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Journal of Engineering Applications

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Automatic cephalometric landmark identification in lateral skull X-Rays using convolutional neural networks

Localización automática de etiquetas cefalométricas en radiografías laterales de cráneo utilizando redes neuronales convolucionales

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Abstract

Cephalometric analysis is a study held in orthodontics, based on the identification of certain points in a skull image obtained through an X-ray image or another method in medical imaging. The indicated points are compared with standard values to evaluate and diagnose the patient. The radiograph's labeling is regularly performed by hand, which makes the labeling process slow and prone to errors due to the visual acuity required. This approach is not much reproducible, because it relies on the domain and expertise of the expert labeler. Many machine learning methods were successfully applied to solve medical imaging tasks, aiming to reduce the health experts' workload and emit more accurate diagnoses in less time and, avoid a more several clinical case. This work shows the design and development process of a machine learning system based on convolutional neural networks to identify 19 cephalometric landmarks for a lateral skull radiograph image as input. The system used a 400 labeled images dataset, from which, 150 were used for training, 150 for model's validation and it was tested in the 100 remaining images.

Cephalometric analysis, Deep learning, Convolutional neural networks

Resumen

El análisis cefalométrico es un estudio realizado en ortodoncia, basado en la identificación de puntos en una imagen del cráneo obtenida mediante radiografía o por otro método de imagenología. Los puntos ubicados son comparados con valores estándar para la evaluación y diagnóstico del paciente. El etiquetado de las radiografías se realiza regularmente de manera manual, lo cual lo hace lento y susceptible a errores debido a la agudeza visual requerida. Este enfoque es poco reproducible ya que depende del dominio y criterio del experto que etiqueta. Diversos métodos de aprendizaje de máquina se han aplicado de manera exitosa a tareas que involucran imágenes médicas, buscando reducir la carga de trabajo de los profesionales de la salud y emitir diagnósticos más certeros en menor tiempo y, que eviten un cuadro clínico más grave. Este trabajo muestra el proceso de diseño y desarrollo de un sistema de aprendizaje automático basado en redes neuronales convolucionales para la identificación de 19 etiquetas cefalométricas para una radiografía lateral de cráneo como entrada. El sistema utilizó un conjunto de datos 400 imágenes etiquetadas de las cuales, 150 se utilizaron para entrenamiento, 150 para validación del modelo y se probó en las 100 imágenes restantes.

Análisis cefalométrico, Aprendizaje profundo, Redes neuronales convolucionales

Citation: LÓPEZ-RAMÍREZ, José Luis, CALDERÓN-SASTRE, Enrique, QUINTANILLA-DOMÍNGUEZ, Joel and AGUILERA-GONZÁLEZ, José Gabriel. Automatic cephalometric landmark identification in lateral skull X-Rays using convolutional neural networks. Journal of Engineering Applications. 2021. 8-25:1-9.

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Introduction

The cephalometric analysis is an essential tool in orthodontics. It allows physicians to detect related craniofacial pathologies, orthodontics diagnoses, or maxillofacial surgery planning. The cephalometric analysis makes use of lines traced in skull radiographs to make both linear and angular measurements that will be compared against standard values. To trace the lines is necessary to label the radiograph with the required cephalometric landmarks to accomplish the corresponding study.

There exist as many cephalometric landmarks as necessary, new landmarks can be created if they fulfill two conditions (Rakosi, 1982): Easy to locate it (aiming that radiograph's quality and overlapping anatomic tissues have the least possible impact), and that the landmark's location have little influence by sex, race or age aspects. Cephalometric analysis has many diverse applications. In the orthodontics field there are four main applications (Kula & Ghoneima, 2018):

- Malocclusion.

- Brute inspection: To emit a general landscape about the morphology of maxillofacial structures.

- Treatment generation based on craniofacial evaluation.

- Growth analysis and evaluation of previous treatments: This analysis is possible due to the cephalometric analysis' reproducibility and the capability of cephalograms to overlap it.

In addition to the orthodontics applications, cephalometric analysis can reveal important information about other pathologies like (Athanasiou, 1995): Identification of some pathologies in the pituitary gland, or abnormalities in skull, mandible, cervical spine, or maxillary and paranasal sinuses.

Although cephalometric analysis is a mandatory step in most orthodontics treatment and diagnosis, the labeling process in cephalometric analysis is mostly carried by hand, which makes it prone to detection and interpretation errors caused by limitations in the eye-brain human system, presence of overlapping structures that hide relevant features to the study (Giger *et al*., 2008), labeler's fatigue or lack of expertise.

Lateral Cephalometric Radiographs (LCR), also known as cephalographs, is a 2D radiograph that favors visualization of teeth, cranial bones, and soft tissue. The LCRs are used to carry cephalometric analysis. Figure 1 shows an example of LCR.

With the demand for medical services and diagnoses, the physicians need more tools to automate or reduce the times of certain processes. The implementation and use of Computer-Aided Diagnosis (CAD) systems allow early detection and progress measurement of certain pathologies, and at the same time, reduce the image-reading times. The CAD systems serve as a second opinion to the physician, this in a complementary way to reinforce or refute the initial hypothesis regarding the study in turn.

The first CAD system approved by the Food and Drug Administration in 1998 (Freer & Ulissey, 2001), the system detects lesions in mammographs. By 2016, 92% of the mammograph screening involved some CAD system (Fujita, 2020).

The aim of this work is to create a CAD system that can reduce the physicians' workload by identifying 19 cephalometric landmarks from a digital cephalograph as input, using a Convolutional Neural Network to find the (x,y) coordinates of each landmark. The landmarks were selected according to the only public database available, which is the one released during the IEEE International Symposium on Biomedical Imaging 2015 (IEEE ISBI 2015). Table 1 provides the names of the landmarks used in this work. Figure 2 shows the location of the cephalometric landmarks used.

