Air supply system maintenance proposal using the Finite Element Method

Propuesta de mantenimiento de un sistema de suministro de aire por el Método de los Elementos Finitos

Jesús Manuel Viera Callar jviera@ecg.minem.cu [1]

https://orcid.org/0009-0001-3178-1984

Rosendo Jahaziel Rosabal Hernández rrosabal@mecanica.ismm.edu.cu [2]

https://orcid.org/0009-0005-7663-5947

Uberlandi Torrell Quinta utorrel@ismm.edu.cu [2]

https://orcid.org/0009-0000-8939-4170

[1] Ernesto Che Guevara Nickel Company, Moa, Cuba

[2] University of Moa, Moa, Cuba

Abstract: This paper proposes a predictive maintenance system for an air supply system's storage tank, by using the finite element method. To achieve this, the strength conditions or stresses in the tank were determined as part of a design verification to ascertain whether it would withstand the pressure to which it would be subjected. For a pressure of 4 bar, the safety factor is 2.4, demonstrating that no fractures will occur. Based on these results, a predictive maintenance plan is proposed for the system as a whole. The proposal spans 20,000 machine-hours, including 12 inspections, 4 minor repairs, 1 medium repair, and 1 major repair. The time between medium repairs is 10 000 machine-hours, the period between minor repairs is 3,333.33 machine-hours, and the period between interventions is 1,111.11 machine-hours.

Keywords: air storage, maintenance management, numerical methods

Resumen: En este trabajo se propone un sistema de mantenimiento predictivo para un tanque de almacenamiento de un sistema de suministro de aire por el método de elementos finitos. Para ello se determinaron las condiciones de resistencia o las tensiones en el tanque como parte de una comprobación del diseño, a fin de verificar si resistiría la presión a la cual estaría sometido, donde, para una presión de 4 bares el factor de seguridad es de 2,4, lo que demuestra que no habrá roturas en el mismo.

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Según estos resultados, al sistema en su conjunto se le propone un mantenimiento predictivo. La propuesta presenta una duración de 20 000 horas-máquinas con 12 revisiones, 4 reparaciones pequeñas, 1 reparación mediana y 1 reparación general, con un tiempo entre reparaciones medianas de 10 000 horas-máquinas, el periodo entre reparaciones pequeñas de 3 333,33 horas-máquinas y el período entre intervenciones de 1 111,11 horas-máquinas.

Palabras claves: almacenamiento de aire, gestión de mantenimiento, métodos numéricos

Introduction

Predictive maintenance is defined as the inspection of machines and equipment to ensure proper operation and prevent future failures (Arroyo & Obando, 2022). It is systematic in nature, performed at scheduled times and routines that monitor equipment condition to maintain functionality and reduce wear (Alvarez, Lozano & Bravo, 2022; Nunes, Santos & Rocha, 2023). It encompasses all activities for preservation and care (Pillado Castillo & de la Riva, 2022; Crespo, Arias & Zhigüe, 2024), ensures product quality, and minimizes unplanned downtime (Tiddens, Braaksma & Tinga, 2020; Lee *et al.*, 2020; Hernández-Montero, Anías-Calderón & Ruiz-Barrios, 2023).

The finite element method is highly useful for the design and predictive maintenance of mechanical systems and equipment (Ramírez *et al.,* 2022; Orejuela-Mendoza *et al.,* 2024; Simbaña *et al.,* 2024; Simbaña *et al*., 2025) as it increases equipment reliability, efficiency, and durability. Authors such as Nacimiento & Cardoso (2024), Medina *et al.* (2024), and Pineda (2025) have demonstrated this method's suitability to predict future failures, allowing for the anticipation and reversal of wear and breakdowns.

Air supply systems facilitate air distribution within a space by using different designs and materials. They create favorable environments through air renewal, thus contributing to human productivity and well-being, which makes their efficiency and performance necessary in various scenarios. This work proposes a predictive maintenance system using the Finite Element Method for a storage tank belonging to an air supply system.

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Materials and Methods

SolidWorks 2020 software (Montijo & Martínez, 2020; Mustapha, 2022) was used to model and simulate the air supply system's components. This software allows for the creation of 3D models, simulations, and manufacturing drawings. According to Torrell Quinta *et al.* (2024), taking precise measurements is crucial for accurate parts modeling, especially elements under pressure.

