SIMIO® de la red hídrica de la ciudad de Huatusco, Veracruz, para analizar su consumo y distribución de esta para sus diferentes sectores: domésticos, urbanos, comerciales, industriales, residenciales e interés social. Se empleó la metodología de simulación discreta implementada por Law y Kelton, que incluyo la caracterización de la infraestructura, la recopilación de datos históricos de consumo y la construcción de un modelo que representa los ciclos de suministro, para evaluar patrones de uso. Posteriormente, se procedió a validar el modelo contra el sistema real a partir de la prueba t-pareada. El resultado es un modelo validado estadísticamente el cual puede servir como una herramienta de apoyo para la toma de decisiones en la gestión hídrica de la ciudad, facilitando la proyección escenarios futuros y la detección de posibles desequilibrios en la distribución.



Simulation. Water Network, Distribution

Area: Advocacy and attention to national problems

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Introduction

Access to safe drinking water is a fundamental resource for human development, public health and economic development. Its management is a global and national priority, in Mexico, many cities currently face serious challenges in their water distribution network. At the national level, the National Water Program (PNH, 2024) identifies critical problems such as insufficient and inequitable access to water, with only 58% of the total population receiving this resource daily, which is due to inefficient use and losses in distribution networks that can reach up to 60% of the total volume and with a growing demand associated with population growth.(National Water Commission, 2020).

The problem to be solved in this work focuses specifically on the need to analyze and characterize the consumption and distribution of water in the water network of Huatusco, Veracruz, in order to improve the local management of the resource. Faced with this challenge, there is a need to use technical tools such as discrete simulation, which allows representing, analysing and projecting future scenarios of the behaviour of the city's water distribution network system.

In this context, simulation model technology has emerged as a tool of enormous importance, providing the basis for hydraulic calculation, planning, operation and management of distribution networks. The added value of simulation lies in its ability to analyze the complexity of the system under different conditions, including temporal variations, which allows various solution alternatives to be quickly evaluated, a crucial advantage for decision-making.

Unlike traditional analysis techniques that focus on designing new networks with theoretical parameters, simulation models for in-service distribution networks focus on the accurate estimation and calibration of modified parameters, such as actual demand, resulting in a deeper and more realistic understanding of system operation.(National Water Commission, 2014b) (National Water Commission, 2014a).

Water systems modeling encompasses a variety of approaches, depending on the objective. One can be the prediction of resources and adaptation to climate change: there are works focused on the projection of long-term water availability, analyzing supply and demand under the influence of climate change (Díaz León & Olarte Escobar, 2025). For example, in the Rimac River basin, the water balance is evaluated until 2050. These studies often employ advanced artificial intelligence (AI) methods, such as Recurrent Neural Networks (RNNs) or Bidirectional Neural Networks (BNNs) to predict hydrometeorological variables such as temperature, or Artificial Neural Networks (ANNs) to forecast monthly water availability. (Taboada Valenzuela, 2025)-

Another type of approach is the quantification of groundwater resources, these models focus on the dynamics of groundwater, using software such as MODFLOW6 to develop flow number models in aquifers, quantifying resources, reserves and the effect of artificial recharge using system dynamics as a method.(Giussepe Massone Grez, 2025)

This study is part of the operational simulation approach of the infrastructure. The main objective of this study was the development and validation of a simulation model using the SIMIO software, applying the discrete simulation methodology of the SIMIO® software. The simulation model focuses on representing the current supply cycles and evaluating the usage patterns of the different consumer sectors. Averill M. Law and W. David Kelton, (2000).

Having as the scope of this work a statistically validated model that represents the current situation of supply and consumption of the water network of the municipal capital of the city of Huatusco Veracruz, according to the number of intakes and average consumption of the different sectors identified, with which it can be constituted as a support tool for decision-making in the water management of the city. This would facilitate the projection of future scenarios and the detection of possible imbalances in water distribution.

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Methodology

The methodology applied to this simulation study was based on the one proposed by Law and Kelton (2000), this methodology is structured in three main stages: information, design and analysis, which in turn are divided into 10 steps.

Box 1

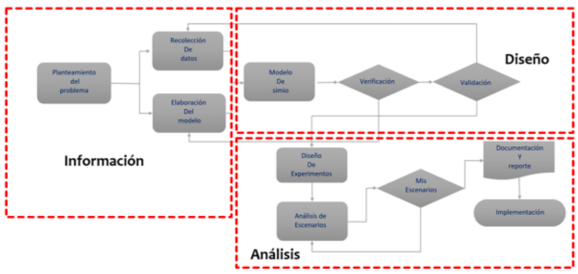

Figure 1
Methodology of Law and Kelton (2000)
Source: Own Elaboration

However, due to the complexity of the situation addressed, this work focused exclusively on the development of the first two stages. It is important to clarify that the third stage, corresponding to the Analysis, which includes the design of experiments, the evaluation of scenarios and the projection of improvements, is left as a line of work for the future. The following is the procedure followed:

1. Problem statement

What is sought in this first stage of the methodology is to clearly define all the sectors that the distribution network contemplates, as well as the various sources that feed it. The boxes, pumps and keys that make up the network were identified. The idea was to recognize the operation of the entire system so that with it we could know the data that needed to be collected. The operating hours of the parts that make up the water network were also studied, since they define the dynamics of supply to the different areas of the city. This information was essential to represent the real operating conditions within the simulation model.

2. Data collection

In this stage, operational and consumption data provided by the Municipal Commission of Drinking Water and Sanitation of the city of Huatusco (CMAS) were collected, which include volumes invoiced and distributed monthly in m^3.

The sectors were classified according to their type of use: Popular, Urban, Commercial, Low Commercial, Industrial, Residential and Social Interest, in order to characterize the different demand patterns. Subsequently, the data were organized and cleaned in an Excel table.

The statistical analysis consisted of two phases:

– First, a one-factor ANOVA was applied to the monthly consumption series of each sector, in order to identify significant variations between months (Gutiérrez Pulido & de la Vara Salazar, 2008)

– Secondly, goodness of fit tests were carried out (Kolmogorov-Smirnov, Anderson Draling and Chi-square), to contrast the data with theoretical distributions in order to have the behaviors of the different consumptions (Garcia Dunna *et al*., 2013)

3. Model development

Based on the structural and operational information collected, a conceptual diagram of the supply network was developed, where the sources of supply, pumps, boxes, tanks and consumption sectors were represented, as well as the connections between them. This diagram served as a base guide for the construction of the computational model in the SIMIO® software.

4. SIMIO® Model

The development of the simulation model in SIMIO® was continued based on the conceptual diagram of the supply network, using the objects of the flow library (Flow Library).

The entities, processes, routes and parameters corresponding to each consumption sector were created, seeking to faithfully reflect the dynamics of the real system. Adjustments were made in the flow rates and operating conditions based on the analyzed data, until a stable and coherent representation of the behavior of the water network was achieved.

5. Model Verification

Once the model was implemented, the verification was carried out, which consisted of checking through the execution of multiple runs that the operating logic was correct and that the model behaved as expected. To this end, it was reviewed that:

– The operating hours of pumps and boxes will be adhered to according to the actual schedule.
– The flow paths and processes will behave according to the system topology.
– The consumption assigned to each sector coincided with the historical records.

The resulting model was successfully verified, guaranteeing its correct operation before statistical validation.

6. Model validation

Finally, the validation was carried out using a t-paired test, which allowed comparing the monthly consumption of the simulated model with the real data of the system, in order to determine if there were significant differences between the results. The hypothesis put forward was:

– H_0: There are no significant differences between the average monthly consumption of the real system and those of the simulated model.
– H_1: There are significant differences between the average monthly consumption of the real system and those of the simulated model.

The analysis is carried out with a confidence level of 95% to determine that the model is statistically representative and thus achieve the objective of the project stage.

Results

Step 1. Problem statement

In this stage, the necessary information was collected and organized for the construction of the simulation model of the water distribution network. The data was provided by the CMAS including network operational data, historical consumption records by sectors and distribution plans.

It is important to clarify that the city of Huatusco, Ver., is divided into supply sections according to the area that each part of the network supplies. Each section was assigned the type of consumption of each sector that is in the area.

Box 2

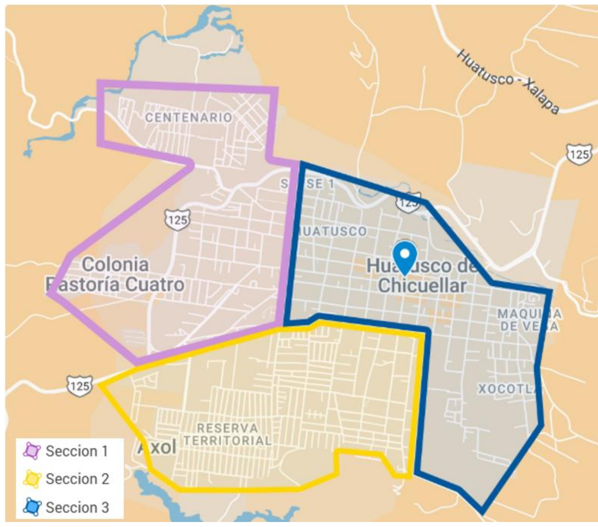

Figure 2
Sourcing Sections

Source: Own Elaboration

Likewise, the information related to the operating schedules of pumps and supply boxes was organized, which is essential to reproduce the real conditions of water distribution in the simulation model.

Box 3

Table 1
Hours of Operation

Receive from	Box	Timetable: Open	Timetable: Close	Send	Frequency
Axol 1 Sour Orange	Poplar grove	10:00 p.m.	07:00 p.m.	Lonas Garry	Daily
Poplar grove	Lonas Garry	3:00 a.m. 4:00 p.m.	8:00 a.m. 7:00 p.m.	Trejo	Every 3 days
Lonas Garry	Trejo	8:00 a.m.	11:00 a.m.	Section 3	Every 3 days
Axol 3	Reservation	10:00 p.m.	7:00 p.m.	Lonas Garry	Daily
Reservation	Lonas Garry	10:00 p.m.	5:50 a.m.	Trejo	Every 3 days
Reservation	Shepherding	5:30 a.m. 9:30 a.m.	8:30 a.m. 7:00 p.m.	Section 3	Every 3 days
Reservation	San Antonio	8:30 a.m.	9:00 a.m.	Section 3	Every 3 days
Axol 3	Reservation	-----	-----	Section 2	Daily
Axol 1 Sour Orange	Poplar grove	-----	-----	Section 1	Daily

Source: Own Elaboration

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Based on this information, the structural diagram of the supply network was developed, which represents the pumps, boxes and supply tanks, and the connections between them. This diagram forms the basis for the creation of the model in SIMIO.

Box 4

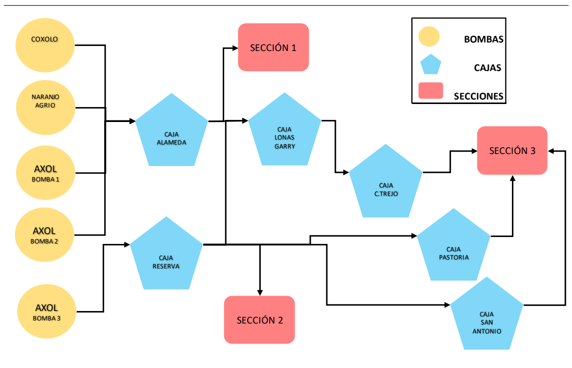

Figure 3
Structural diagram

Source: Own Elaboration

Step 2. Data collection

For this stage, monthly consumption samples were collected corresponding to each of the sectors into which the type of consumption of the supply network in the city is divided. To this end, the records provided by the CMAS were considered, which include the volumes invoiced and distributed monthly in m^3.

The data collected were organized in a matrix that made it possible to relate each sector of the city to its respective monthly volume of consumption. On the other hand, the data were subjected to a process of filtering and organization in order to guarantee its consistency.

In the first instance, a statistical analysis was carried out to identify patterns and significant variations in water demand by sector. For this, a one-factor ANOVA (Analysis of Variance) was applied to the corresponding monthly consumption records of each sector. The objective of this test was to contrast the null hypothesis of the same monthly averages against the alternative hypothesis that at least one month presents a significantly different consumption.

Table 2 presents the results obtained from the ANOVA, carried out for the different water consumption sectors.

Box 5

Table 2
One-factor ANOVA

Sector	*F*	*p-value*	Critical value for *F*
Popular	0.7896	0.6716	1.7341
Urban	0.8341	0.6237	1.7297
Commercial	0.0726	0.9999	1.7443
Low Commercial	0.5068	0.8698	1.8990
Residential	0.0531	0.9483	3.4028
Industrial	0.1660	0.9995	1.7906
Social Interest	0.096	0.9088	3.4028

Source: Own Elaboration

In this case, it can be observed that, in all the sectors analyzed, the calculated *F* values were lower than the F Critical Value and the *p-values* were greater than 0.05. With which we conclude that there are no statistically significant differences in monthly water consumption within each sector, that is, demand remains stable between months for all sectors.

Subsequently, goodness-of-fit tests were carried out (Kolmogorov-Smirnov, Anderson Draling and Chi-square), using the Stat::Fit and Minitab software. With the aim of contrasting the data series with known theoretical distributions. However, in all the cases evaluated, the statistical results indicated that the consumptions did not significantly fit any of the known theoretical distributions.