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Figure 1 Example of a lateral cephalometric radiograph

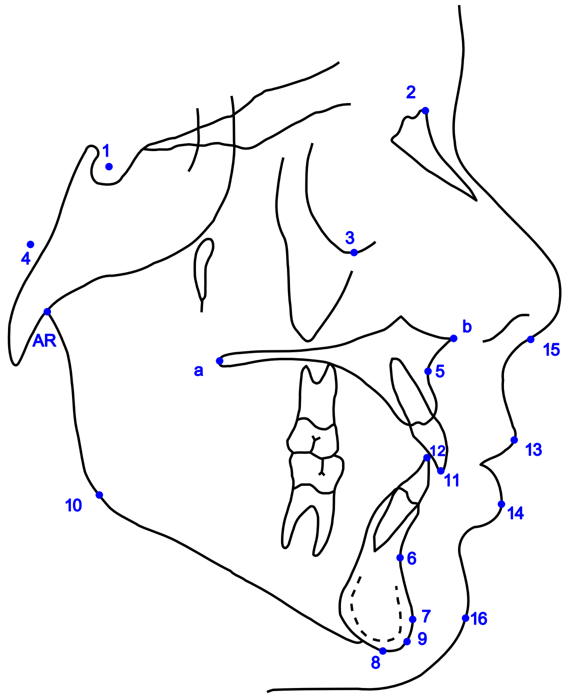

Figure 2 Location of the 19 cephalometric landmarks
Source: Adapted from (Wang et al., 2015)

Identifier	Landmark
1	Sella turcica
2	Nasion (N)
3	Orbitale (Or)
4	Porion (P)
5	Subspinale
6	Supramentale
7	Pogonion (Pog)
8	Menton (Me)
9	Gnathion (Gn)
10	Gonion (Go)
11	Lower incisal incision
12	Upper incisal incision
13	Upper lip
14	Lower lip
15	Point PM or MN
16	Soft tissue pogonion
a	Posterior nasal spine
b	Anterior nasal spine
AR	Articulate

Table 1 Name of the 19 cephalometric landmarks to label with the system presented
Source: Adapted from (Athanasiou, 1995), (Gill & Naini, 2011), (Foster, 1990), (Cardillo & Sid-Ahmed, 1994), (Leonardi et al., 2009)

Related Work

In addition to the new capture techniques, cephalometrics has taken advantage of the available computational tools, an example of this is the use of tools to automatically trace the cephalograms and CAD systems that help physicians to take decisions regarding treatments.

We can classify the CAD systems for cephalometric landmark detection into three main categories (El-Feghi *et al.*, 2004):

- A mix of image processing techniques to extract relevant edges to the landmarks.

- Geometric techniques with edge detection based on template matching coded with previous knowledge to reduce the region of interest.

- Computational intelligence techniques.

Below are some representative CAD systems for cephalometric analysis according to the categories presented above:

The first CAD system applied to cephalometric analysis was developed in 1986 by Lévy-Mandel *et al.* (Lévy-Mandel et al., 1986).

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The system proposes a system with a pre-processing step, followed by edge detection, and a priori coded algorithm to follow the most characteristic lines where cephalometric landmarks are commonly located. The system works in 256 x 256 gray-scale cephalograms.

In 1994, Cardillo and Sid-Ahmed (Cardillo & Sid-Ahmed, 1994) presented a system based on mathematical morphology to be applied in gray-scale images. The system was trained using 40 images and obtained an 85% detection rate in 20 landmarks.

In 1999, Chen et al. (Chen et al., 1999) presented the first CAD system for cephalometric analysis based on neural networks and genetic algorithms. The system uses a multi-layer perceptron with a neuron in the last layer to indicate if there is a similarity between the output and the pattern to identify.

In 2004, El-Feghi et al. (El-Feghi et al., 2004) presented a similar features clustering algorithm connected with a neuro-fuzzy block to get an estimated location and refine the results using template matching techniques.

In 2014, the Automatic Cephalometric X-Ray Landmark Detection Challenge was hosted during the IEEE International Symposium on Biomedical Imaging. In this challenge, the organizers provided a 300 images dataset. The dataset included the location of the 19 cephalometric landmarks shown in Table 1 for each cephalogram. None of the five first places used a neural network-based approach. The winner of the challenge (Ibragimov et al., 2014) used an approach based on game theory and random forest to obtain 72.2% in the 2 mm range. One year later, in the IEEE ISBI 2015, another challenge was carried out. In this edition of the challenge, the organizers provided a bigger public database with 400 images, labeled with the location of the 19 landmarks shown in Table 1. The 1st and 2nd places of the challenge (Lindner & Cootes, 2015) and (Ibragimov et al., 2015) used approaches based on random forests. In recent years, computational intelligence techniques have shown the best results in solving this challenge. For a more extensive revision and comparison of recent CAD systems in cephalometric landmark detection, please see (Lopez-Ramirez et al., 2020).

Methodology

The approach used to solve the problem is the use of convolutional neural networks to create a regression model to predict the (x,y) coordinates of the 19 landmarks of the input image. In literature, this approach is known as *Vanilla deep regression*, in which the final layer of the architecture performs the regression. Figure 3 shows the diagram of an architecture of a convolutional neural network that makes a regression.

Dataset

The dataset used contains 400 labeled cephalograms. The images were labeled twice by two expert orthodontists with six and 15 years of experience. For each of the labeled images, a plain text file was provided. The file includes the (x,y) coordinates of each of the 19 cephalometric landmarks. The ground truth of the location is the average of the labels made for each coordinate. Table 2 shows the characteristics of the database used.