The Finite Element method was used to perform simulations to determine the optimal parameters for elements under pressure. These simulations allow for the evaluation of stress, displacement, and safety factor effects. The methodology used for the simulation process is illustrated in Figure 1.
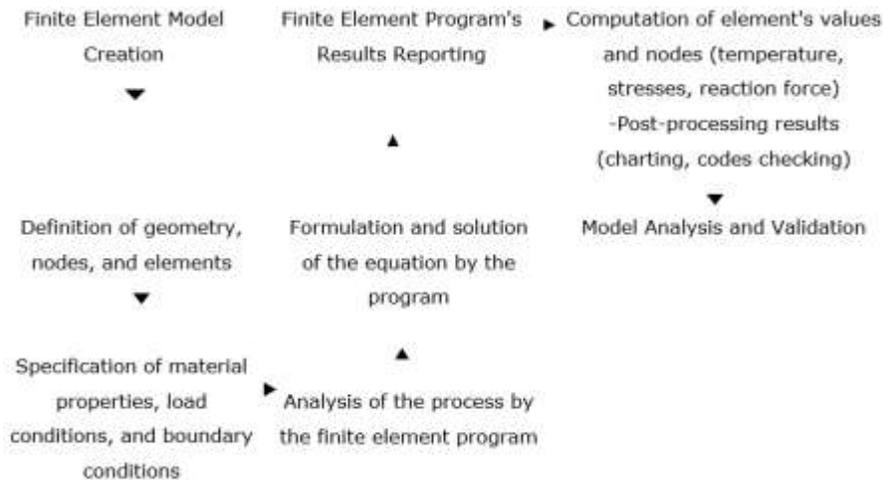

Figure 1. Simulation process flowchart.

The von Mises method was used for the maximum stress simulation, a static strength criterion applied to ductile materials.

Storage tank modeling and simulation

Experimental Verification

With the results obtained, a study will be conducted on the storage tank to verify its design and capacity to withstand the conditions to which it will be exposed. This analysis will cover several aspects, including the tank´s structural strength, its ability to safely contain fluid, and its response to internal loads, such as pressure. The strength of the

material used will be assessed to verify if it endures the internal pressures generated by the stored fluid.

Model Meshing

In the simulation process, after defining the materials and their properties, and generating the geometry, a mesh is constructed with the chosen element type associated with that geometry. Therefore, the average element size must be specified, which can later be reduced. A fine surface-*Shell*-elements meshing was performed, with high-order quadratic elements having a size of 3.34189 cm, structured with 11,464 nodes and 5,603 elements (Figure 2).
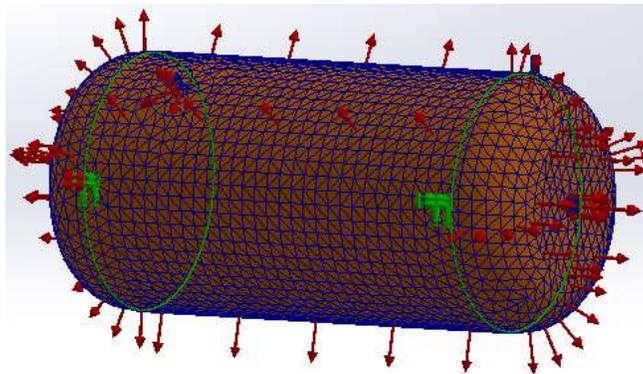

Figure 2. Model meshing.

Boundary Conditions

Once the loads for the pressure study have been defined, constraints are limited, where movement in "X", "Y", and "Z" directions must be suppressed, but rotation is not, which is known as constraining the part to be welded (Figure 3).
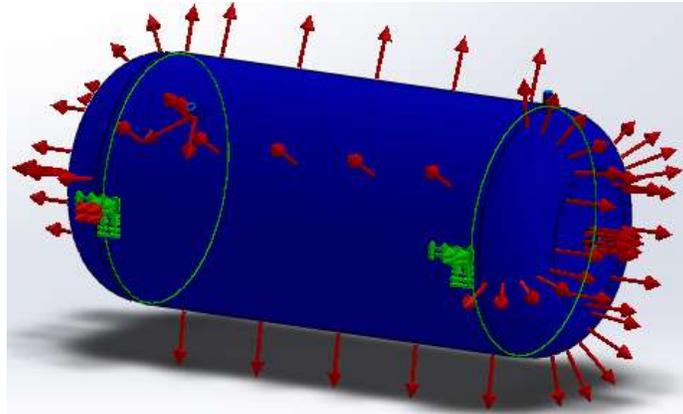
Figure 3. Boundary conditions for the compressed air supply system.