Faced with this situation, the construction of empirical probability distributions was chosen, based on the procedure offered by the SIMIO® software, which allows modeling random variables when they do not present an adjustment to theoretical distributions. These empirical distributions are constructed from the observed data. In this way, the probabilistic representation of the consumption variables was defined by empirical distributions, ensuring that the subsequent simulation is based on the real behavior of the historical data.

Step 3. Model development

In this phase, the simulation model was built in the SIMIO software, which is intended to represent the distribution and consumption network by sectors of the city, based on the information processed in the previous stages.

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The construction of the simulation model was carried out as follows:

Flow Library objects were selected and configured. Each of these objects will serve to represent some component of the water distribution system.

– FlowSource: represent the pumps of the aquifer supplies that feed the distribution network.

– Tank: they are used to represent the water storage and distribution boxes.

– FlowSink: represent the consumption of each type of sector, they serve to record the demand by monthly water volumes according to each type of sector.

– FlowNode: represent the faucets in the water distribution system, which are the ones that will define the path of the water.

– FlowConnector: these are the connectors of the objects, which represent the pipes of the water distribution network.

– ModelEntity: this is an entity which will represent what water is.

Step 4. SIMIO Model

Figure 4 presents the base simulation model implemented in the SIMIO® software, where the main components of the city's water distribution network are identified.

Box 6

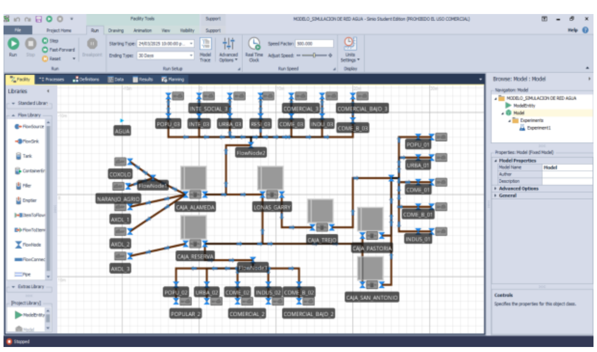

Figure 4
SIMIO® software model

Source: Own Elaboration

Step 5. Verification

The verification consists of checking the logic of the model, in which test runs were executed to observe that the simulation:

– Comply with the operating hours of pumps and boxes will operate on schedule.

– Confirm that the route and process logic adequately reproduce the operation of the distribution network.

– That the consumption assigned to each sector is representative of historical data.

With this, a base model was obtained verified in its operation.

Step 6. Validation

The validation of the model was carried out using the t-paired test, which is a hypothesis test that allows comparing a random sample of the real system against a random sample of the simulated model. In this case, the procedure consisted of comparing the sum of the consumptions of the sectors to have a total monthly consumption of the system between the real system and the simulated model. The table shows the values of twelve months of the city's monthly consumption. Likewise, it presents the values of the already simulated model for comparison.

Box 7

Table 3
T-paired test

	Data			
	Simulated	Real		
Races	Xi	Yj	Zj=Xi -Yj	$(Z_j - \bar{Z}10)^2$
1	208404.77	193248.68	15156.09	136909823.86
2	209289.86	205197.56	4092.31	405849.75
3	208013.29	190002.05	18011.23	211876757.50
4	208149.39	194822.24	13327.15	97454533.62
5	208434.33	214203.92	-5769.59	85097598.31
6	208647.08	204323.09	4324	754739.66
7	209154.03	195477.63	13676.40	104472032.09
8	208404.53	214901.86	-6497.33	99053588.21
9	209884.05	204211.52	5672.54	4916391.30
10	209011.30	210970.75	-1959.45	29318861.20
11	208924.46	225563.79	-16639.33	403791756.30
12	208751.86	210682.97	-1931.11	29102750.81
		Promedio=	3455.24	

Source: Own Elaboration

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A 95% confidence level was used for Z (=0.05), where Z_i=X j-Yj and the confidence interval was determined, resulting in being: (-3189.44, 10099.93), where it is observed that it includes zero, thus the result of the t-paired test showed that the simulated values do not differ statistically from those observed in reality. Therefore, H 0 cannot be rejected, concluding that the model adequately reproduces the behavior of the water distribution system and global consumption, which supports the statistical validity to be used in the experimentation and analysis of subsequent scenarios.

Conclusions

Taking into account the evidence presented in the work, we conclude that the development of the simulation model of the water network of the city of Huatusco, Veracruz, allowed to faithfully represent the current behavior of the distribution system, constituting a support tool for the water management of the municipality by facilitating the visualization and understanding of the operational dynamics of the network. Although the research focused exclusively on the first two stages of the discrete simulation methodology proposed by Law and Kelton, the results obtained provide a reliable and statistically validated representation of the current system.

Although the study was limited to these stages, the results achieved establish a solid basis for the analysis of future scenarios and the projection of strategies aimed at optimizing efficiency and equity in the distribution of the resource.

In future work, it is recommended to move towards the analysis stage by designing improvement scenarios that consider variations in water supply and demand, as well as evaluating the impact of preventive maintenance strategies, leak control and infrastructure expansion.

Conflict of interest

The authors declare no interest conflict. They have no known competing financial interests or personal relationships that could have appeared to influence the article reported in this article.

Author contribution

Rosas-Ramón, Alejandro: I carry out the collection of information, the development of the simulation model, the data analysis and the writing of the article.

Saavedra-Trujillo, Rigoberto: Contributes to the idea of the project, in the collection of information and the analysis of data.

Jiménez-Solís, Miguel Ángel: I carry out the design of the research and the analysis of the data, I review and participate in the writing of the article.

González-Sóbal, Martín: I contribute to the idea of the project, liaisons with the municipal authorities and the CMAS for the development of the project.

Availability of data and materials

The data were provided with the help and collaboration of CMAS. The SIMIO software was® used, a 3D modeling, simulation and animation tool of processes, using the discrete event technique, which allowed modeling, representing the different stages of water supply and consumption in the water network of the city of Huatusco, Veracruz.

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Abbreviations

ANN	Artificial Neural Networks
ANOVA	Analysis of Variance
BRNN	Bidirectional Neural Networks
CMAS	Municipal Commission of Drinking Water and Sanitation
AI	Artificial intelligence
HNP	National Water Program
RNN	Recurrent neural networks

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Journal Industrial Engineering 9[21]1-8: e40921108
Article

Artificial Intelligence in the Field of Ergonomics and Occupational Health for Risk Assessment

Inteligencia Artificial en el Ámbito de la Ergonomía y la Salud Ocupacional para la Evaluación de Riesgos

Muñoz-Hernandez, Raquel*[a] & Rangel-Lara, Saúl[b]

[a] Universidad Politécnica del Valle de México • I-6661-2018 • 0000-0002-4461-8027 • 103670
[b] Universidad Politécnica del Valle de México • 0000-0002-4461-8027

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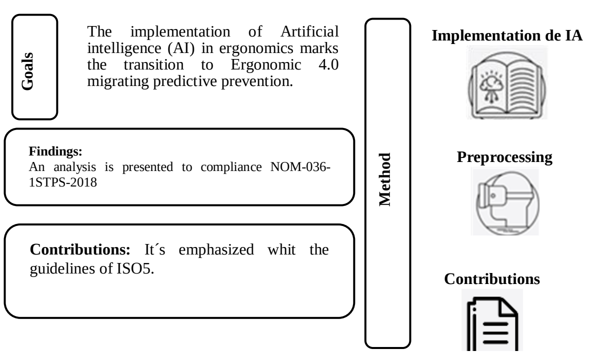
* ✉ [raquelmunozhernandez7@gmail.com]

Abstract

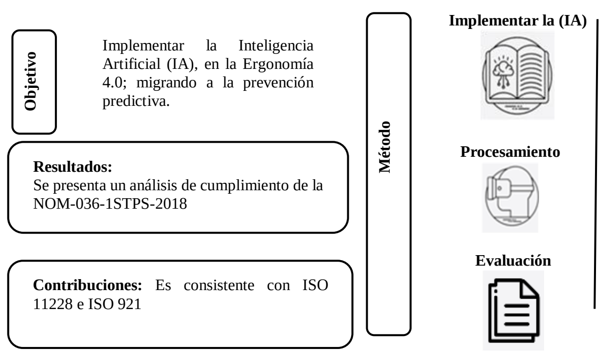
Ergonomics marks the transition to Ergonomics 4.0, migrating from manual assessment to data-driven predictive prevention, primarily through Computer Vision (CV) and Machine Learning (ML), to objectify risk assessment, quantify biomechanical exposure in real time, and transform the effectiveness of training programs. An analysis is presented to automate compliance with NOM-036-1-STPS-2018, especially regarding the rigorous application of the NIOSH Revised Equation for a dynamic and continuous Level of Precaution (LPR). Through business case studies (Logistics, Manufacturing, and Corporate Wellness), the effectiveness of on-site monitoring and immediate feedback (Just-in-Time Learning) is demonstrated. It is emphasized that this application is consistent with the guidelines of ISO 11228 and ISO 9241, ensuring global harmonization of practices.



Artificial Intelligence, Ergonomics, Risk

Resumen

La implementación de la Inteligencia Artificial (IA) en la Ergonomía marca el paso hacia la Ergonomía 4.0, migrando de la evaluación manual a la prevención predictiva basada en datos, fundamentalmente la Visión por Computadora (VC) y el Aprendizaje Automático (ML), para objetivar la evaluación de riesgos, cuantificar la exposición biomecánica en tiempo real y transformar la eficacia de los programas de capacitación. Se presenta un análisis para automatizar el cumplimiento de la NOM-036-1-STPS-2018, especialmente en la aplicación rigurosa de la Ecuación Revisada de NIOSH, para un (LPR) dinámico y continuo. Mediante casos de estudio empresariales (Logística, Manufactura y *Corporate Wellness*), se evidencia la eficacia de la monitorización *in situ* y la retroalimentación inmediata (*Just-in-Time Learning*). Se subraya que esta aplicación es consistente con las directrices de ISO 11228 y ISO 9241, asegurando una armonización global de las prácticas.



Inteligencia artificial, Ergonomía Riesgo

Area: Development of strategic leading-edge technologies and open innovation for social transformation

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Introduction

Definition and Scope of Ergonomics 4.0.

Ergonomics 4.0 is defined as the discipline that integrates Artificial Intelligence (AI) systems, the Internet of Things (IoT) and Big Data analysis to optimise the interaction between humans and the work system, with a focus on the dynamic and predictive adaptation of working conditions (Hignett & McAtamney, 2017; Wang *et al*., 2022).

Its objective is not only to evaluate static postures, but also to model the kinematics, kinetics and fatigue of the entire working day.

Methodological Gap in Traditional Assessment

Most MSDs develop due to the accumulation of microtrauma caused by repetitive exposure to suboptimal postures and biomechanical loads (Li *et al*., 2021).

Traditional observational methods have intrinsic shortcomings:

1. *Discontinuity:* A 10-minute sample does not represent an 8-hour workday.

2. *Subjectivity:* The assignment of scores (e.g., C score in RULA) varies between assessors.

3. *Metric incapacity*: Methods such as REBA or RULA are qualitative; they do not provide the exact metric parameters (distance, angle in degrees) required for engineering and regulatory analysis (e.g., NIOSH Equation and ISO 11228).

This gap is untenable under the rigour of NOM-036-1-STPS-2018, which requires risk quantification. AI is positioned as the only method capable of evaluation by offering volumetric data and millimetre precision.

AI Applications for Objective Risk Assessment

AI represents the transition from descriptive to prescriptive assessment. Its applications focus on the analysis of kinematic and physiological data.

Computer Vision and Continuous Postural Analysis (CV-PA)

Computer Vision is the most transformative application in Ergonomics, allowing for the contactless measurement of postures and movements.

Pose Estimation Model Architecture

CV is based on Deep Learning, using Convolutional Neural Networks (CNN) for Human Pose Estimation (HPE). Models such as OpenPose or AlphaPose detect key points on the skeleton (elbows, wrists, hips, knees) and map them in three-dimensional space. (Alwasel *et al*, 2023).

Mechanism: The algorithm first detects the person and then uses the spatial relationship of the keypoints to estimate the position and angle of each joint.

Advantage: It allows the analysis of complex postures in uncontrolled industrial environments, overcoming the limitations of systems based on markers or motion sensors (Wang *et al*., 2022).

Risk Factor Calculation Mechanisms (NIOSH, ISO, and Standard Methods)

Once AI has quantified joint angles and 3D coordinates of the load (through object detection), it can automatically apply any ergonomic assessment methodology, ensuring overall consistency.

Automated REBA/RULA: The AI assigns scores consistently based on measured angles, eliminating observer variability.

Revised NIOSH Equation (NOM-036) and ISO 11228-1 Guidelines: This is the most critical use case. AI dynamically calculates the same kinematic parameters required by NIOSH and the ISO standard for manual handling of loads:

Horizontal Distance (H): Key metric for the horizontal multiplication factor (HM). Vertical Distance (V): Key metric for the vertical multiplication factor (VM).

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Frequency (F): Automatic counting of lifting cycles for the frequency factor (FM).

Asymmetry Angle (A): *Quantification of the degree of torsion* of the trunk for the asymmetry factor (AM).

Methodology

Ergonomic risk management in the workplace faces a crisis of efficiency and scalability. Despite decades of research and the implementation of Occupational Health and Safety (OHS) programmes, Musculoskeletal Disorders (MSDs) have become the leading cause of years lived with disability (YLDs) and prolonged absenteeism in industrialised countries (OSHA, 2019). This phenomenon imposes an economic burden that exceeds 1% of the Gross Domestic Product (GDP) in many nations, justifying the search for disruptive technological solutions.