Feature	Value
Machine receptor	Soredex CRANEX Excel Ceph machine
Patient’s age	Between 6 and 60 years.
Resolution	1935 x 2400 pixels.
Output format	TIFF
Pixel size	(0.1x0.1) mm^2
Training images	150
Test images	250

Table 2 Main features of the used database.

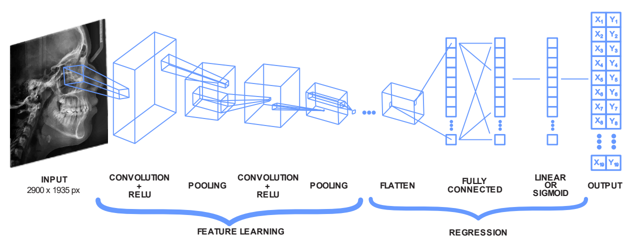

Figure 3 CNN schematic used for vanilla deep regression

The images in the database were randomly split into three datasets: The training set containing 150 images, the validation set *(Test1)* with 150 images, and the test set *(Test2)* with the remaining 100 labeled images.

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Metrics

The Mean Radial Error (MRE) was used as loss function and the Successful Detection Rate (SDR) regarding the ranges {2.0, 2.5, 3.0, 4.0} [mm], based in the pixel size of images (see Table 2). To compute MRE is first needed to calculate the 2D Euclidean distance between the predicted pixel and the expert's pixel. This distance is computed as follows:

$$R = \sqrt{(\Delta X)^2 + (\Delta Y)^2} = \sqrt{(x_p - x_o)^2 + (y_p - y_o)^2} \quad (1)$$

Where:

R = Euclidean distance between two points.

$\Delta X, \Delta Y$ = Distance in each axis.

(x_p, y_p) = Predicted coordinates.

(x_o, y_o) = Objective coordinates.

The Mean Radial Error is defined as follows:

$$MRE = \frac{1}{N}\sum_{i=1}^{N} ||X_{expertos} - X_{CNN}|| = \frac{1}{N}\sum_{i=1}^{N} R_i \quad (2)$$

Where:

N = Number of used images belonging the dataset to evaluate.

$X_{\{expertos\}}$ = Location of the label selected by health experts. This is the ground truth.

$X_{\{CNN\}}$ = Prediction made by the presented model.

R_i = Euclidean distance average of the M cephalometric landmarks to locate, calculated using $R_i = \frac{1}{M}\sum_{j=1}^{M} R_{ij}$.

The Successful Detection Rate p_z is a metric to indicate the percentage of cephalograms that were identified in a precision range z. The SDR is calculated as follows:

$$p_z = \frac{N_z}{N} \times 100\% = \frac{|\{i \in \mathbb{N} : R_i < z, 1 \leq i \leq N\}|}{N} \times 100\% \quad (3)$$

Figure 4. shows a cephalogram marked with the detection ranges.

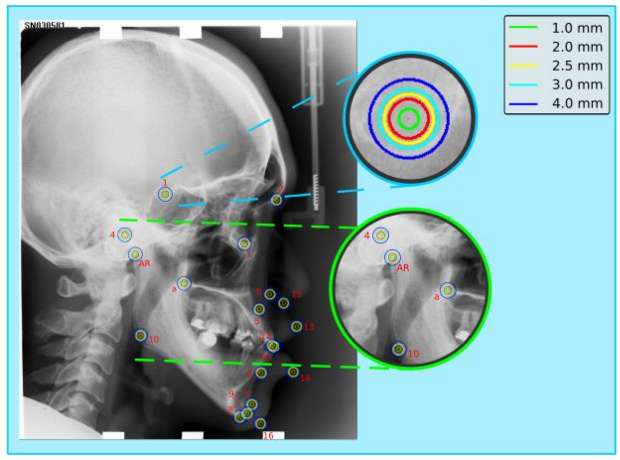

Figure 4 Different marked ranges in comparison with the label made by expert one

Model Architecture

The final choice of the model's hyperparameters is made using grid search to train the model varying from a table and a range of hyperparameters and pick the ones that offer the best results. The hyperparameters to modify were: Learning rate, training epochs, dropout rate, regularization type, neurons or feature maps in each layer, and model's depth.

The database compression, data loading, and model generation were made using the Python programming language. The CNN model was created using the Keras high-level API running in TensorFlow 2.3 backend. Table 3 shows the hardware used.

Feature	Value
Model	MSI GF63
Operative System	Windows 10
Processor	Intel core i5 10^{th} generation.
RAM Memory	16 GB DDR4
GPU	NVIDIA GTX 1650Ti 4GB
Storage	250 GB SSD

Table 3 Hardware used to develop the presented model.

The function that generates the model receives tree parameters: Image height, width, and the number of coordinates to predict. The input layer is created using these data and the input image. After the input layer, there are five convolutional blocks, consisting of convolutional layers for feature extraction and MaxPooling layers for dimensionality reduction. Each convolutional block includes "Same" padding, to keep the dimensionality of the output feature map equal to the input.

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Once the convolutional stage is finished, is necessary to vectorize the output to feed the regression step, this is achieved with the Flatten layer. The output of Flatten layer is connected to a Dense layer with 380 neurons, this is, 10 times the number of coordinates to predict.

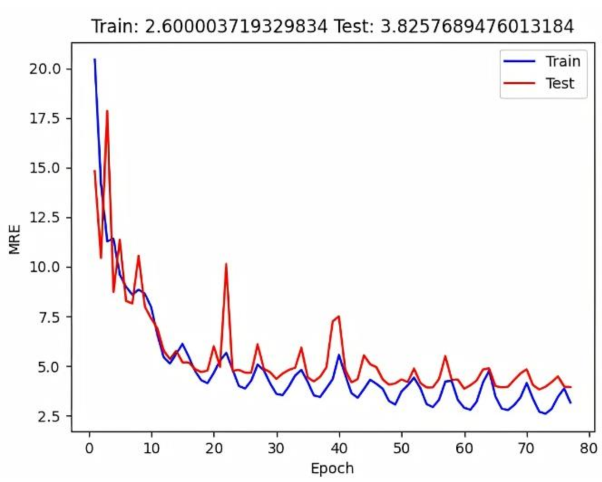
The output layer is a Densely connected layer with 38 neurons, the same as cephalometric landmarks. This layer has a linear activation function. Table 4 shows the final hyperparameters to build the model, and Figure 5 shows a diagram of the architecture.