Maintenance Type Selection

Smith (2016) points out that to select a maintenance cycle, a series of different methodologies have been introduced that analyze, with varying characteristics, different criteria which, applied to the machine as a whole, allow for the determination of the most suitable maintenance system. For this selection, the machine criterion will be used.

According to Smith (2016), this machine criterion is one of the analysis methods responsible for evaluating a piece of equipment or a machine as a whole, considering a series of aspects it features. It follows a chain of coefficients quantifying each aspect to be assessed, which is performed as follows:

C1: High acquisition cost of the machine,

C2: High cost due to production losses,

C3: Absence of machine duplicate,

C4: Possibility of performing machine diagnostics with available instrumentation,

C5: Possibility of performing global parameters control measurements such as: overall vibration levels, temperature, and flow,

C6: High maintenance cost of the machine. This includes material and human resource expenses over a given period,

C7: High loss of lifespan due to disassembly. This refers to machines that, in account of their technical design characteristics, suffer technical condition deterioration due to disassembly,

C8: Serious economic consequences of a breakdown for the machine. Considers that the deterioration of one of its parts due to a failure would make its repair very expensive.

Coefficients that satisfy the condition are set to 1, while those that do not meet the condition are set to 0 (Smith, 2016).

Coefficients Determination

Predictive maintenance coefficient: $C_{PRED} = \dfrac{C_1 + C_2 + C_3 + C_6}{4}$

Corrective/Preventive maintenance coefficient: $C_{CRR/PREV} = \dfrac{C_{LOSSES} + C_{FAILURES}}{5}$

Where:

$C_{LOSSES} = C_1 + C_2 + C_6$
$C_{FAILURES} = C_7 + C_8$

By evaluating these coefficients and assigning values to the corresponding parameters, criteria are established for selecting the most suitable maintenance system, considering the compressor's specific characteristics and its operating conditions. Table 1 shows the criteria used.

Table 1. Rules for maintenance selection

Coefficient Values	Maintenance System
$C_{CORR/PREV} = 0$	Corrective
$C_{PRED} \leq 0,25$ $C_7 = 1$	Preventive, based on reliability indices
$C_{PRED} > 0, 5$ $C_4 = 4$ $C_5 = 1$	Preventive with measurement of parameters and
$0,25 \leq C_{PRED} \leq 0,5$ $C_5 = 1$ $C_4 = 1$ y/o $C_5 = 1$	symptoms
$C_{PRED} > 0, 5$ $C_4 = 1$	Predictive

After evaluating the coefficients describing the compressor and selecting the most suitable maintenance system, it is essential to execute the maintenance cycle evaluation. At this stage, preservation activities to be performed throughout the compressor's useful life are defined and planned.

Maintenance Cycle Evaluation

The maintenance cycle evaluation consists of determining the frequency, duration, and complexity of preventive, predictive, and corrective maintenance tasks to be performed

on the compressor. This includes scheduling regular inspections, replacing worn parts, cleaning components, calibrating equipment, among other activities needed to keep the device in optimal operating condition (González, 2005).

The required maintenance structure or elements are often provided by the manufacturer. Specialists can also use structures from similar equipment, when such information is not available, or employ calculation methodologies.

During the maintenance cycle evaluation, factors such as human and material resources availability, acceptable downtime, costs related to activities, among other relevant aspects must be considered to ensure the efficiency and effectiveness of the process, and to guarantee that maintenance actions are performed in a timely and effective way, contributing to maximizing the compressor availability and reliability, as well as minimizing operating costs and risks of unexpected failures.

After preparing the maintenance cycle, it is necessary to determine its duration, which is equivalent to the time elapsed between two major repairs. It is also the net time the equipment should operate between two major repairs, discounting the time spent on repairs and inspections. To determine or choose the maintenance cycle duration, the time between repairs exposed by González (2005) can be used.