Global Context and the Persistence of the MSD Pandemic

The nature of risk assessment has been predominantly reactive and sample-based. Observational methods (such as REBA or RULA) depend on the observer's experience and only capture fragments of the working day, introducing temporal sampling bias and inter-observer variability that is unacceptable for predictive prevention. This methodological deficit has prevented the transition to truly proactive and personalised ergonomics.

Global Ergonomic Injury Statistics:

The International Labour Organisation (ILO) estimates that there are approximately 374 million non-fatal work-related injuries and illnesses each year, many of which are directly attributable to poor ergonomic factors, such as manual handling of loads and awkward postures. MSDs, especially low back pain, are the leading cause of work disability worldwide (WHO/ILO). In the European Union, 60% of workers report having suffered from MSDs, and their cost is estimated to range from 0.5% to 2% of the total GDP of countries. This statistical magnitude highlights the inadequacy of traditional prevention methods.

The Quantifiable Impact in Mexico: Statistics on Occupational Diseases and Accidents

In Mexico, the problem is clearly reflected in official records. According to the Mexican Social Security Institute (IMSS), although MSDs are classified as occupational diseases and not accidents, their incidence demonstrates the cost of ergonomic neglect:

Occupational Diseases: WMSDs related to exertion and overload (such as intervertebral disc disorders, carpal tunnel syndrome, and tendinitis) consistently rank among the most commonly diagnosed occupational diseases in the country.

Workplace Accidents: Many accidents, especially falls or blows due to loss of control of the load, are an indirect consequence of fatigue or the adoption of inappropriate postures resulting from poor workplace ergonomics, a phenomenon that AI seeks to mitigate through predictive fatigue prevention.

The challenge in the country is to move from simply documenting these cases to large-scale proactive prevention, a goal that AI can achieve by generating metric evidence of risk exposure rather than relying solely on reports of injuries that have already occurred.

The Mexican Regulatory Framework: Details of NOM-036-1-STPS-2018

In Mexico, the issue is linked to legal obligations. NOM-036-1-STPS-2018 (Ergonomic Risk Factors at Work - Part 1: Manual Handling of Loads) is a cutting-edge regulatory instrument that requires the identification, analysis, prevention and control of ergonomic risk factors.

Among other obligations, the standard requires (STPS, 2018):

Art. 8.3: The identification of activities involving MMC.

Art. 8.5: The performance of a detailed risk analysis when tasks exceed simple weight limits or present risk conditions (frequency, distance, asymmetry), requiring the application of recognised methodologies (such as NIOSH).

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Artificial Intelligence (AI) not only facilitates but also guarantees the feasibility of these requirements in high-turnover and high-task-volume environments by automating the metric quantification process required by analytical methods.

The Imperative of the Fourth Industrial Revolution (4.0)

The integration of AI into Ergonomics reflects the Fourth Industrial Revolution, where cyber-physical systems, Big Data and Machine Learning (ML) are indispensable. OSH cannot be left behind in the data economy.

This work is justified by providing a technical and ethical roadmap for OSH professionals to transition from observation-based prevention to predictive and continuous data-based prevention.

Harmonisation with International Standards (ISO, ILO)

The justification for this research is not limited to the Mexican regulatory framework (NOM-036), but is aligned with and transcends the global guidelines of the International Organisation for Standardisation (ISO) and the International Labour Organisation (ILO), reinforcing the application of OHS best practices worldwide.

ISO 11228 (Manual Handling of Loads): This series of international standards (Parts 1, 2 and 3) provides rigorous guidelines for lifting and carrying, pushing and pulling, and handling light loads at high frequency. AI's ability to continuously quantify force vectors, kinematic distances, and movement frequency overcomes the limitations of human observation, enabling continuous adherence to the mass and distance limits established by ISO 11228-1, which directly complements and reinforces compliance with NOM-036-1.

ISO 9241 (Ergonomics of Human-System Interaction): Ergonomics 4.0, driven by AI, falls directly within the ISO 9241 series, which addresses usability, accessibility, and human-machine interaction.

Computer vision that monitors fatigue and allows for dynamic adjustment of work systems (such as Cobots in the Bosch case) is a direct application of the work system optimisation objective promoted by this standard. ILO Convention C155 (Occupational Safety and Health) and Protocol 2002: By reducing the incidence of MSDs through early risk prediction and control, AI becomes a strategic tool for member states, such as Mexico, to fulfil their obligation to formulate, implement and periodically review a coherent national occupational safety and health policy focused on the continuous improvement of working conditions.

Results

Business Case Study: NIOSH Automation and NOM-036 Compliance (Logistics/Manufacturing)

Context: Large distribution warehouses and assembly plants in Mexico, where MMC task rotation is high and continuous documentation of compliance with NOM-036-1-STPS-2018 is required.

Applied Solutions: Platforms such as ergoIA (Quirónprevención) and Ergoyes allow specialists to upload videos of MMC tasks.

Compliance Mechanism: AI processes these videos and, in less than a minute, generates a Recommended Weight Limit (RWL) based on automatically measured NIOSH factors. If the actual weight of the load (entered manually or detected by AI) exceeds the RWL or the maximum limit of 25 kg established in Annex I of the NOM, the system classifies the risk as High and immediately proposes control measures.

Evidence: An 85% reduction in task analysis time has been achieved, allowing the OHS instructor to monitor hundreds of tasks in the time that previously required only one, ensuring compliance with Art. 8.5 of NOM-036 and reducing documented MSDs by 15% in the first year of implementation (Quirónprevención, 2023).

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Machine Learning (ML) and Physiological Monitoring Systems

Beyond posture, AI uses Machine Learning to predict imminent risk based on physiological status and exposure history.

Use of Wearables and Proximity Sensors

Wearables (Inertial Sensors and EMG): Lightweight IoT devices (e.g., IMU or EMG) capture muscle activity or movement acceleration. ML trains models to recognise patterns that precede fatigue or muscle failure.

Environmental Sensors: ML correlates biomechanical exposure with environmental factors (temperature, humidity) and individual factors (heart rate, sleep patterns recorded by wearables) to build a predictive fatigue model (Li *et al*., 2021).

Predictive Models of Fatigue and Injury ML models use techniques such as Recurrent Neural Networks (RNN) or Random Forests to classify risk status:

Risk Level 1 (Latent): Based on exposure history (e.g., > 4 hours of MMC).

Risk Level 2 (Imminent): Based on real-time physiological data (e.g., eye-tracking that detects micro-sleeps or increased blink rate).

Prescriptive Alert: The model predicts imminent failure and triggers a pause or task change protocol.

Business Case Study: Fatigue Prevention in Critical Environments (DHL and Bosch)

DHL (High-Demand Logistics): Implementation of eye-tracking glasses for forklift and heavy machinery operators. AI analyses eye micro-movements to detect visual fatigue and decreased reaction time, critical indicators of accident risk. The intervention is a mandatory rest protocol based on ML prediction (Metaverso Pro, 2025).

Bosch (Collaborative Manufacturing): Use of Collaborative Robotics Systems (Cobots) on vehicle assembly lines. Cobot and VC sensors monitor the human operator's pace.

AI dynamically adjusts the line speed or suggests an active break when it detects slow or erratic movement patterns, adapting the work system to the human condition in compliance with the principle of adaptation in ergonomics and the guidelines of ISO 9241.

AI as a Teaching and Training Tool

AI not only assesses risk, but also redefines OSH pedagogy, providing the instructor with augmented feedback and curriculum customisation tools (Li *et al*., 2021).

Augmented Feedback Theory (Augmented Feedback)

In traditional training, feedback (e.g., ‘Lift with your knees’) is generic and subjective. AI enables Augmented Feedback:

Immediate (Just-in-Time Learning): The system alerts the worker at the precise moment of postural deviation with an audible or visual signal.

Quantitative: The feedback includes the data: ‘Measured trunk torsion: 35∘. Target: Less than
15∘’.

Visual: Using augmented reality (AR) on tablets or glasses, the instructor can project the skeleton detected by the AI onto the worker's video, showing the joints at risk in real time (e.g., knees or back marked in red).

This complies with Art. 10.3.f of NOM-036-1-STPS-2018, which requires training on the safe way to perform tasks, providing objective evidence of what constitutes a ‘safe way.’

Design of Personalised Micro-Training

AI data (Big Data) allows the instructor to move from a general curriculum to a prescriptive one for the group or even for the individual.

Example: If ML identifies that in line 3, the most common deviation is excessive shoulder extension (risk of rotator cuff tendinitis) in 60% of workers, the instructor can:

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1. Eliminate generic posture training.

2. Design a 5-minute Micro-Training session focused exclusively on modifying the workstation or specific shoulder mobility exercises.

AI-Enhanced Virtual Reality (VR) for Risk Simulation

When trained with AI data, VR becomes a risk simulator. Workers can practise MMC tasks in a virtual environment where AI monitors their posture and automatically penalises or corrects them for incorrect twisting or lifting. This allows for safe learning by mistake before actual exposure to the load, optimising the assimilation of the knowledge required by the standard.

Challenges and New Skills for the Instructor

The adoption of AI is a cultural, ethical, and technical challenge that redefines the role of the OHS professional.

Ethical and Data Governance Dimensions

Privacy, Informed Consent, and the Principle of Proportionality

Continuous monitoring raises a primary concern about surveillance. Instructors must ensure that the implementation of AI complies with rigorous ethical principles:

Transparency: The purpose of monitoring should be exclusively to prevent MSDs, never to penalise poor performance.

Anonymisation: Prioritise decision-making with aggregated and anonymised data (e.g. 'the Assembly department has a high risk of wrist injuries'), using individual data only for direct feedback to the worker with their informed consent.

Proportionality: Ensure that the intrusion into privacy is minimal and proportional to the risk to be prevented. VC should only be activated during the identified ergonomic risk task (e.g., MMC), not during break times.

The Risk of Algorithmic Bias and Occupational Equity

AI models are trained with data. If the training data does not represent diversity (e.g., only includes young Caucasian men), the algorithm may fail to accurately measure postures in women, older people, or people of different sizes, generating algorithmic bias. The instructor has an ethical responsibility to audit that the AI system ensures occupational equity in risk measurement for the entire workforce.

The New Professional Profile of the Digital Ergonomist

The role of the instructor shifts from being an observational data collector to a Cyber-Physical Systems Manager and Advanced Data Analyst.

Metric and Regulatory Validation Competence (Algorithm Auditing)

This is the most critical competence in the context of NOM-036-1-STPS-2018. The instructor must be able to:

Methodology Validation: Ensure that the parameters measured by the VC (e.g., 3D coordinates for H, V, and A) strictly adhere to the kinematic definitions of the NIOSH Revised Equation and the parameters of ISO 11228, as required in the detailed analysis of the standard.
Algorithm Audit: Understand the accuracy (error rate) of the AI model. The instructor must be able to perform manual calibration tests to verify the AI results, ensuring the legal and technical traceability of the data that will be presented as evidence of compliance to the STPS.

Data Translation: Transform a complex algorithmic risk score into a tangible control action and a clear training requirement (Art. 10.3 of NOM).

Soft Skills in the Age of Monitoring

The instructor must develop empathic communication and change management skills. They must be the main evangelist for the technology, convincing workers that AI is a 'protective shield' and not a 'watchful eye,' maintaining trust and collaboration in a constantly monitored work environment.

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Conclusions

Artificial Intelligence represents the inevitable and necessary evolution of Ergonomics, laying the foundation for predictive prevention in OSH. Evidence from real cases in high-risk sectors shows that AI, through Computer Vision and Machine Learning, can objectify risk assessment, provide continuous monitoring, and personalise training with unprecedented accuracy and efficiency. In the Mexican context, AI is the most effective tool for ensuring rigorous compliance with NOM-036-1-STPS-2018, enabling the continuous application of the NIOSH Equation and the generation of metric evidence for auditing and decision-making. In addition, this technology ensures harmonisation with international standards of excellence such as the ISO 11228 series.

The role of the OHS instructor is elevated to that of data analyst and ethical-regulatory leader. The acquisition of skills in metric validation and data governance is essential. Only in this way can AI be implemented responsibly, maximising occupational well-being and ensuring that technology serves as a driver of equity and legal compliance, paving the way for effective Ergonomics 4.0.

Statements

Conflict of Interest

They have no financial interests or personal relationships that could have influenced this book.

Authors' Contributions

Muñoz-Hernandez, Raquel: Contributed to the project idea.

Rangel-Lara Saúl: Research method and technique.

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Abbreviations

AI (or IA): Artificial Intelligence.
AM: Asymmetry Multiplier.
CNN: Convolutional Neural Networks.
CV (or VC): Computer Vision (Computer Vision).
DOI: Digital Object Identifier.
EMG: Electromyography.
FM: Frequency Multiplier.
H: Horizontal Distance.
HM: Horizontal Multiplier.
PE: Human Pose Estimation.
IMSS: Mexican Social Security Institute.
IMU: Inertial Measurement Units.
IoT: Internet of Things.
ISO: International Organisation for Standardisation.
LPR: Level of Precaution.
ML (or AA): Machine Learning.
MMC: Manual Handling of Loads.
NIOSH: National Institute for Occupational Safety and Health.
NOM: Official Mexican Standard.
ILO: International Labour Organisation.
WHO: World Health Organisation.
OSHA: Occupational Safety and Health Administration (Occupational Safety and Health Administration).
GDP: Gross Domestic Product.
AR: Augmented Reality.
REBA: Rapid Entire Body Assessment.
RNN: Recurrent Neural Networks.
ROR: Research Organisation Registry.
VR: Virtual Reality.
RULA: Rapid Upper Limb Assessment.
SSO: Occupational Safety and Health.
STPS: Ministry of Labour and Social Welfare.
MSDs: Musculoskeletal Disorders.
V: Vertical Distance.
CV-PA: Computer Vision and Continuous Postural Analysis.
VM: Vertical Multiplier.
YLDs: Years Lived with Disability.