Hyperparameter	Value
Hidden layers	12
Loss function	MRE
Optimizer	Nadam with CLR Triangular
Learning rate	0.0001-0.001
Training epochs	77
Kernel size	3 x 3
Stride	1
Padding	“Same”
Pooling	Max-Pooling

Table 4 Chosen hyperparameters to build the model.

Results

Graphic 1 shows the loss curve versus training epochs. It is easy to see the influence of CLR in the triangular shape of the graph. Table 5 shows the MRE average results both in validation and test obtained with the presented model.



Graphic 1 Curve of loss versus training epochs

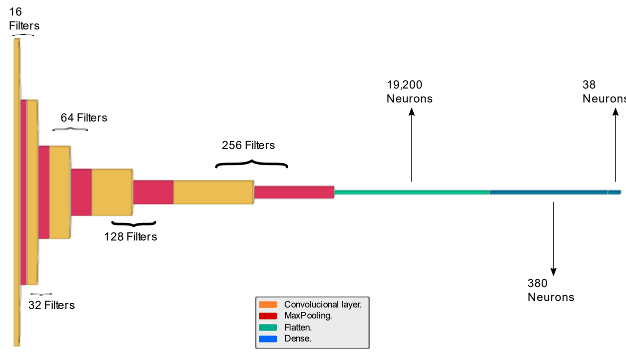


Figure 5 Layer organization of the presented model

Cephalometric landmark	Average MRE [mm]	
	Test1	Test2
1.- Sella turcica	3.94	4.22
2.- Nasion (N)	3.78	4.36
3.- Orbitale (Or)	3.16	3.67
4.- Porion (P)	3.99	5.25
5.- Subspinale	3.41	3.65
6.- Supramentale	3.29	3.90
7.- Pogonion (Pog)	4.51	4.46
8.- Menton (Me)	4.49	4.50
9.- Gnathion (Gn)	4.58	4.40
10.- Gonion (Go)	4.53	5.50
11.- Lower incisal incision	3.43	3.67
12.- Upper incisal incision	3.63	3.88
13.- Upper lip	3.75	4.12
14.- Lower lip	3.79	4.30
15.- Point PM or MN	3.20	3.49
16.- Soft tissue pogonion	4.43	4.49
a.- Posterior nasal spine	3.04	3.64
b.- Anterior nasal spine	3.47	3.49
AR.- Articulate	4.27	5.17
Average	**3.83**	**4.22**

Table 5 Average MRE obtained for each cephalometric landmark

From Table 5, we can conclude that the Posterior nasal spine was the best-identified landmark, and Gonion had the worst average results. Figure 6 shows some of the test images labeled with the presented model. Graph 2 shows the distribution of average MRE for the datasets used. As it can be seen, there are some outlier values that strongly impact the calculation of the average MRE.

Regarding the SDR, Table 6 shows the breakdown of the two datasets and their belonging ranges.

	SDR Range (%)				
	2 mm	2.5 mm	3 mm	4 mm	5 mm
Test1	2.67	12.67	32.00	60.67	86.00
Test2	1.00	13.00	27.00	66.00	82.00

Table 6 SDR range for Test1 and Test2 datasets

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Future work

To refine the results obtained with this model, is planned to apply transfer learning to the model and use the state-of-the-art architectures for feature extraction. Transfer learning can help to overcome the lack of labeled images challenge with their powerful feature extraction stages.

As a solution to the variability that means analyzing the cephalogram as a whole by genetic reasons or issues while capturing the radiograph, applying a regression model to every cephalometric landmark to identify can reduce the identification error. To make this, is necessary to extract fixed-size patches.

In addition to the model improvements, a new public database is planned, this will allow us to train the model with a higher quantity of labeled images and increase the generalization ability of the model.

Thanks

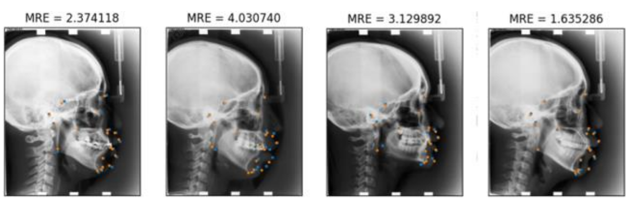
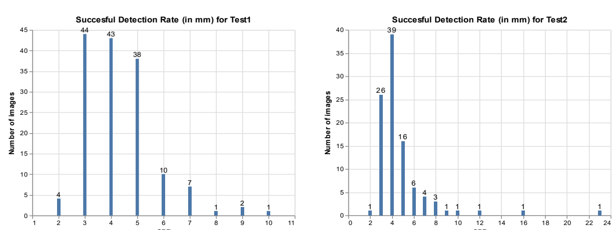


Figure 6 Labeled cephalograms using the presented model



Graphic 2 Average MRE distribution for Test1 and Test2 sets

Conclusions

The model is a good complementary tool to reduce the identification times by narrowing the search region, although the 2 mm range was not yet reached.

The model is susceptible to great changes in chin shape, these changes impact directly in the prediction accuracy. Also, the landmarks near the Hindhead (sella turcica, porion, and articulate) are severely affected by the distance between the chin and the inferior border of the cephalogram.