Repair Cycle Periods

Once the maintenance cycle structure and its duration are defined, the time between two consecutive services and between two repairs can be determined. The following criteria can be used to define them:

Period between medium repairs: refers to the equipment's operating time between two consecutive planned medium repairs, expressed in machine-hours:

$$t_{rm} = \frac{T}{NM + 1}$$

Period between repairs: equipment operating time between two planned minor repairs, expressed in machine-hours:

$$t_r = \frac{T}{NM + NP + 1}$$

Period between interventions: equipment operating time between two interventions; i.e., between two consecutive inspections or between a repair and an inspection:

$$t_o = \frac{T}{NM + NP + NR + 1}$$

Where:

t_{rm}: period elapsed between two medium repairs, machine-hours

t_r: period elapsed between two consecutive repairs, machine-hours

t_o: period elapsed between two maintenance services, machine-hours

T: repair cycle duration; machine-hours

NR: number of inspections, dimensionless

NP: number of minor repairs, dimensionless

NM: number of medium repairs, dimensionless

Components Assembly

Figure 4 shows the air supply system after all components have been assembled. It is shown the tank with the compressor located at the top and secured with four screws. The engine will be placed where slots exist. The hermetic compressor is located at the bottom.
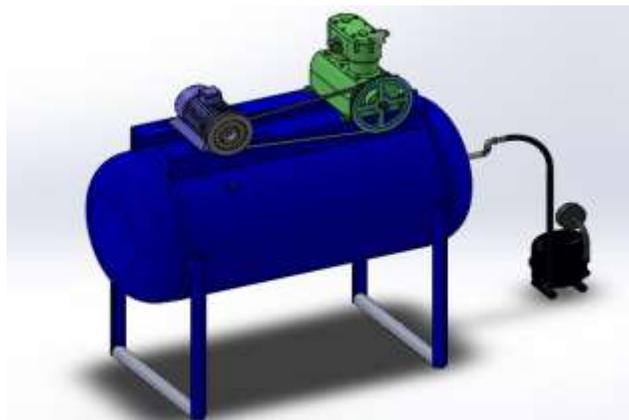

Figure 4. Air supply system assembly.

Stress Analysis

Figure 5 shows the stresses applied to the tank under extreme conditions. It was detected that stresses reach a minimum value of 0.021 MPa on the walls, while on the heads the maximum value of 78.414 MPa is reached.
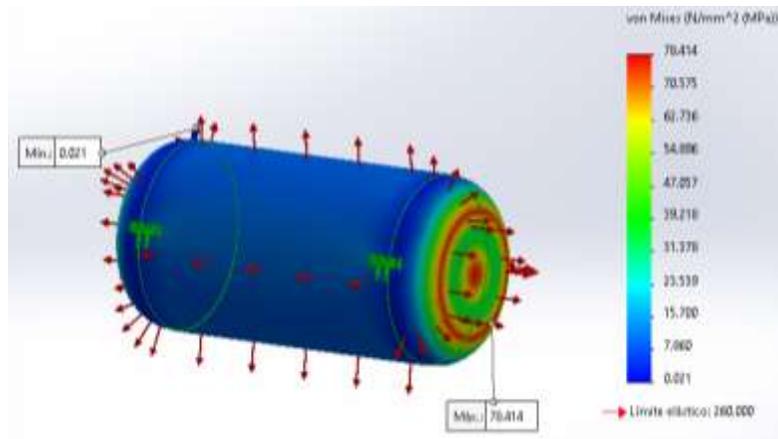
Figure 5. Maximum stress of the storage tank.

Displacement Analysis

According to Torrell Quinta *et al.* (2024), displacement analysis by using von Mises method indicates the material´s stretching when a it is subjected to a load, which indicates whether it can be sheared or not during operation. This maximum allowable value must be less than 1 mm. All structures or components deform when loaded, the change in geometric configuration causes their points to experience small displacements, as observed in Figure 6, where red colors correspond to maximum displacement values and those closer to the blue range are the minimum; indicating the maximum displacement the tank material can suffer under operating conditions.
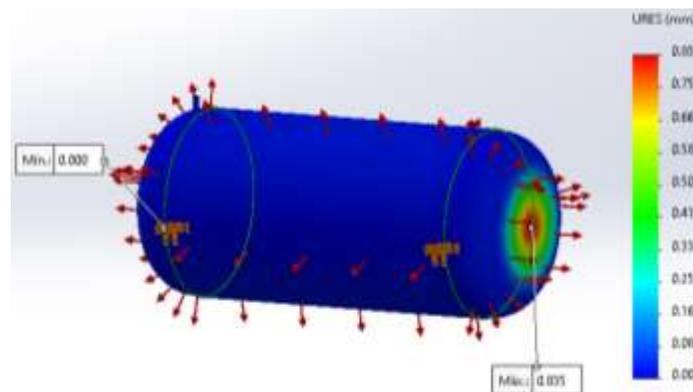

Figure 6. Analysis of storage tank displacement.