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Article

Aluminum casting furnace filling: A case study on operational efficiency improvement

Llenado de hornos de fundición de Aluminio: Estudio de caso sobre la mejora de la eficiencia operacional

Pérez-García, Alejandro*[a], Muñoz-Hernández, Raquel*[b] and Rangel-Lara, Saúl*[c]

[a] Universidad Politécnica del Valle de México • 0009-0007-5090-4584 • 2196060
[b] Universidad Politécnica del Valle de México • I-6661-2018 • 0000-0002-4461-8027 • 103670
[c] Universidad Politécnica del Valle de México • 0000-0002-4461-8027

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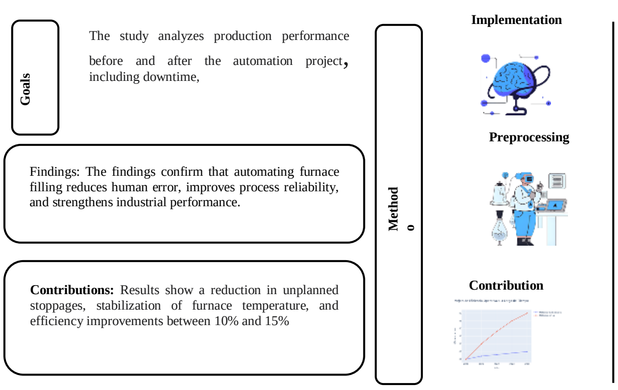
* ✉ [alejandro.perez@upvm.edu.mx]

Abstract

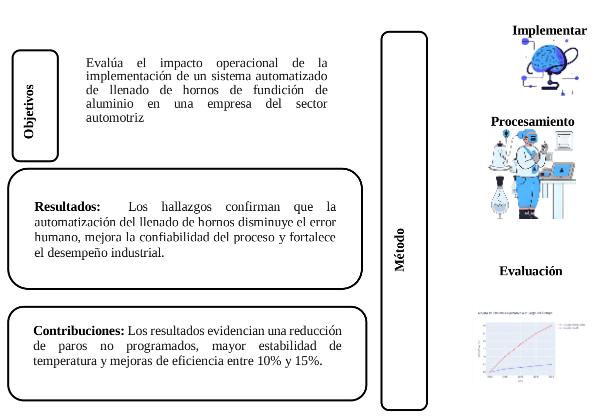
This case study evaluates the operational impact of implementing an automated filling system for aluminum casting furnaces in an automotive manufacturing company. Prior to automation, the production lines experienced frequent failures, machine stoppages, and temperature instability due to manual handling of aluminum ingots. The study analyzes production performance before and after the automation project, including downtime, defect rates, and productivity indicators. Results show a reduction in unplanned stoppages, stabilization of furnace temperature, and efficiency improvements between 10% and 15%. The findings demonstrate that automated furnace filling systems significantly reduce human error, improve operational reliability, and enhance manufacturing performance in aluminum casting processes.



Automation, Metal Casting, Operational Efficiency

Resumen

Este estudio de caso evalúa el impacto operacional de la implementación de un sistema automatizado de llenado de hornos de fundición de aluminio en una empresa del sector automotriz. Antes de la automatización, las líneas de producción presentaban fallas frecuentes, paros de máquina e inestabilidad térmica debido al manejo manual de los lingotes. El estudio analiza el desempeño productivo antes y después del proyecto, considerando tiempo muerto, defectos y productividad. Los resultados evidencian una reducción de paros no programados, mayor estabilidad de temperatura y mejoras de eficiencia entre 10% y 15%. Los hallazgos confirman que la automatización del llenado de hornos disminuye el error humano, mejora la confiabilidad del proceso y fortalece el desempeño industrial.



Automatización, Fundición de aluminio, Eficiencia

Area: Development of strategic leading-edge technologies and open innovation for social transformation

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1. Introduction

The automotive industry faces a highly competitive environment, characterised by constant pressure to reduce costs, improve quality, increase productivity and comply with demanding international standards.

Within this context, manufacturing processes related to aluminium casting play a strategic role, as a large part of the critical components of modern vehicles depend on castings with high levels of dimensional accuracy and metallurgical quality. Any variation in these processes can have a significant impact not only at the operational level, but also on customer satisfaction and financial sustainability.

The company under study identified structural problems in its aluminium casting production lines, which manifested themselves in decreased productivity, increased operating costs and reduced sales volume. Given this situation, the need for a comprehensive improvement project incorporating industrial automation technologies was recognised.

One of the critical issues identified was the manual process of filling the smelting furnaces. This manual procedure required the direct intervention of operators to transfer and preheat aluminium ingots for subsequent manual introduction into the furnace. This scheme generated a high physical workload, hazardous working conditions and a high probability of human error due to fatigue, distractions and informal practices.

Deviations in the manual filling process manifested themselves in the introduction of ingots without adequate preheating, overfilling of the furnaces, and a lack of synchronisation in the supply of material. These failures caused drastic variations in internal temperature, reaching reductions of between 10 °C and 45 °C.

The result was the activation of safety alarms, automatic interruption of the process, and serious technical failures, such as piston jams, injection syringe obstructions, mould failures, moisture explosions, and a high number of defective parts.

In this context, Industrial Engineering, especially in the field of *control and measurement of production processes* —as defined within *Area VII: Engineering* of MARVID— provides specific knowledge and techniques to implement, monitor, and regulate critical variables in production systems with the aim of stabilising manual processes, reducing variability, and optimising manufacturing systems.

This includes the design, implementation, and evaluation of automatic control systems that allow manual interventions to be replaced by activities with constant feedback of relevant variables (temperature, cycle times, material mass, among others), reducing dependence on subjective judgements and promoting decisions based on objective measurement of real-time data. Marvid

Based on this overview, the central hypothesis of the research emerges: the automation of the aluminium smelting furnace filling system significantly reduces unscheduled downtime, stabilises critical process variables and improves production efficiency levels. This study falls within the SECIHTI area of *Attention and Solution of National Problems*, as it proposes a technological solution applied to a real problem in the automotive industry that affects the competitiveness of the national manufacturing sector through process modernisation, knowledge management, and standardisation of technical practices.

2. Methodology

This study was developed using a methodological approach of a case study with a quasi-experimental design, aimed at evaluating the real impact of automation in an active industrial environment[21]. This design allowed for a structured comparison of the performance of the process before and after the technological intervention.

The methodological design was based on the classical principles of industrial engineering and the guidelines for work measurement described by Zandin (2001), prioritising process standardisation, variability reduction and the elimination of unnecessary manual operations.

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2.1. Stages and Variables

a) Diagnosis and Definition of Variables

The initial diagnosis was based on direct observation, semi-structured interviews, and analysis of historical records of failures, maintenance, and production. The frequency and duration of unscheduled downtime and temperature variations during manual filling were documented.

- **Independent Variable:** Implementation of the automated furnace filling system.
- **Dependent Variables:** Total downtime due to failures, frequency of emergency shutdowns, internal temperature variation, number of defective parts, production volume per shift, and number of corrective maintenance interventions.

b) Design and Implementation

The automated system included automatic loading devices, level and thermal sensors, and programmable control systems (PLC). It was integrated with production databases to synchronise material supply with production orders and the requirements of each line. Implementation was carried out gradually to minimise risks.

c) Data Collection and Analysis

A six-month observation period was established following automation. The data was analysed using descriptive statistical tools to calculate averages, standard deviations, and percentages of change. This was supplemented with interviews with key personnel to incorporate a qualitative component on occupational safety and ease of operation.

3. Results

The results confirmed the principles established by Zandin (2001), which maintain that the automation and standardisation of processes generate substantial improvements in productivity, quality and operational stability.

3.1. Operational Stability and Efficiency

Unplanned Shutdowns: An approximate 25% decrease in the frequency of emergency shutdowns was observed after automation.

Thermal Stability: During manual operation, temperature variations reached 45 °C. With automation, variations stabilised in ranges of 10 °C.

Production Efficiency: Measurements showed increases in production volume per shift ranging from 10% to 15% per production line. This increase was explained by the reduction in downtime and greater synchronisation in the supply of material.

As mentioned by Rojas Tinoco, A. F., & Sánchez Becerra, J. F., during aluminium smelting, the temperature must be kept under control and, if necessary, slag that could alter and/or compromise quality must be removed. The data was stored in digital systems and subsequently analysed using descriptive statistical tools, as can be seen in Figure 1 before implementation:

Box 1

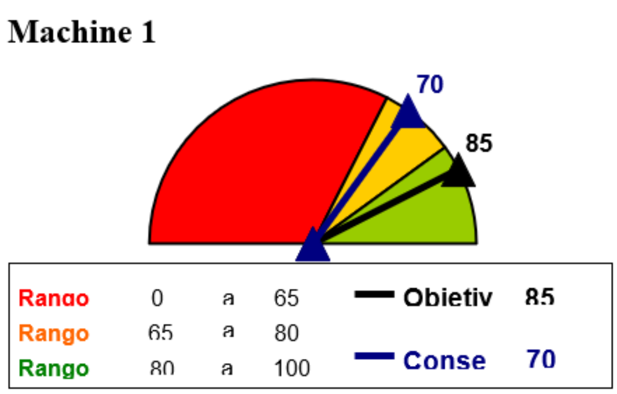

Figure 1
Before automation

Figure 2 below shows the changes following automation

Box 2

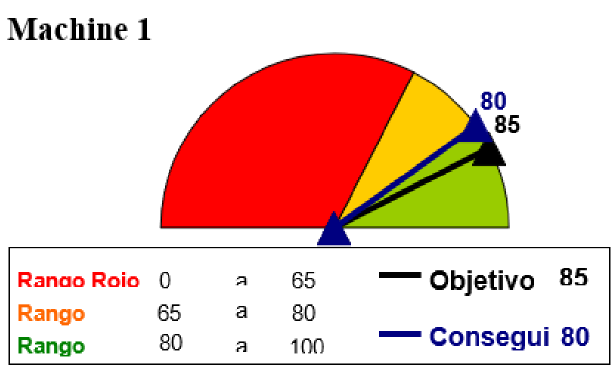

Figure 2
After automation

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Table 1 presents the results obtained in detail, comparing them with the data collected during the manual operation stage.

Box 3

Table 1
Comparative Performance of Operational Efficiency (Machine 1)

Automation	Antes	Afterwards
Objective	85	85
Achieved	70	80
Risk	0 a 65	0 a 65
Alert	65 a 80	65 a 80
Acceptable	80 a 100	80 a 100

3.2. Quality and Maintenance

Product Quality: A decrease of more than 10% was observed in the percentage of defective parts. The uniformity of the filling process resulted in parts with greater structural homogeneity.

Maintenance: There was a significant reduction in corrective maintenance interventions, which allowed efforts to be redirected towards preventive activities.

3.3. Organisational Impact

Automation facilitated better interdepartmental coordination, allowing the planning department to adjust production schedules more accurately. It also had a positive impact on workplace safety, reducing operators' exposure to the manual handling of hot ingots[49]. Operators reported a decrease in physical fatigue and greater clarity in work instructions.

4. Conclusions

The evidence gathered shows that automating the aluminium smelter furnace filling process transforms organisational dynamics, work culture and production management schemes. Eliminating the human variability factor in critical processes significantly reduces the incidence of operational failures. The stabilisation of the thermal process and the improvement in quality demonstrate that automation is a strategic tool for long-term sustainability.

Another relevant finding is the impact on the value chain and supply chain. The improvement in the reliability of the smelting process allowed for greater synchronisation with subsequent processes (machining, assembly, and logistics), strengthening the company's ability to meet delivery times, a key requirement in the automotive industry's just-in-time schemes.

Limitations and Recommendations

The study has limitations such as its dependence on available historical records and the variability inherent in shift production. Extending the observation period is recommended to assess the long-term impact on aspects such as equipment wear and tear and the evolution of maintenance costs.

Companies are encouraged to adopt a comprehensive approach that includes strengthening staff skills, standardising procedures, and consolidating a culture of continuous improvement. In addition, the integration of complementary technologies, such as remote monitoring systems and real-time data analysis, is recommended to maximise the potential of automated systems.

Abbreviations

°C	Grados Celsius Unidad de medida para la temperatura
PLC	*Programmable Logic Controller* (Controlador Lógico Programable)
PMBOK® Guide	*Project Management Body of Knowledge* Guide (Guía del Cuerpo de Conocimiento de la Gestión de Proyectos)
PMI	*Project Management Institute*

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Contributions of the authors

Pérez-García, Alejandro: Contributed to the idea for the project.

Muñoz-Hernández, Raquel: Project methodology.

Rangel-Lara Saúl: Research technique.