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Wall thickness determination study for a plastic injection barrell due to the internal pressure

Estudio para la determinación del espesor de pared adecuado para un cañón de inyección de plástico debido a la presión interna

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Abstract

The use of Plastics is a very common activity nowadays, there are many different types of Injection Machines varying in size, the capacity of the material to inject, one of the main machines classifications is due to the injection pressure. One of the things to consider when the designing process is carried out is the factor of safety, this factor helps designers to avoid possible failures in mechanical elements of mechanisms, it provides a safety margin that aims to protect against any unexpected incident. The advantage of Simulation is that allows us to predict the behavior of elements under stress. In the Injection Process, barrels are elements subject to high pressure. This encourages analyzing wall thickness to find a suitable barrel wall thickness. The present study is focused on the design of the wall thickness, seeking reduce machining time that are required when producing the barrels that may be needed and to select the proper commercial barrel size reducing material waste.

Barrel wall thickness, Internal pressure, Factor of safety, Injection process

Resumen

El uso de plásticos es una actividad muy común en la actualidad, existen diferentes tipos de máquinas de inyección, estas varían en: tamaño, capacidad de material a inyectar y una de las clasificaciones principal es debida a la presión de inyección. Una de las cosas a considerar cuando se realiza el proceso de diseño es el Factor de Seguridad, este factor ayuda a los diseñadores a evitar posibles fallas en elementos mecánicos o mecanismos, provee un margen de seguridad que busca proteger contra incidentes inesperados. La simulación ayuda a predecir el comportamiento de elementos sometidos a esfuerzos. En el proceso de inyección, los cañones se someten a altas presiones. Debido a lo anterior se ve la necesidad de analizar el espesor de pared a fin de encontrar un tamaño que se adecuado. El presente estudio se centra en el diseño del espesor de pared, buscando reducir tiempos de maquinado que se requieren al producir los cañones y seleccionar el tamaño comercial adecuado para disminuir el desperdicio.

Espesor de pared, Presión interna factor de seguridad, Proceso de inyección

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Introduction

Injection Processes have increased during recent years, this caused work on design improvement, one of the more effective tools used is the Finite Element Method (FEM). Using FEM, parts can be tested under different conditions such as mechanical stress due to pressure. Barrels are vessels subjected to internal forces caused for pressure which is considered for this study. The barrel is a vessel structure subjected to combined loadings (normal and shear stresses) which govern their design.

By varying the wall thickness of the barrel we can propose a change in design to reduce material, this may impact the final cost of the barrel.

Pressure in injection process

Injection Machines use very high pressures to make the polymer flow inside the mold cavity, before it can be done, the material must be accumulated at the front, in the metering zone or injection Chamber (**Figure 1**) causes that pressure to increase at this section.

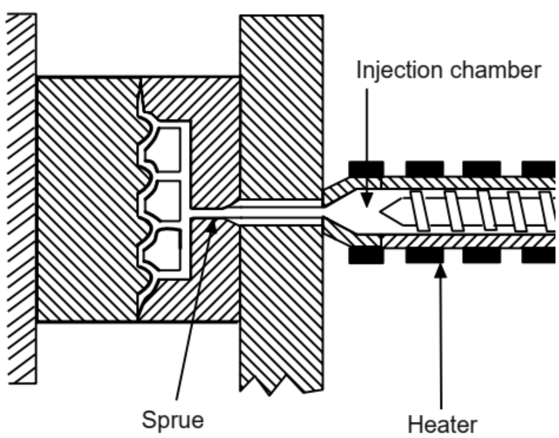

Figure 1 Bulk Material at the front of the barrel
Source: (Chanda, M, 2008). [1]

Under this context, the barrel (metering zone) can be considered as a cylindrical pressure vessel that has a closed structure, these elements may contain liquids or gases under pressure. Cylindrical pressure vessels with a circular cross-section, as shown in **Figure 2**, are found in industrial settings (compressed air tanks and rocket motors), in homes (fire extinguishers and spray cans), and the countryside (propane tanks and grain silos).

Pressurized pipes, such as water-supply pipes and penstocks, are also classified as cylindrical pressure vessels. The geometry for the injection cylinder falls in the last examples.

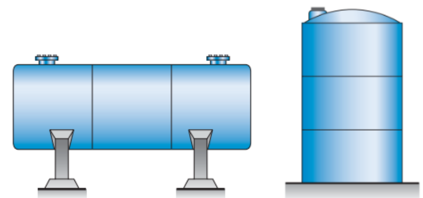

Figure 2 Cylindrical pressure vessels with a circular cross-section
Source: (Gere, J,2009), [2]

To determine the circumferential stress σ1, we make two cuts (mn and pq) perpendicular to the longitudinal axis and distance b apart (Figure 3a). Then we make a third cut in a vertical plane through the longitudinal axis of the tank, resulting in the free body shown in Figure 3b. This free body consists not only of the half-circular piece of the tank but also of the fluid contained within the cuts. Acting on the longitudinal cut (plane mpqn) are the circumferential stresses σ1 and the internal pressure *P*. The normal stresses σ_1 and σ_2 acting on the side faces of this element are the membrane stresses in the wall. No shear stresses act on these faces because of the symmetry of the vessel and its loading. Therefore, stresses σ_1 and σ_2 are principal stresses.