In the tank, under initial filling conditions, displacement begins with a minimum of 0.084 mm. As air pressure increases, it reaches a value of 0.418 mm on the heads; as it approaches the center of the head, these displacements increase to 0.835 mm, the maximum allowable value. Exceeding this value produces cracking due to pressure effects.

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Safety Factor Analysis

Torrell Quinta *et al.* (2024) note that, according to the von Mises method, for the part or component design to be acceptable and reliable regarding maximum stress or force, the safety factor must be above 1. When calculating this value, it must be over this parameter to establish that the analyzed component withstands the load conditions it is subjected to without presenting deformation that affects its functionality.

In the conditions the storage tank will be under, the minimum safety factor is 2.4, and the maximum manifests at the outlet nozzle with a value of 4.009. Therefore, the condition of being higher than 1 is met, meaning the element will withstand the conditions to which it will be subjected, posing no risk of deformation and shearing (Figure 7). It can be stated that the safety factor for ASTM A512 steel meets the requirements to be used to manufacture the air supply system, considering that it will operate under conditions different from those for which it was designed.
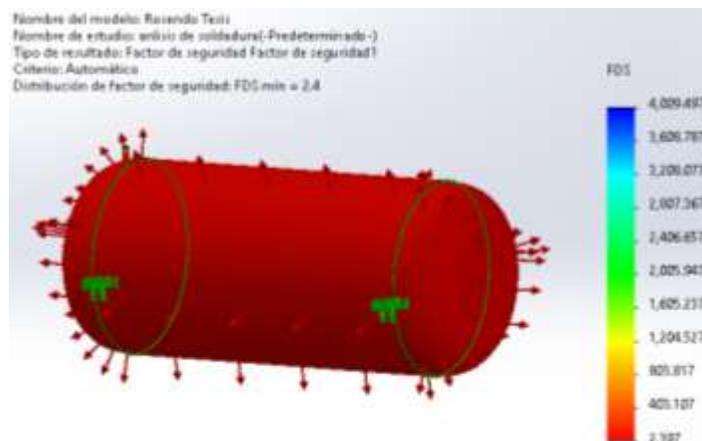

Figure 7. Storage tank safety factor analysis.

Maintenance System Selection

This air supply system implies a high acquisition cost in the industry because it requires two compressors. These are essential to guarantee an adequate   compressed air supply, especially in operations such as varnishing and painting. The presence of two compressors, one open and one closed, operating according to specific needs, reflects the air supply system's complexity.

This ability to adapt to changing production demands ensures a constant and optimal compressed air supply for several operations, which require specific levels of pressure

and quality. Table 2 presents the results of the evaluation coefficients according to the machine-level criterion.

Table 2. Evaluation coefficients according to the machine-level criterion

Coefficient	Comprises	Value
C1	High acquisition cost of the machine	1
C2	High cost due to production losses	1
C3	Absence of machine duplicate	0
C4	Possibility of performing machine diagnostics with available instrumentation	1
C5	Possibility of performing global parameters control measurements such as: overall vibration levels, temperature, and flow	1
C6	High maintenance cost of the machine.	1
C7	High loss of lifespan due to disassembly	0
C8	Serious economic consequences of a breakdown for the machine	1

Based on the values from the evaluation coefficients according to the machine-level criterion presented in Table 2, the predictive maintenance coefficient and the corrective/preventive maintenance coefficient were determined. These have values of 0.75 and 0.8, respectively, considering for the corrective/preventive maintenance coefficient the values of C_{LOSSES} and $C_{FAILURES}$, whose values are 3 and 1, respectively.

Considering Table, the achieved indices, and in correspondence with the proposed methodology, the maintenance system to be applied to the air supply system is preventive maintenance with measurement of parameters and symptoms such as temperature, pressure, and vibrations.

According to Thielsen (1970), mechanical vibrations should be revealed in preventive and predictive maintenance. The main interest should be the identification of the predominant amplitudes of vibrations detected in the equipment, the determination of their causes, and the correction of the problem they pose.