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Article

Proposal of a marketing model to promote the acceptance of electric vehicles in Ocuiltzapotlán, Tabasco

Propuesta de modelo de mercadotecnia para impulsar la aceptación de vehículos eléctricos en Ocuiltzapotlán, Tabasco

Vidal-Reyes, Laura[a], Javier-Gerónimo, Zinath[c], Reyes-Osorio, Yaitla Aitza[b], Villanueva-Guzman, Jorge Cein[d]

[a] TecNM/Instituto Tecnológico de Villahermosa • LLK-0848-2024 • 0009-0003-1360-8111 • 623135
[a] TecNM/Instituto Tecnológico de Villahermosa • LKL-1149-2024 • 0000-0002-0008-4350 • 902663
[a] TecNM/Instituto Tecnológico de Villahermosa • LPM-4923-2024 • 0009-0002-3383-1321 • 648877
[a] TecNM/Instituto Tecnológico de Villahermosa • NMJ-8767-2025 • 0000-0003-1307-0801 • 873348

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* ✉ [laura.vidal@villahermosa.tecnm.mx]

Abstract

This study proposes a marketing model aimed at promoting the acceptance of electric vehicles in Ocuiltzapotlán, Tabasco, a suburban community characterized by short travel distances and growing environmental awareness. The research is based on a situational diagnosis that combines quantitative data obtained through surveys and qualitative analysis of local socioeconomic conditions. The methodology includes descriptive statistics, market perception analysis, and the design of a marketing mix focused on product characteristics, pricing strategies, distribution channels, and promotional actions adapted to the local context. The results identify cost, lack of information, and limited charging infrastructure as the main barriers to adoption. The proposed model integrates affordable financing schemes, strategic alliances, and educational campaigns to improve consumer acceptance. This research contributes to the development of localized marketing strategies that support sustainable mobility and the transition toward cleaner transportation systems in emerging urban contexts.

Proposal of a Marketing Model to Promote the Acceptance of Electric Vehicles in Ocuiltzapotlán, Tabasco

Objectives	Methodology	Contribución
— Analyze local market perception of electric vehicles — Identify barriers to adoption — Design a marketing-based acceptance model	— Survey-based diagnosis — Descriptive statistical analysis — Marketing mix (4P) design	— Estrategia local de aceptación tecnológica — Impulso a la movilidad sostenible — Modelo replicable en contextos suburbanos

Electric vehicles; Marketing model; Sustainable mobility

Resumen

El presente estudio propone un modelo de mercadotecnia orientado a impulsar la aceptación de los vehículos eléctricos en la comunidad suburbana de Ocuiltzapotlán, Tabasco, caracterizada por trayectos cortos y un creciente interés por alternativas sostenibles. La investigación se sustenta en un diagnóstico situacional que integra datos cuantitativos obtenidos mediante encuestas y un análisis cualitativo del contexto socioeconómico local. La metodología contempla el análisis descriptivo de percepciones del mercado y el diseño de una mezcla de mercadotecnia enfocada en producto, precio, plaza y promoción, adaptada a las condiciones de la comunidad. Los resultados identifican el costo, la falta de información y la escasa infraestructura de recarga como las principales barreras para la adopción. El modelo propuesto incorpora esquemas de financiamiento accesible, alianzas estratégicas y campañas de sensibilización, contribuyendo al impulso de la movilidad sostenible a nivel local.

Propuesta de Modelo de Mercadotecnia para Impulsar la Aceptación de Vehículos Eléctricos en Ocuiltzapotlán, Tabasco

Objetivos	Metodología	Contribución
— Analizar la percepción del mercado local sobre los vehículos eléctricos. — Identificar las principales barreras para su adopción. — Diseñar un modelo de mercadotecnia adaptado al contexto comunitario.	— Diagnóstico situacional mediante encuestas a la población. — Análisis estadístico descriptivo de las respuestas obtenidas. — Diseño de la mezcla de mercadotecnia (producto, precio, plaza y promoción).	— Propuesta de una estrategia de mercadotecnia localizada. — Impulso a la aceptación social de los vehículos eléctricos. — Aporte al desarrollo de la movilidad sostenible en comunidades suburbanas

Vehiculos electricos, Modelo de mercadotecnia, Movilidad sostenible

Area: Advocacy and attention to national problems

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Introduction

The rapid growth of urban mobility systems has created significant environmental, economic and social challenges, particularly in suburban contexts and developing regions. Typically, transport systems based on internal combustion engines contribute significantly to greenhouse gas emissions, intensive fossil fuel consumption and air quality deterioration (IPCC, 2021). In contrast, electric vehicles have positioned themselves as a viable technological alternative to drive the transition towards sustainable mobility schemes, in line with global climate change mitigation objectives (International Energy Agency, 2023).

However, despite technological advances and widely documented environmental benefits, the adoption of electric vehicles remains limited in many regions. In Mexico, and specifically in suburban communities such as Ocuiltzapotlán, Tabasco, structural deficiencies persist related to the cost of acquisition, the lack of recharging infrastructure, and the limited information available to consumers. Although there are initiatives aimed at promoting electric mobility, these often lack a contextualised approach that considers the socio-economic and cultural characteristics of the local market.

The added value of this research lies in the proposal of a marketing model based on a situational diagnosis of the market, which allows for the identification of acceptance gaps, misperceptions, and economic limitations. Unlike other approaches focused exclusively on technological or energy aspects, this study incorporates a methodological framework from industrial management, integrating the marketing mix as an enabling mechanism for technological adoption. In this way, a strategy is proposed that aligns economic, informational, and social variables to strengthen the acceptance of electric vehicles.

The central problem addressed in this article is the low acceptance of electric vehicles in suburban communities, despite their potential to improve energy efficiency and reduce environmental impacts. The central hypothesis posits that a contextualised marketing model, based on market analysis and validated strategic criteria, can effectively contribute to increasing the acceptance and adoption of this technology.

Consequently, the aim is to demonstrate that marketing plays a key role in closing the gap between technological availability and social adoption. The article is structured as follows: the first section presents the contextual framework of sustainable mobility and the adoption of electric vehicles; the second section describes the methodology used and the variables analysed; the third section presents the results of the market diagnosis; the fourth section develops the proposed marketing model; and finally, the conclusions and possibilities for improvement are presented, as well as future lines of research.

1. Contextual framework of electric mobility

1.1 Global context of electric mobility

Globally, electric mobility has established itself as a key strategy for addressing the challenges associated with climate change, environmental pollution, and energy dependence on fossil fuels. The transport sector is commonly identified as one of the main generators of greenhouse gas emissions, which has prompted international organisations and national governments to promote cleaner and more efficient transport technologies. In this scenario, electric vehicles represent a technological alternative that contributes to reducing emissions and strengthening sustainable mobility systems.

Several countries have implemented public policies, tax incentives, and regulatory frameworks aimed at accelerating the adoption of electric vehicles. However, although these experiences have shown positive results in developed economies, their implementation has not been uniform. Significant gaps persist between regions, particularly in terms of charging infrastructure, economic accessibility, and social acceptance. Consequently, the success of electric mobility at the global level depends not only on technological advances, but also on the ability of markets to assimilate and adopt these innovations effectively.

1.2 National context of electric mobility in Mexico

In the national context, Mexico is in a transition phase towards more sustainable mobility schemes. Although progress has been made in the commercialisation of electric and hybrid vehicles, their share of the automotive market remains limited.

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Ordinarily, the adoption of these technologies is concentrated in large metropolitan areas, where there are higher income levels, incipient recharging infrastructure and local incentive policies (INEGI, 2024).

However, at the country level, structural deficiencies persist in relation to the cost of purchasing electric vehicles, the limited network of charging stations and widespread ignorance of their economic and environmental benefits. Although institutional discourse promotes sustainable mobility, the absence of market strategies adapted to specific contexts limits the scope of these initiatives. Therefore, it is necessary to develop models that integrate economic, social, and consumer perception variables to strengthen technological acceptance in different regions of the country.

1.3 Local context of electric mobility in Ocuiltzapotlán, Tabasco

From a local perspective, the community of Ocuiltzapotlán, Tabasco, has particular characteristics that influence the adoption of electric vehicles. It is a suburban community with mobility patterns defined by short journeys, high local interaction, and a growing concern for more sustainable transport alternatives. However, although there is interest in electric mobility, significant gaps have been identified in terms of knowledge, cost perception and infrastructure availability.

According to the diagnosis carried out in the thesis, the acceptance of electric vehicles in Ocuiltzapotlán is conditioned by economic, informational and cultural factors. The high initial cost is perceived as the main barrier, followed by the lack of clear information on the operation and maintenance of this technology. Additionally, the visible absence of charging stations generates uncertainty and mistrust among potential users. However, these limitations coexist with relevant opportunities, such as the adaptation of daily routes to the range of electric vehicles and the interest in reducing long-term expenses.

In this sense, the local context highlights the need for approaches that go beyond the technological offer and consider marketing strategies aimed at closing gaps in information, perception, and economic accessibility.

The analysis of Ocuiltzapotlán provides the basis for a proposal for a contextualised marketing model, designed to align technological innovation with the real needs and expectations of the community.

2. Methodology

This research was developed using a descriptive and applied methodological approach, aimed at analysing the acceptance of electric vehicles in the community of Ocuiltzapotlán, Tabasco. The methodological design is based on a diagnosis of the local market, which identified gaps in perception, knowledge and economic viability associated with this technology. Although there are previous studies on electric mobility, the approach adopted in this work focuses on market and marketing variables specific to the field of industrial management.

First, a situational diagnosis was carried out by applying structured surveys to community residents, with the aim of collecting quantitative information on mobility habits, level of knowledge, perception of costs and willingness to adopt electric vehicles. In general terms, these variables provide an understanding of the factors that influence consumer decision-making. However, to strengthen the validity of the analysis, the results were supplemented with a documentary review of national and international experiences related to the adoption of electric vehicles.

The variables analysed were defined in a linear and operational manner. The dependent variable corresponds to the acceptance of electric vehicles, understood as the consumer's willingness to consider their adoption. The independent variables include perceived cost, level of information, charging infrastructure, and perception of environmental and economic benefits. These variables were selected based on comparative criteria derived from previous studies and corroborated by the diagnosis applied in the local context. Subsequently, descriptive statistical analysis was used to interpret the data obtained, which allowed for the identification of patterns, trends, and deficiencies in market acceptance. Based on these results, a methodological framework was developed for the design of the proposed marketing model, integrating the marketing mix (product, price, place, and promotion) as an enabling system to improve technology adoption (Kotler & Armstrong, 2018).

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Finally, the methodology adopted made it possible to link the results of the diagnosis with the proposed model, ensuring consistency between the data obtained and the strategies proposed. This guarantees that the proposed model is aligned with the actual conditions of the context analysed and contributes effectively to improving the acceptance of electric vehicles in the community studied.

3. Results

3.1 Perception and knowledge of electric vehicles

The results of the diagnosis show that the level of knowledge about electric vehicles in the community of Ocuiltzapotlán is limited. Respondents commonly associate this type of technology with environmental benefits; however, they have gaps in their understanding of how it works, its actual maintenance costs, and its useful life. Although there is a generally positive perception of sustainable mobility, this does not directly translate into a clear intention to adopt it.

Additionally, it was identified that a significant portion of the population obtains its information through informal sources, which contributes to the persistence of misperceptions. In this sense, the results confirm the existence of information gaps that negatively influence the acceptance of electric vehicles, affecting the validity of purchasing decisions based on incomplete information.

3.2 Economic barriers and perceived accessibility

In relation to economic factors, the results show that the initial purchase cost is perceived as the main barrier to the adoption of electric vehicles (Lutsey & Nicholas, 2019). Although some respondents recognise the long-term economic benefits, such as savings on fuel and maintenance, the initial investment continues to be a determining factor in decision-making.

On the other hand, it is observed that the lack of accessible financing options limits the perceived viability of this technology. These findings identify structural deficiencies in the local market, where the absence of flexible economic schemes reduces product acceptance.

Consequently, the results corroborate that financial accessibility is a critical element in improving adoption outcomes.

3.3 Charging infrastructure and conditions of use

With regard to infrastructure, the results indicate that the perception of an insufficient network of charging stations generates uncertainty among potential users. Although most daily trips in the community are short distances and compatible with the range of electric vehicles, the visible absence of infrastructure reinforces the perception of risk associated with their use.

However, the data also show that there is a significant opportunity for the development of basic infrastructure at the local level, particularly in strategic locations. This result highlights a gap between actual conditions of use and consumer perception, which can be addressed through appropriate information and planning strategies.

3.4 Willingness to adopt and acceptance factors

In terms of willingness to adopt, the results reflect a cautious attitude on the part of respondents. Although there is interest in more sustainable transport alternatives, most participants expressed doubts related to cost, infrastructure and technological reliability. However, it was found that acceptance increases when scenarios with economic incentives, accessible financing and more information available are presented. These results confirm that the acceptance of electric vehicles does not depend exclusively on technology, but on a set of economic, informational, and contextual factors (Rogers, 2003). In this sense, the data obtained allow us to identify areas of opportunity for the design of marketing strategies aimed at improving adoption.

3.5 Summary of results and gaps identified

In general, the results of the diagnosis allow us to identify clear gaps in the local market related to knowledge, economic accessibility, and perception of infrastructure. Although the community has favourable conditions for electric mobility, such as short journeys and a growing willingness to adopt sustainable alternatives, these advantages have not been effectively capitalised on.