The following formula is set for the *circumferential stress in a pressurized cylinder*:

$$\sigma_1 = \frac{Pr}{t} \tag{1}$$

Where *P* is the internal pressure, *r* is the inner radius of the cylinder and *t* is the wall thickness. This stress is uniformly distributed over the thickness of the wall. The longitudinal stress σ2 is obtained from the equilibrium of a freebody of the part of the vessel to the left of cross section mn (Figure 3c). The stresses σ2 act longitudinally and have a resultant force equal to σ2(2*P*rt). The resultant force P_2 of the internal pressure is a force equal to $P\pi r^2$. Thus, the equation of equilibrium for the free body is

$$\sigma_2(2\pi rt) - P\pi r^2 = 0 \tag{2}$$

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Solving this equation for σ2, we obtain the following formula for the *longitudinal stress* in a cylindrical pressure vessel:

$$\sigma_2 = \frac{Pr}{2t} \quad (3)$$

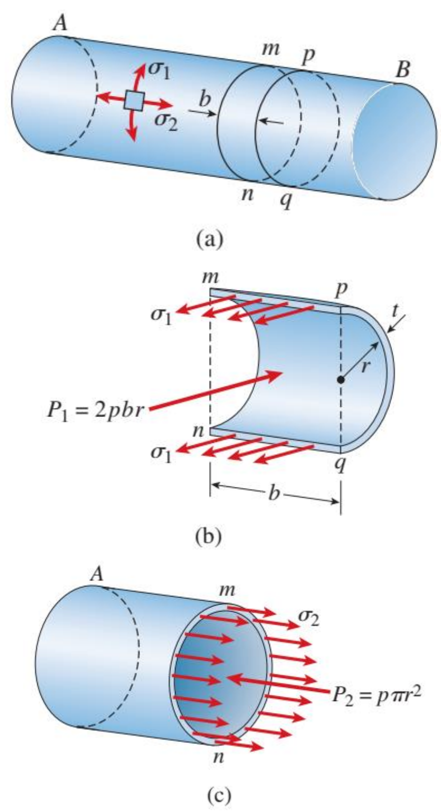

Figure 3 Principal stresses on cylindrical pressure vessels with a circular cross-section
Source: (Gere, J,2009)

Allowable stresses

Factors of safety are defined and implemented in various ways. For many structures, it is important that the material remains within the linearly elastic range to avoid permanent deformations when the loads are removed. Under these conditions, the factor of safety *n* is established concerning the yielding of the structure. Yielding begins when the yield stress is reached at any point within the structure. Therefore, by applying a factor of safety with respect to the yield stress (or yield strength), we obtain allowable stress (or working stress) that must not be exceeded anywhere in the structure [2]. Thus,

$$Allowable\ Stress = \frac{Yield\ strength}{Factor\ of\ Safety} \quad (4)$$

$$or \quad \sigma_{allowable} = \frac{\sigma_y}{n}$$

These points can be seen in the Stress-strain diagram of Figure 4 and it helps to predict the possible failure of an element among other properties.

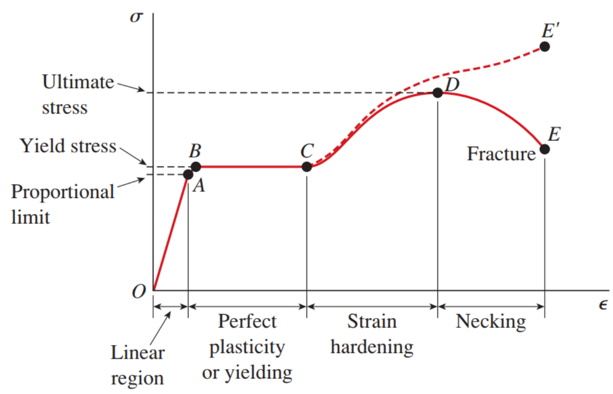

Figure 4 Stress-Strain diagram
Source: (Gere, J,2009)

Finite element method

The Finite Element Method is a technique used to predict the mechanical behaviour of elements under different loads like thermal, electrical, or mechanical. This Technique is used for numerically solving differential equations that come from the discretization of the model, create small elements connected by nodes.

Engineers are interested in evaluating effects such as deformations, stresses, temperature, fluid pressure, and fluid velocities caused by forces such as applied loads or pressures and thermal and fluid fluxes. The nature of the distribution of the effects (deformations) in a body depends on the characteristics of the force system and for the body itself. The aim is to find this distribution of the effects. For convenience, we shall often use displacements or deformations u (Figure 5) in place of effects. Subsequently, when other problems such as heat and fluid flow are discussed they will involve the distribution of temperature and fluid heads and their gradients [3].

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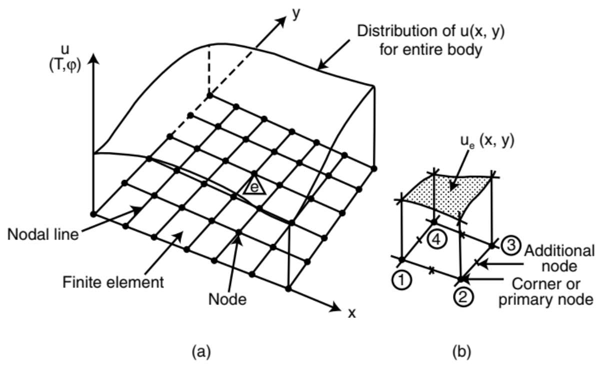

Figure 5 Distribution of displacement u, temperature T, or fluid head f. (a) Discretization of two-dimensional body and (b) Distribution of u_e over a generic element e
Source: (Desai, Chandrakant, 2001)

Several softwares help with the modeling of parts and assemblies, they also provide platforms for FEM analysis. Solidworks helps us to simulate the elements and try to predict their behavior showing color stripes depending on the stress intensity, where colors red and blue are the maximum and minimum stress zones (Figure 6).

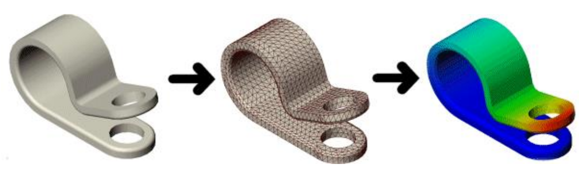

Figure 6 Element, mesh, and Stress intensity representation
Source: (Solidwoks,2020) [3]

Stress analysis

Process conditions

From previous research and applying the concept of stationary point for a function of one variable can set the following conditions for Injection Pressure and cycle time: 8.75MPa and 8.607s respectively [4].