Once the feasibility and convenience of performing predictive maintenance is determined, it is necessary to identify the physical variables to be controlled that indicate the system's condition. The aim is to review in detail the techniques commonly used in monitoring according to condition, so that they serve as a guide for general selection, as reported by Chávez-Basantes (2004).

Proposal for the Repair Cycle Structure

The cycle to be applied to each piece of equipment should be determined in each production area by analyzing the working machine individually. Hence it should be chosen according to the experience and data available for the equipment. The duration of the repair cycle in machine-hours depends on its design characteristics, as well as operating conditions and production types.

In this case, the air supply system has two compressors, an electric engine, and a pressure regulator that purifies the air of contaminants that could damage the painting process. For the semi-hermetic compressor, belonging to a ZIL 130, maintenance was established to be applied at 20,000 hours. Based on this value, a maintenance proposal will be made for the entire air supply system assembly.

Considering typical maintenance cycle structures for industrial machines and equipment, the system can be included into equipments of Group 7, establishing a range of 17,280 to 20,160 machine-hours between major repairs. A maintenance cycle duration of 20,000 machine-hours was chosen. Figure 8 shows the proposal for the repair cycle structure.
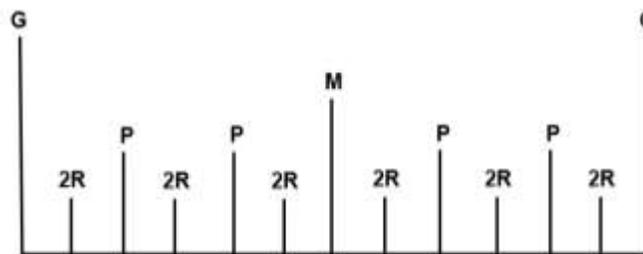

Figure 8. Proposal for the repair cycle structure.

As Figure 8 shows, the proposed maintenance cycle for the air supply system under study includes 12 inspections, 4 minor repairs, and one medium repair.

Once the period that will elapse between major overhauls and the maintenance cycle structure have been established; the period between one medium repair is defined as 10 000 machine-hours and the period between repairs as 3,333.33 machine-hours. The calculation of the period between interventions or maintenance services results in 1,111.11 machine-hours. With this proposal, the maintenance cycle is guaranteed with total reliability for the system.

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Conclusions

To guarantee the equipment's functionality, it was proposed a maintenance system to be performed over a period of 20,000 h for the compressor and 10,000 h for the electric motor, considering its usage characteristics in the construction industry.

By determining the stresses under which the supply tank will operate, it was found that these stresses reach a minimum value of 0.021 MPa on the walls, while on the heads, the maximum value of 78.414 MPa is reached. These values guarantee its resistance when working at maximum capacity.

Bibliographic References

Alvarez, L.I., Lozano, D.A., & Bravo, C.A. (2022). Metodología para el mantenimiento predictivo de transformadores de distribución basada en aprendizaje automático. *Ingeniería, 27*(3). https://doi.org/10.14483/23448393.17742

Arroyo, C.S. & Obando, R.F. (2022). Importancia de la implementación de mantenimiento preventivo en las plantas de producción para optimizar procesos. *E-idea Journal of Engineering Science, 4*(10), 59-69. https://doi.org/10.53734/esci.vol4.id240

Chávez-Basantes, W.I. (2004). *Gestión del análisis de riesgos aplicados en procesos de inspección técnica de tanques de almacenamiento.* (Degree Thesis, University of Cuenca). http://www.dspace.edu.ec/handle/123456789/14674

Crespo, H. E., Arias, C. P., & Zhigüe, C. (2024). Evolución del Análisis de Vibraciones en Mantenimiento Predictivo en Relación a los Patrones de Vibración en Elementos Mecánicos. *Ciencia Latina, 8*(4), 2443-2452. https://doi.org/10.37811/cl_rcm.v8i4.12488

González, F. (2005). *Teoría y práctica del mantenimiento industrial Avanzado.* Fundación Confemetal.