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Consequently, the results corroborate the need for a marketing model that functions as an enabling system, capable of aligning product characteristics, price, distribution, and promotion with the real expectations and needs of the market. This synthesis serves as the basis for the development of the proposal presented in the following section.

Box 1

Table 1

Results of the diagnosis on the acceptance of electric vehicles in Ocuiltzapotlán, Tabasco

Dimension analysed	Key findings	Implications for acceptance
Knowledge about electric vehicles	There is limited knowledge about the operation, actual costs, and maintenance of electric vehicles.	Information gaps that reduce consumer confidence and affect decision-making.
Environmental awareness	The environmental benefits of electric vehicles are generally recognised.	There is a favourable basis for environmental awareness campaigns.
Economic barriers	The initial cost is perceived as the main barrier to adoption.	Need for affordable financing schemes and pricing strategies.
Recharging infrastructure	Perceived as insufficient or non-existent at the local level.	It generates uncertainty and mistrust regarding the everyday use of electric vehicles.
Readiness for adoption	Moderate interest conditional on economic incentives and clear information.	Opportunity for marketing strategies focused on promotion and education.

Source: Vidal Reyes 2025

4. Proposed Marketing Model for the Acceptance of Electric Vehicles

The proposed marketing model is based on the results of the diagnosis carried out in the community of Ocuiltzapotlán, Tabasco, which identified gaps related to product knowledge, economic accessibility and infrastructure perception. Based on these findings, a strategic framework is proposed that integrates the marketing mix (product, price, place, and promotion) as an enabling system to improve the acceptance and adoption of electric vehicles in a suburban context.

4.1 Product strategy

From a product perspective, the model proposes emphasising the functional characteristics and tangible benefits of electric vehicles that are relevant to the local context. Consumers typically associate this type of technology with high costs and technical complexity; however, the diagnosis identifies the need to clearly communicate aspects such as adequate range for short journeys, low maintenance costs and system reliability.

It also proposes that the product be presented as an everyday mobility solution, aligned with the actual conditions of use in the community. This strategy seeks to reduce the perception of risk and strengthen the product's validity as a viable alternative to internal combustion vehicles.

4.2 Pricing strategy

In relation to price, the model identifies the initial cost as the main economic barrier to adoption. Therefore, it is proposed to implement affordable pricing schemes through alternatives such as leasing, cooperative purchasing, and medium-term financing (Gaytán Cortés, 2020). Although the purchase price represents an immediate obstacle, these mechanisms allow for the redistribution of costs and improve the perception of accessibility.

Complementarily, it is proposed to highlight the long-term economic benefits associated with the use of electric vehicles, such as savings in fuel and maintenance. This pricing strategy seeks to align the consumer's economic perception with the real benefits of the product, contributing to improved acceptance outcomes.

4.3 Place strategy (distribution)

The placement strategy aims to facilitate access to the product and reduce barriers associated with availability. In this regard, the model proposes the use of local points of sale, alliances with regional distributors, and the implementation of community demonstration schemes. Although the charging infrastructure is limited, the diagnosis shows that local mobility patterns allow for the initiation of domestic or semi-public charging solutions.

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In addition, the strategic location of charging points in high-traffic areas is proposed, which would help improve the perception of the system's availability and reliability. In this way, the distribution strategy acts as an enabler for technological adoption.

4.4 Promotion strategy

Finally, the promotion strategy is conceived as a key component in closing the identified information gaps. The model proposes information and awareness campaigns aimed at explaining the operation, economic and environmental benefits, and actual conditions of use of electric vehicles. Although there is interest in sustainable alternatives, the lack of clear information limits acceptance. The use of local media, community workshops, and practical demonstrations is suggested as promotional tools. These actions strengthen consumer confidence and improve the information literacy necessary for decision-making. Consequently, promotion becomes a central mechanism for improving social acceptance and validating the proposed model.

Box 2

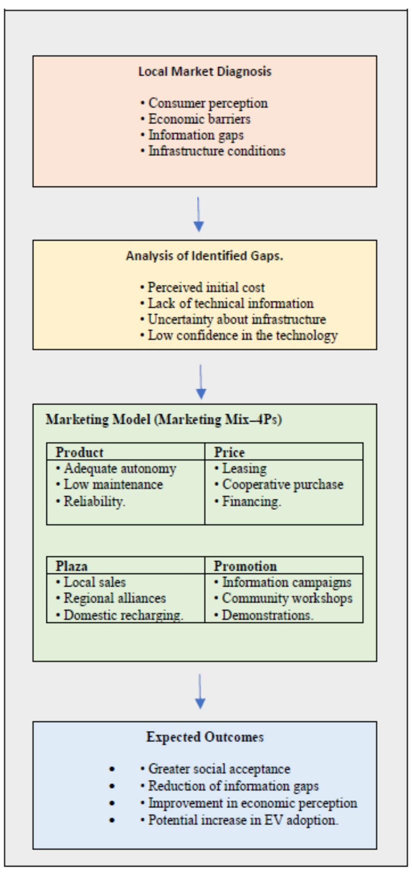

Figure 1
Diagnosis of the local market and the proposed marketing model

Source: Vidal Reyes 2025

5. Conclusions

This research demonstrated that the acceptance of electric vehicles in the community of Ocuiltzapotlán, Tabasco, does not depend exclusively on technological availability, but rather on a set of economic, informational, and contextual factors that influence consumer decision-making. Based on the diagnosis, significant gaps were identified in terms of knowledge, perception of initial cost and uncertainty regarding charging infrastructure, which limit the adoption of this technology in suburban contexts.

The results confirm that, although there is a positive perception of the environmental benefits of electric vehicles, this does not directly translate into a clear intention to adopt them. However, it was found that willingness to consider this technology increases when accessible financing schemes, clear information strategies, and distribution alternatives adapted to the local context are proposed. In this sense, marketing is consolidated as an enabling element to close the gap between technological innovation and social acceptance.

The proposed marketing model coherently integrates the variables identified in the diagnosis and articulates the marketing mix as a strategic system aimed at improving acceptance results. Unlike approaches focused solely on technical or energy aspects, this proposal emphasises the importance of aligning the product, price, place and promotion with the real needs of the local market, strengthening the validity of the model and its applicability in communities with similar characteristics.

In terms of possibilities for improvement, there is a recognised need for further longitudinal studies to evaluate the impact of the proposed model in the medium and long term. It is also relevant to extend the analysis to other suburban contexts in southeastern Mexico in order to corroborate the replicability of the model and adjust its components according to the particularities of each region. Similarly, the incorporation of local public policies and institutional alliances could enhance the effects of the model and contribute to the consolidation of more sustainable mobility systems.

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Finally, it is concluded that electric mobility can become a driver of change in suburban communities if it is promoted through contextualised, inclusive marketing strategies that are aligned with the socio-economic conditions of the environment. The proposed approach offers a methodological and strategic basis for strengthening the adoption of electric vehicles and contributing to the development of more efficient and sustainable transport systems.

Annexes

Operational definition of the study variables

This annex provides an operational description of the variables considered in the research, with the aim of strengthening the methodological validity of the study and facilitating understanding of the marketing model proposed for the acceptance of electric vehicles in the community of Ocuiltzapotlán, Tabasco.

Box 3

Table 2

Operational definition of study variables

Variable	Variable type	Operational definition	Measurement scale
Acceptance of electric vehicles	Shop assistant	Degree of consumer willingness to consider adopting an electric vehicle as an alternative for everyday mobility.	Ordinal scale (Low, Medium, High)
Knowledge about electric vehicles	Independent	Level of information possessed by consumers regarding the operation, maintenance, and benefits of electric vehicles.	Ordinal scale
Perceived cost	Independent	Consumer perception of the purchase price and costs associated with using an electric vehicle.	Ordinal scale
Perceived charging infrastructure	Independent	Consumer perception of the availability and accessibility of charging stations in their environment.	Ordinal scale
Perception of environmental benefits	Independent	Consumer assessment of the positive impact of electric vehicles on the environment.	Ordinal scale
Willingness to finance	Independent	Level of consumer openness to using financing, leasing or cooperative purchase schemes to acquire an electric vehicle.	Ordinal scale
Influence of promotional information	Independent	Degree to which information received through campaigns or media influences the intention to adopt electric vehicles.	Ordinal scale

Source: Vidal Reyes 2025

Disclosures

Conflict of interest

The authors declare that they have no conflicts of interest. They have no known competing financial interests or personal relationships that could have appeared to influence the article reported in this paper**.**

Contribution of autors

Vidal-Reyes, Laura: Contributes with the project idea and research development.

Javier Gerónimo, Zinath: Contributes with research development and data analysis.

Reyes-Osorio, Yaitla Aitza: Contributed to the review and editing of the manuscript.

Villanueva Guzman, Jorge Cein: Contributed to the research method and data analysis.

Availability of data and materials

The datasets used or analysed during the present study are available from the corresponding author upon reasonable request.

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Abbreviations

INEGI	National Institute of Statistics and Geography
ODS	Sustainable Development Goals

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Article

Enhancing stem learning through augmented reality: Applications in CAD and Mechanical systems

Mejora del aprendizaje de los tallos mediante la realidad aumentada: Aplicaciones en CAD y sistemas mecánicos

Meraz-Mendez, Manuel*[a], Corral- Ramirez, Guadalupe[b], Muñoz-Lopez, Luis Enrique[c] and Duarte-Loera, Jorge[d]

[a] Universidad Tecnológica de Chihuahua • S-4565-2018 • 0000-0001-8254-957 • 250582
[b] Universidad Tecnológica de Chihuahua • IDX-9786-2019 • 0000-0003-4874-4036 • 520946
[c] Universidad Tecnológica de Chihuahua • X-9772-2019 • 0000-0003-3184-7602 • 456614
[d] Universidad Tecnológica de Chihuahua • JRX-9176-2023 • 0000-0002-6721-1406 • 69449

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* ✉ [mmeraz@utch.edu.mx]

Abstract

This study presents the development of immersive applications using augmented reality (AR) technologies to enhance the teaching and learning process of computer-aided design (CAD) and mechanism simulation in the engineering education program. The research focuses on increasing student engagement, improving spatial understanding, and providing blueprint manufacturing interpretation. AR tools were designed and implemented in university-level courses, with an emphasis on interactivity, technical precision, and real-time feedback. Results indicate significant improvements in spatial reasoning, blueprints interpretation, and assembly's manipulation, confirming the value of immersive learning environments in science, technology, engineering and mathematics (STEM) education.

Augmented Reality, Computer-Aided Design, Mechanism Simulation, STEM Education, Immersive Learning

Resumen

Este estudio presenta el desarrollo de aplicaciones inmersivas utilizando tecnologías de realidad aumentada (AR) para mejorar el proceso de enseñanza y aprendizaje del diseño asistido por computadora (CAD) y la simulación de mecanismos en la educación en ingeniería. La investigación se enfoca en mejorar la comprensión espacial y la interpretación de planos de manufactura. Las herramientas de AR fueron diseñadas e implementadas en cursos a nivel universitario, con énfasis en la interactividad, la precisión técnica y la retroalimentación en tiempo real. Los resultados indican mejoras significativas el razonamiento espacial, interpretación de planos y la manipulación de ensambles, lo que confirma el aprendizaje inmersivo en la educación, ciencia, tecnología, ingeniería y matemáticas (STEM).

Realidad aumentada, diseño asistido por computadora, simulación de mecanismos, educación STEM, aprendizaje inmersivo

Area: Development of strategic leading-edge technologies and open innovation for social transformation

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Introduction

Engineering students often face challenges when transitioning from theoretical knowledge to applied design and mechanism simulation. Traditional CAD instruction relies on 2D interfaces and screen-based interactions, which may limit students' spatial reasoning and understanding of mechanical motion (Adurangba et al., 2023; S. -M. Wang et al., 2024). Similarly, interpreting mechanical systems behavior from static diagrams or simplified animations often lacks the immersive depth required for full comprehension (Li et al., 2020; Ka, J. et al., 2025)

To address these limitations, this research proposes the development of AR applications that transform the way students interact with CAD models and mechanical systems. These tools aim to enhance learning outcomes, improve conceptual visualization, and foster active, self-directed learning in safe, repeatable virtual environments (Akçayır & Akçayır, 2022; Meraz & Reynoso, 2022; Makransky & Petersen, 2021).

Background

The advancement of engineering education in the context of Industry 4.0 demands pedagogical strategies that integrate emerging technologies capable of enhancing students' spatial reasoning, system-level understanding, and hands-on technical skills. Among these technologies, AR and virtual reality (VR) have gained attention as transformative tools that enable immersive, interactive, and student-centered learning environments—particularly in domains such as CAD and mechanical systems (Li et al., 2020; Akçayır & Akçayır, 2022).

AR enriches the physical environment with digital content, allowing students to visualize 3D models overlaid on real-world objects, while VR enables full immersion in simulated environments where learners can interact with mechanical systems without the constraints of physical equipment (Radianti et al., 2020). These capabilities have proven valuable in supporting spatial understanding, procedural learning, and safe experimentation (Bower et al., 2020; Nasija et al, 2024).

Spatial reasoning is widely recognized as a critical skill for success in engineering education, especially in early design and mechanical systems courses (S. -M. Wang et al., 2024). However, traditional tools—such as orthographic drawings, 2D diagrams, and static physical models—often fall short in helping students internalize complex 3D relationships and dynamic motion. As a result, many students struggle with interpreting CAD representations, assembling mechanical systems, and predicting kinematic behavior (Ka, J. et al 2025).