The injection process is carried out by a cylindrical barrel moved by an ¾ hp electrical motor coupled a chain transmission. The material is loaded into a hoper manually and carried in the barrel by the screw rotation to the front of the barrel. Every shot uses about 19 gr of Polypropylene neglecting the process losses.

One thing to keep in mind is the heat distribution, for this work it is considered to be uniform, but it does not occur that way, there is an analysis carried out for Diaz, A which recommends a procedure to set the heat bands around the barrel (Diaz, A,2021). There is recommend waiting for 10 minutes in order to get a correct distribution of the heat in all the barrel. Another thing is the power needed for the heaters, there is shown how to make an estimation of the power consumption [5].

For this study Figure 7 represents the injection Machine used for the analysis, more accurately the Melt, here can be seen the melted material at the end of the reciprocating screw.

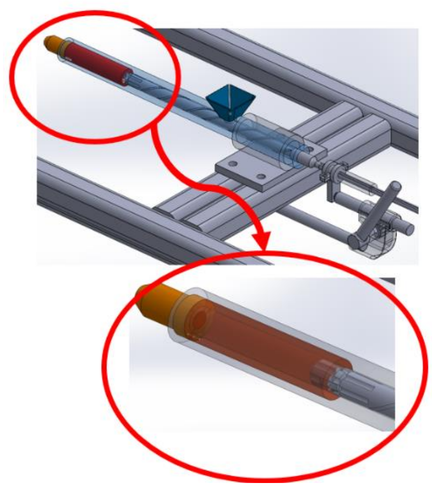

Figure 7 Material melts at the front of the barrel
Source: *Own work [Solidworks]*

The part under analysis is selected (Domain) and to apply de FEM method discretization is needed as shown in **Figure 8**.

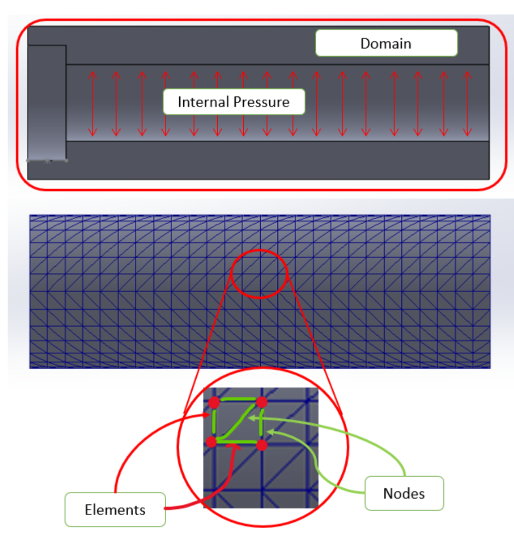

Figure 8 Domain and discretization to apply FEM
Source: Own work [Solidworks]

The Material Characteristics for the analysis are taken from the database of Solidworks using an AISI 1020 Steel, Mechanical Properties are as shown in Table 1.

Modulus of Eleasticity E	200 GPa
Poisso'n Ratio n	0.29
Shear Modulus of Elasticity	77 GPa
Mass Density	7900 kg/m^3
Traction Limit	420.5 MPa
Yield Stress	35.15 MPa
Coefficient of thermal expansion a	$15x10^{-6}$ /K
Thermal Conductivity	47 W/(mK)

Table 1 Mechanical Properties for AISI 1020 Steel.
Source (Solidworks,2020)

The Injection Chamber is isolated and considered a thus the different essays decreasing the wall thickness take place Figure 9.

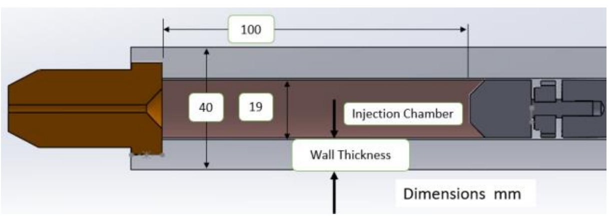

Figure 9 Wall thickness considered for analysis
Source: Own work [Solidworks]

Using Solidworks software the simulation parameters and boundary conditions are set for the model as shown in Figure 10.

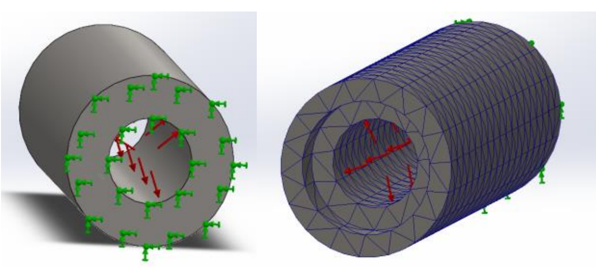

Figure 10 Model with boundary condition applied
Source: Own work [Solidworks]

After all the conditions are set simulation takes place presenting the following results (Figure 11). The test was taken place reducing the wall thickness by 0.5 mm each time, from this we can see the results in Table 2, there are presented the Maximum Stress, displacement, and deformation for each essay.

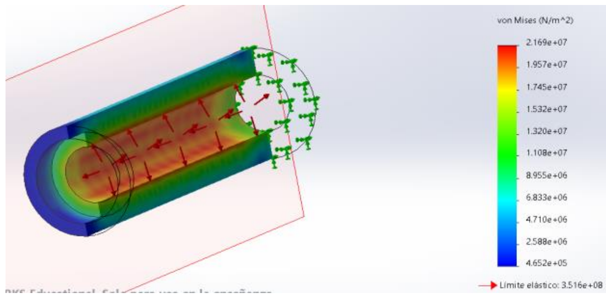

Figure 11 FEM Stress analysis results
Source: *Own work [Solidworks]*

In Figure 12 are plotted the results for the Maximum Stress. There can be seen that at a wall thickness of 3.5 mm the Maximum stress is 37.7 MPa. It overpasses the stress allowable for safety conditions. Maximum stress is give in the internal wall of the barrel and it propagates through the wall thickness. Here the main stress is radial and is a combination of the pressure and the thermal expansion of the material.