Hernández, J.A., Flores, C.G., González, V.A., Chacón, G., & López, J. (2024). Predicción de propiedades mecánicas de metamateriales obtenidos por Manufactura aditiva. *Padi Boletín Científico de Ciencias Básicas e Ingenierías del ICBI,* 90. https://dialnet.unirioja.es/servlet/articulo?codigo=10097381

Hernández-Montero, F.E.E., Anías-Calderón, C. & Ruiz-Barrios, M.L. (2023). El camino hacia la implementación del mantenimiento predictivo 4.0 en Cuba. *Ingeniería Industrial*, *44*(3), 17-28. https://dialnet.unirioja.es/servlet/articulo?codigo=9456541

Lee, J., Ni, J., Singh, J., Jiang, B., Azamfar, M., & Feng, J. (2020). Intelligent Maintenance Systems and Predictive Manufacturing. *Journal of Manufacturing Science and Engineering, 142*(11), 110805. https://doi.org/10. 1115/1.4047856

Montijo, E.E. & Martínez, M.P. (2020). Cálculo de esfuerzos mediante simulación con elementos finitos: una herramienta para implementarse en ingeniería. *Pro Sciences: revista de Producción, Ciencias e Investigación, 4*(34), 70-78. https://journalprosciences.com/index.php/ps/article/view/248

Mustapha, K.B. (2022). *Simulaciones prácticas de elementos finitos con SOLIDWORKS 2022: Guía ilustrada para realizar análisis estáticos con SOLIDWORS Simulation*. Packt Publishing Ltd.

Nacimiento, P.H., & Cardoso, L. (2024). Análise de dinâmica por Métodos dos Elementos finitos. *Brazilian Journal of Development, 10*(7), 1-16. https://doi.org/10.34117/bjdv/10n7-056

Nunes, P., Santos, J. & Rocha, E. (2023). Challenges in predictive maintenance – A review. *CIRP Journal of Manufacturing Science and Technology, 40,* 53–67. https://doi.org/10.1016/j.cirpj.2022.11.004

Orejuela-Mendoza I.C., Suárez-Reyes D.J., Pino-Tarrago, J.C., Regalado-Jalca J.J. (2024). Diseño de Conexiones Soldadas RCFT mediante Elementos Finitos en Pórticos a Momento. *INGENIAR*, 7(14). https://doi.org/10.46296/ig.v7i14.0215

Pillado, M., Castillo, V.H., & de la Riva, J. (2022). Metodología de administración para el mantenimeinto preventivo como base de la confiabilidad de las máquinas. *Revista Iberoamericana para la investigación y el desarrollo educativo, 12*(24). https://doi.org/10.23913/ride.v12i24.1218

Pineda, J. (2025). Optimización de la Fabricación del Servo de Retro del Vehículo HMMWV. *Ciencia y Reflexión, 4*(9), 272-290. https://cienciayreflexion.org/index.php/Revista/article/view/540

Ramírez, I.M., Rivera, M.G., Cruz, J.N., Torres, I.E., & Moreno, S.H. (2022). Optimización geométrica de estructuras metálicas ligeras para aplicaciones prácticas utilizando el método de elemento finite. *Ingenio Magno, 13*(2), 89-94. https://revistas.santototunja.edu.co/index.php/ingenio/article/view/2676

Simbaña, I., Quitiaquez, W., Cabezas, P., & Quitiaquez, P. (2024). Estudio comparativo de la eficiencia de colectores solares de placa plana rectangular y triangular mediante el método de elementos finitos. *Revista Técnica "Energía", 20*(2), 81–89. https://doi.org/10.37116/revistaenergia.v20.n2.2024.593

Simbaña, I., Vaca, X., Andrade, C., & Sevillano, W. (2025). Análisis numérico computacional de la estructura de soporte de un tanque de almacenamiento de agua de Lluvia. *Revista Digital Novasinergia, 8*(1), 6-18. https://doi.org/10.37135/ns.01.15.04

Smith, G.T. (2016). *Machine Tool Metrology: An Industrial Handbook. Springer.*

Thielsen, A. (1970). *Mantenimiento predictivo y vibraciones mecánicas.* Editorial McGraw-Hill.

Tiddens, W., Braaksma, J., & Tinga, T. (2020). Exploring predictive maintenance applications in industry‖. *Journal of quality in maintenance engineering*, *28*(1), 68-85. https://doi.org/10.1108/JQME-05-2020-0029

Torrell Quinta, U., Matos Mendoza, E., Viera Callar, J.M., Fernández Pérez, Y., & Martínez Rojas, R. (2024). Simulación de partes y piezas de un ariete hidráulico. *Ciencia & Futuro, 4*(1), 42-55. https://revista.ismm.edu.cu/index.php/revistacyf/article/view/2484