Studies have shown that AR and VR can mitigate these challenges by offering real-time manipulation of 3D models, simulated animations, and guided interaction, which lead to better conceptual understanding and higher student motivation (Ferrer-Torregrosa et al., 2020; Salgado F. et al., 2022). In particular, immersive learning environments encourage active exploration and experiential learning, both of which are linked to deeper cognitive engagement and improved knowledge retention (Makransky & Petersen, 2021).

Despite promising results, many implementations of AR/VR in engineering remain isolated or exploratory, lacking robust integration into the instructional design process or formal assessment of their educational impact (Adurangba V. et al., 2023). This project aims to address that gap by developing a series of targeted AR and VR applications embedded into CAD and mechanical simulation curricula, designed to align with learning outcomes and rigorously evaluated for effectiveness in improving student performance and engagement.

Methodology

This study adopts a design-based research (DBR) approach to the development and evaluation of AR applications in the contextof STEM education. The goal is to enhance the teaching and learning process of CAD and mechanism systems simulation in the maintenance engineering and mechanical education programs particularly focusing on improving spatial visualization, conceptual understanding, and student engagement.

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The methodology shown in Figure 1 consists of five integrated stages: (1) curriculum analysis, (2) system design, (3) development and implementation, (4) instructional deployment, and (5) evaluation.

Box 1

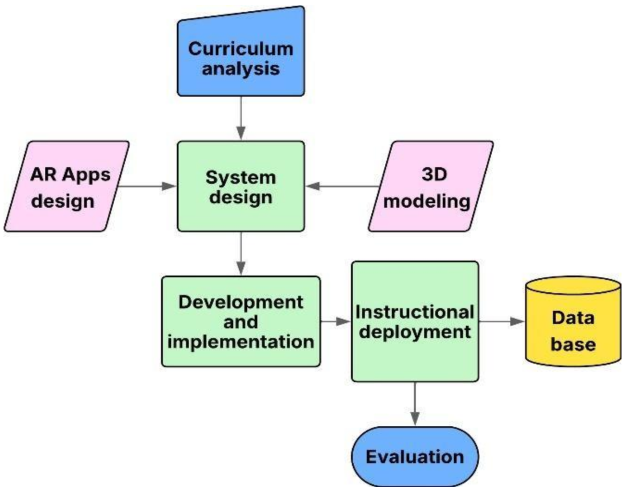

Figure 1
Methodology for AR environments implementations in STEM education

Curriculum and Needs Analysis

The first stage involved a thorough analysis of the curriculum of two undergraduate engineering courses: "Computer-Aided Design" and "Mechanical systems." A gap analysis was conducted through interviews with instructors, direct observation of student challenges during practical sessions, and examination of previous student performance data. Particular attention was given to read and interpret mechanical drawings that presented cognitive and spatial difficulties, such as interpreting orthographic projections, manufacturing symbols, and visualizing component assemblies. These findings informed the selection of learning objectives to be enhanced through AR.

In parallel, a technology readiness assessment was conducted to evaluate the availability and suitability of existing hardware (AR headsets, AR-enabled tablets) and software platforms (Unity, Unreal Engine, SolidWorks) within the university's infrastructure.

System and Content Design

The instructional design process was guided by principles of STEM education focused in the immersive learning, emphasizing active exploration, manipulation, and visualization.

Learning Scenarios: Scenarios were analyzed to solve specific learning problems:

– Learning problems in interpreting drawings and manufacturing symbols in blue prints (Figure 2).

– Learning problems in visualization of exploded views and part relationships in CAD assemblies (Figure 3).

– Learning problems in training assemblies' operations (Figure 4).

Box 2

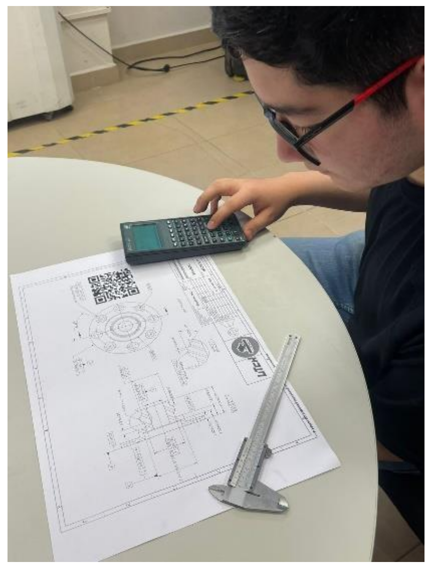

Figure 2
Student trying to interpret manufacturing symbols

Box 3

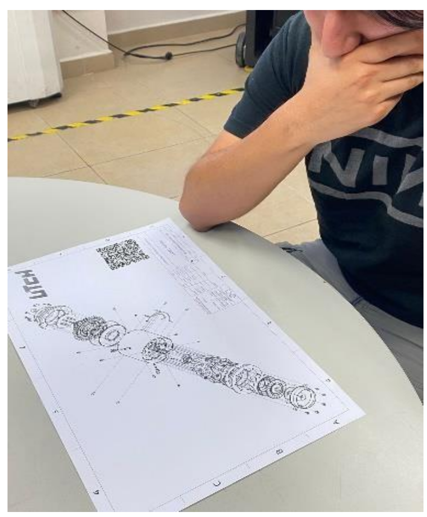

Figure 3
Student trying to interpret explode views in assemblies

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Box 4

Figure 4
Student trying to resolve mechanical assemblies

Design Criteria

To address these problems, AR-Apps were designed to meet the following criteria:

- Pedagogical alignment: Directly support course outcomes and assessment criteria.
- Interactivity: Enable real-time manipulation of 3D models or simulation parameters.
- User-friendly interface: Accessible to students with minimal training.
- Technical accuracy: Models and simulations must reflect engineering standards and behaviors.

Storyboards, wireframes, and mockups were iteratively developed and reviewed by instructors and student focus groups to ensure usability and pedagogical value.

AR Applications Development and Integration

To develop the AR apps industry-standard tools were used:

3D Modeling: SolidWorks was used to design CAD models of mechanical systems (e.g., gear trains, cams, linkages), as shown in Figure 5. These models were then exported in Collada format.

AR Application: Unity 3D with the Vuforia SDK was used to develop marker-based and spatial AR applications, which were deployed on Android tablets.

Unreal Engine was used to build immersive environments, interactive simulations, and user- controlled interfaces compatible with MetaQuest, as shown in Figure 6.

Box 5

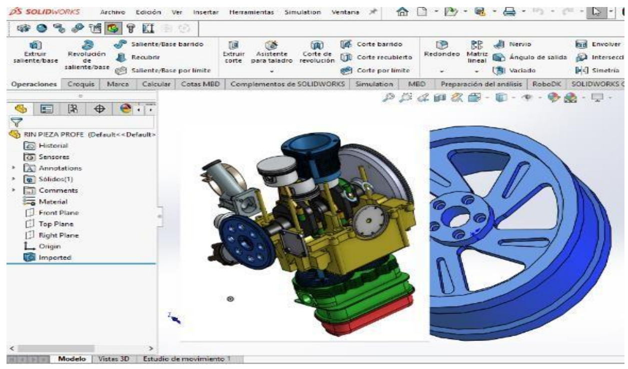

Figure 5
SolidWorks modeling

Box 6

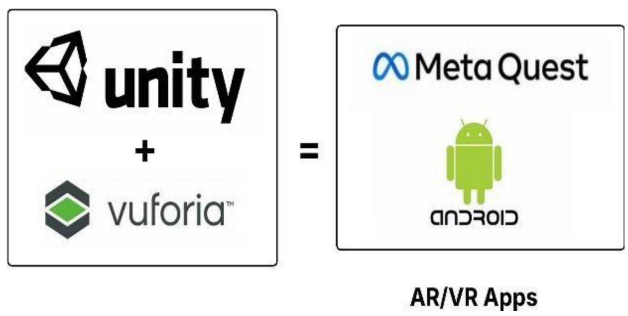

Figure 6
AR Apps design

Specific features included:

AR-Apps overlay of exploded views and technical annotations on physical printouts and lab equipment, as shown in Figure 7.

Box 7

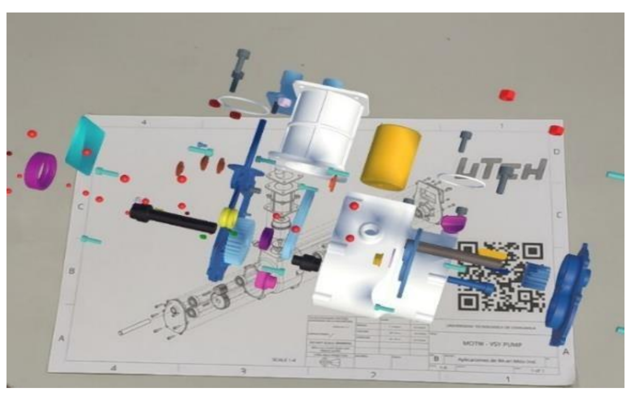

Figure 7
AR-Apps for assemblies exploded views

Meraz-Mendez, Manuel, Corral- Ramirez, Guadalupe, Muñoz-Lopez, Luis Enrique and Duarte-Loera, Jorge. [2025]. Enhancing stem learning through augmented reality: Applications in CAD and Mechanical systems. Journal Industrial Engineering. 9[21]-1-11: e70921111
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AR-Apps based in interactive mechanism labs with assembly comprehension, as shown on Figure 8.

Box 8

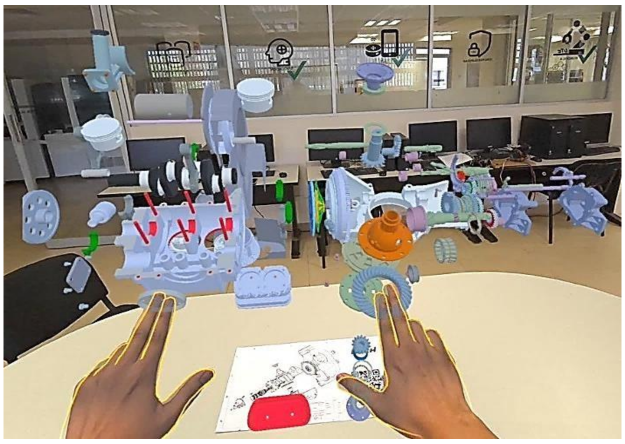

Figure 8
AR-Apps for assembly comprehension

Virtual assembly trainers, allowing students to practice positioning and constraining components in mechanical systems using virtual tools as shown in Figure 9.

Box 9

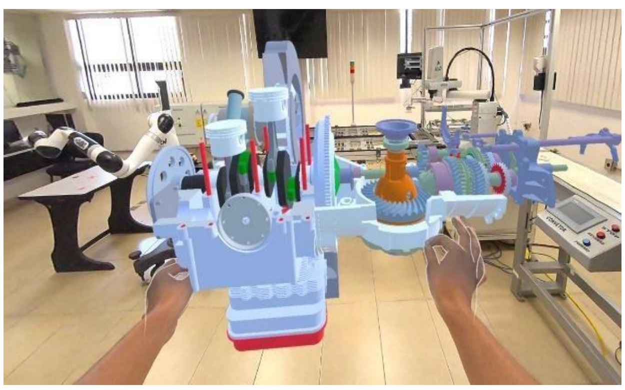

Figure 9
AR-Apps for assembly positioning and constraining components

AR-Apps based in interpretation of manufacturing symbols, as shown in Figure 10.

Box 10

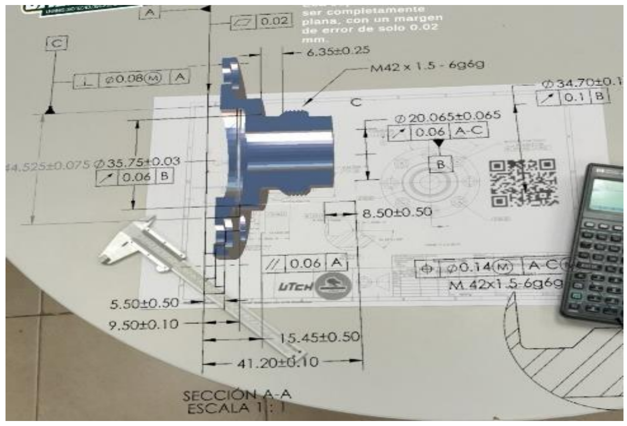

Figure 10
AR-Apps for interpreting manufacturing symbols

Cross-platform compatibility and lightweight model optimization were prioritized to ensure smooth performance on consumer-grade hardware. Additionally, learning analytics and user interaction logging were integrated into the backend to support post-deployment analysis.

Instructional Deployment

The AR-Apps were implemented in two engineering education institutions: The Technological University of Chihuahua (UTCH) and the National Technologic of Mexico campus Chihuahua (ITCH), in two courses: Computer-Aided Design (CAD) and mechanical systems, both in theoretical and practical sessions.

Participants: A total of 120 students, 60 from Maintenance Engineering (UTCH) and 60 from Mechanical Engineering (ITCH), corresponding to their second and fourth semesters, participated across CAD and Mechanisms analysis using AR immersive applications.

Delivery model: AR-Apps Applications were introduced during class under instructor guidance, and made available for self-paced learning in designated AR lab spaces.

Instructor training: Faculty members received training sessions to integrate the AR-Apps tools into their lessons and to interpret usage data for formative feedback.

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The AR-Apps implementation overcomes to solve STEM educational problems because it incorporates: Science (understanding of physical, optical, and spatial principles in the visualization of objects), Technology (use of AR software, programming, and mobile applications), Engineering (interpretation of technical drawings, CAD modeling, and mechanical design), and Mathematics (scaling, spatial coordinates, 3D geometry, and precise measurement for model overlay).

Evaluation and Data Collection

A mixed-methods approach was employed to evaluate the impact of the developed AR-Apps applications. Data collection methods included:

Pre- and Post-Tests: Standardized assessments were administered to measure learning gains in spatial reasoning, assembly comprehension, and mechanism analysis.

Surveys and Questionnaires: The questionnaire detailed in Table 1 was implemented to assess the development of technical competencies in AR environments in Industrial maintenance and Mechanical engineering. This instrument was designed to gather empirical evidence on the effectiveness of the AR-Apps compared to traditional instructional methods.

The questionnaire measures four key aspects for learning CAD and mechanism simulation, which are: Identification of mechanical parts, visualization of explode views in assemblies, training in assembly execution and assistance in procedures for practical activities.

Box 11

Table 1

Questionnaire: Technical Competency in AR Environments

Identification of Mechanical Parts

1. Do AR environments facilitate the understanding of geometric shapes by manipulating 3D models more effectively than reading traditional 2D blueprints?

☐ Yes ☐ No

2. Does the use of labels on 3D models in AR environments provide a clearer understanding of information than reading traditional 2D blueprints?

☐ Yes ☐ No

Visualization of Exploded Views in Assemblies

1. Is visualizing an assembly in ARenvironments clearer and more comprehensible than viewing it on a printed blueprint?

☐ Yes ☐ No

2. Is it easier to identify assembly relationships between parts in AR environments than when identifying them on a printed blueprint?

☐ Yes ☐ No

Training in Assembly Execution

1. Do AR applications facilitate training for executing complex mechanical assemblies?

☐ Yes ☐ No

Focus Groups: Semi-structured group interviews were applied to 60 students from the UTCH and 60 students from the ITCH were conducted with students and instructors to gather qualitative insights into user experience, technical performance, and instructional value. Quantitative data were analyzed using ANOVA to determine the statistical significance of learning improvements.

Results

The results of the evaluation process for the AR applications were organized into three categories: (1) quantitative assessment of learning outcomes, (2) student perception and engagement, and (3) qualitative insights from instructors and focus groups.

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Quantitative Assessment of Learning Outcomes

Pre- and Post-Test Performance

To assess the cognitive impact of the immersive applications, students completed concept-based tests before and after using the AR-Apps tools evaluating understanding of spatial geometry, manufacturing symbols, and component assembly logic. Table 2 presents the cognitive impact results

Box 12

Table 2
Cognitive impact results

Evaluated Aspect	Sample Question	Yes (%)
Identification of Mechanical Parts	Do AR environments improve understanding of 3D shapes vs. 2D drawings?	95.1%
	Do labels in AR 3D models offer clearer understanding than 2D drawings?	92.7%
Visualization of Exploded Views	Is it clearer to visualize an assembly in AR than in a printed drawing?	95.1%
	Is identifying part relationships easier in ¿AR than in printed drawings?	92.7%
Training in Assembly Execution	Do AR apps help train complex mechanical assembly tasks?	95.1%
Assistance in Practical Procedures	Do AR apps present clearer step sequences than printed instructions?	92.7%

Source [Questionarie results from UTCH-ITCH Students]

Analysis showed statistically significant improvements across all groups:

CAD Course: Students' average test scores increased from 63.4% (pre-test) to 95.1% (post- test) after using AR-Apps in interpretation of manufacturing symbols, visualizations of assemblies and exploded views.

Mechanism Course: Average scores rose from 58.2% to 92.7%, particularly in questions involving motion prediction of linkages and gear interactions.

ANOVA analysis was conducted to assess learning improvements. Table 3 shows the results for the 120 students across both learning methods: with AR-Apps and without.

Box 13

Table 3
ANOVA results

Source	SS	df	F	p-value)
Group	2134.44	3	294.61	0.000038
Residual	9.66	4		

Source [Own]

The p-value of 0.000038, indicates that there are statistically significant differences between the groups (CAD_Pre, CAD_Post, Mech_Pre, Mech_Post).

Spatial Reasoning Improvement

The Spatial Visualization Test (SVT) was administered to measure spatial cognition. Students using AR-Apps showed an average gain of 28.4%, compared to a 12.1% gain in the control group using traditional 2D learning materials.

This suggests that immersive environments contributed significantly to students' spatial comprehension, which is essential for CAD and mechanical systems.

Student Perception and Engagement

Usability and Satisfaction

Post-intervention surveys using a 5-point Likert scale (1 = strongly disagree, 5 = strongly agree) revealed high levels of user satisfaction:

"The AR tools helped me understand complex concepts more easily": 4.7 average "I feel more confident in my CAD/mechanism skills after using the applications": 4.5 average "The immersive applications were engaging and enjoyable to use": 4.8 average

Students particularly appreciated the ability to manipulate 3D models in real time and explore mechanical motion from any angle, as this aligned closely with how real-world systems function through a MetaQuest Headset as shown in Figure 11.

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Box 14

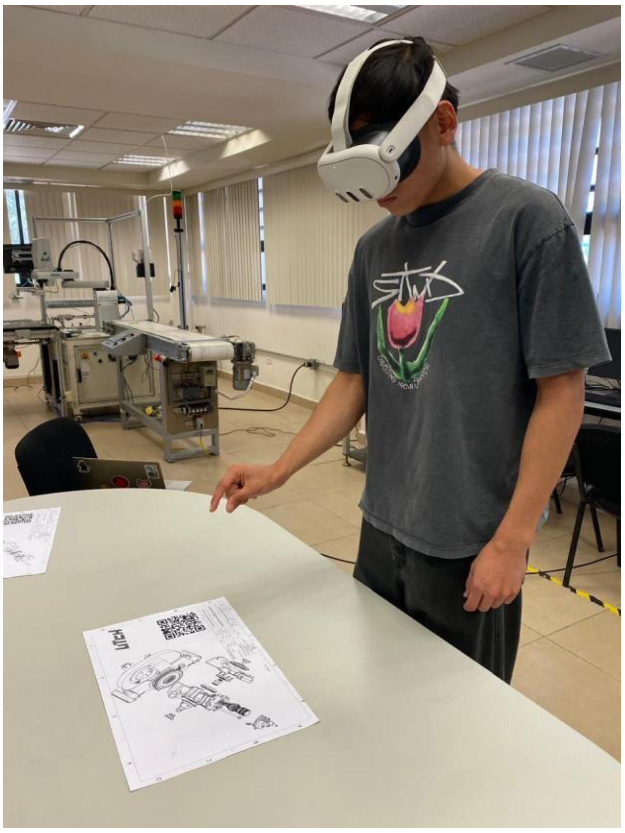

Figure 11
Student using MetaQuest for AR

Cognitive Load and Learning Efficiency

Cognitive load was measured during the AR sessions. Most students reported moderate levels of mental demand but lower frustration and higher performance scores, indicating a positive balance between challenge and learning effectiveness.

In addition, time-on-task analysis revealed a significant difference in engagement between the learning modalities. Students voluntarily spent more time interacting with the immersive AR tools, averaging 43 minutes per session, compared to just 21 minutes when using traditional software tutorials.

This increased time-on-task not only reflects higher intrinsic motivation and user engagement but also correlates with improved learning outcomes observed in subsequent assessments.

Qualitative Findings

Student Focus Groups

Three focus groups (8 students each) were conducted at the end of the semester. Thematic analysis of transcripts yielded several key insights:

Visualization and Comprehension: Students consistently reported that "seeing" the mechanism in 3D made it easier to understand how parts interact, particularly for gear trains and crank-slider systems Figure 12.

Engagement: Students expressed that learning felt more like "exploring" than studying, which increased motivation.

Confidence Building: Several students indicated that immersive learning reduced anxiety in labs because they had already practiced virtually.

Box 15

Figure 12
Student explaining how easy is to interpret assemblies using AR-Apps

Sample comment:

"Before, I was just guessing what would happen when parts moved. In AR-Apps, I can see the motion of components right away. It's like having x-ray vision."

Instructor Feedback

Instructors noted improvements in classroom dynamics and learning depth:

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Conceptual Discussions: Students asked more precise, technically informed questions after AR sessions.

Independent Learning: Students were more inclined to experiment independently using the provided applications.

Assessment Quality: The quality of student projects and design reports improved noticeably, with better articulation of spatial and functional reasoning.

One faculty member remarked:

"This is the first time I've seen students actually excited about understanding mechanism constraints—they weren't just completing assignments; they were exploring design ideas."

Observational and Interaction Data

Interaction logs from the AR-Apps applications revealed distinct usage patterns:

– Average number of model manipulations per session: 96
– Average time spent in virtual assembly task: 22 minutes
– Most common actions: zoom, rotate, isolate component, view section cuts

These metrics suggest high levels of interactivity, aligning with engagement survey data. No technical issues were reported during classroom deployment, aside from brief headset calibration times, which were resolved through orientation protocols.

Discussion

The data suggest that integrating AR-Apps into the CAD and mechanisms curriculum yields substantial benefits in both cognitive and affective learning domains. Gains in test performance, spatial reasoning, and student confidence demonstrate that immersive technologies are not just motivational tools but effective pedagogical instruments when properly aligned with learning goals. The improvements in spatial understanding and component interaction are particularly significant for engineering education, where 3D thinking is critical for success in design, simulation, and problem-solving.

Furthermore, the interactive and exploratory nature of the tools contributed to more active learning behaviors, a core principle in modern engineering pedagogy.

Conclusions

The study demonstrates that the strategic development and integration of AR-Apps applications into STEM education significantly enhance student learning in CAD and mechanism courses. By aligning immersive tools with curricular objectives, and by designing interactive, pedagogically grounded learning scenarios, the project achieved measurable improvements in student performance, engagement, and spatial reasoning ability.

Quantitative results showed statistically significant gains in conceptual understanding and spatial cognition, particularly in areas traditionally considered difficult, such as 3D visualization and mechanical motion prediction. Students not only performed better on assessments but also reported higher levels of engagement, confidence, and motivation. Qualitative feedback further confirmed that AR-Apps supported deeper learning and enabled students to bridge the gap between abstract concepts and physical intuition.

From an instructional perspective, faculty observed enhanced classroom dynamics, more meaningful student questions, and higher-quality project submissions. The immersive tools promoted active, exploratory learning and supported a learner-centered pedagogy aligned with the demands of modern engineering practice.

The success of this implementation highlights the potential of immersive technologies to transform the way engineering concepts are taught and understood, particularly in disciplines where spatial awareness and system-level reasoning are critical. These tools also open new possibilities for blended and remote learning, offering rich, interactive environments beyond the limitations of physical labs.

Future work will focus on expanding the scope of the applications to include dynamic system analysis, control simulation, and integration with digital twins for predictive maintenance training.

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Additional studies are also planned to explore long-term learning retention, scalability across different institutions, and accessibility for diverse learner populations.

Conflict of interest

The authors declare no conflicts of interest.

Author's contribution

Manuel Meraz Méndez: Contributed to the project idea, research method, algorithms design, virtual reality design apps, augmented reality design apps and technique.

Guadalupe Corral Ramirez: Contributed to the research method and article writing.
Professor-

Luis Enrique Muñoz López: Contributed to the research method, data analysis, and results

Jorge Duarte Loera: Contributed to the blue print drawings and 3D modeling design

Octavio Chimal Corrales: Contributed to the AR MetaQuest design applications

Humberto Alejandro Arrollo Salado: Contributed to the AR Android design applications

Francisco Iván Gallegos Gonzalez: Contributed to modeling 3D and Blue prints design

Availability of materials and data

MetaQuest Headset (2), Android tablet (3), Unity software, Solidworks software

Founding

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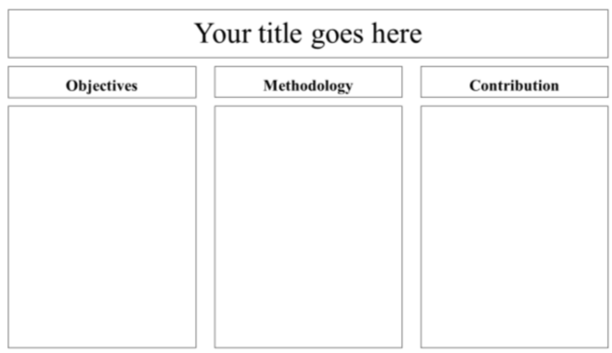

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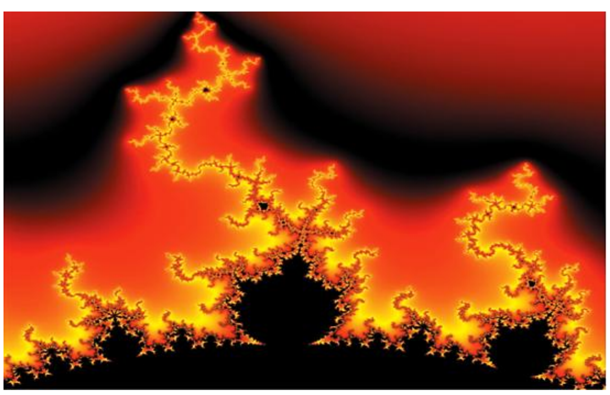

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