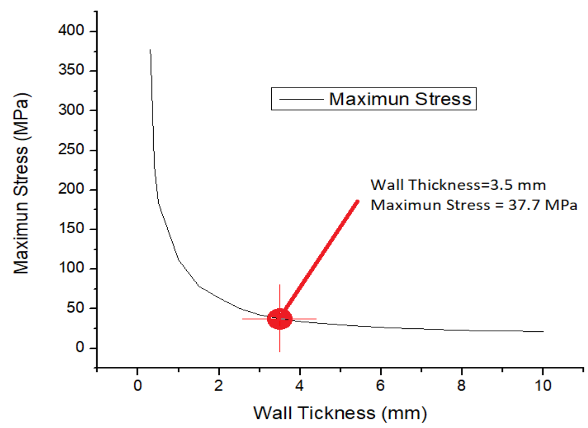

Figure 12 Wall thickness vs maximum stress diagram
Source: *Own work*

Essay	Wall Thickness t (mm)	Maximum Stress s (MPa)	Maximum Displacement d (E-03 mm)	Maximum Deformation ϵ (E-06 mm/mm)
1	10	21.22	1.183	74.87
2	9.5	21.69	1.242	76.47
3	9	22.33	1.311	79.33
4	8.5	22.2	1.382	81.43
5	8	22.97	1.47	83.76
6	7.5	23.71	1.569	87.51
7	7	24.61	1.687	92.27
8	6.5	25.57	1.826	96.97
9	6	26.68	1.995	101.2
10	5.5	28.06	2.206	107.6
11	5	29.77	2.465	114.7
12	4.5	31.82	2.76	121.6
13	4	33.95	3.138	132.9
14	3.5	37.7	3.63	137.1
15	3	42.44	4.308	155.8
16	2.5	50.63	5.218	181.7
17	2	63.78	6.636	221
18	1.5	78.6	9	292.7
19	1	111.8	13.21	419.9
20	0.5	183.6	23.23	731.4
21	0.4	231.1	26.64	891
22	0.325	347.5	43.88	1265
23	0.3	378.5	47.64	1384

Table 2 Essay Results for the injection chamber
Source: Own work [Solidworks]

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Results and Discussion

If the factor of safety (*n*) is set at 1.5 the $\sigma_{allowable}$ is:

$$\sigma_{allowable} = \frac{\sigma_y}{n} = \frac{35.15\ MPa}{1.5}$$

$$= 23.43\ MPa$$

For this $\sigma_{allowable}$ the wall thickness would be 7.5 mm which results in a Maximum Stress of 23.71 MPa, this is a conservator value for the barrel.

The graph in Figure 13 shows the relation for a factor of safety from 1 to 1.5. If the safety factor is set at 1 the wall thickness could be reduced to 3.5 mm but the failure margin is risky. On the other hand, if the value of 1.5 is considered for the wall thickness it will be very close to $\sigma_{allowable}$ but this ensures that our barrel won't fail. Another thing to keep in mind is the fact that there's still the Strain Hardening zone which helps us prevent any possible unexpected failure.

It is recommended to reduce the wall thickness due to its relation to the barrel weight, this may impact the budged required for further designs and productions of injection barrels.

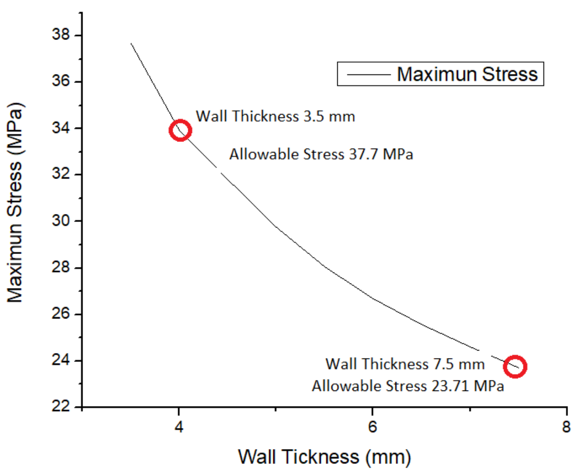

Figure 13 Factor of safety vs Allowable Stress diagram
Source: Own work.

Another thing to keep in mind is that to reduce the wall thickness material must be removed and this requires time and manufacturing cost so the most proximal outer diameter must be selected and considering also the original internal diameter for commercial tubes.

Simulation helps to find a starting point for the design of machines and mechanisms, the main points to keep in mind are: what kind of material are we working with, work conditions, material imperfections. The simulation also is a recommendable tool due to it doesn't require buying any material or machining. The parameters can be changed easily. The issues are computing time, computer and software requirements, and the understanding of the theory related to the phenomena. After developing the present

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Article

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Industrial safety analysis based on national and international standards for the operation of boilers in Mexico

Análisis de seguridad industrial basado en normas nacionales e internacionales para la operación de calderas en México

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Abstract

At present, there are still explosions caused by boilers, either due to lack of maintenance or because of poorly qualified personnel to operate them, causing human and economic losses and environmental damage. In Mexico, the government authority responsible for the protection and promotion of employment is the Secretary of Labor and Social Security (STPS), the regulations they manage are known as Official Mexican Standards (NOM). The regulation that establishes the safety requirements for the operation of boilers is NOM-020-STPS-2011. The objective of this research is to analyze referred standard, adequately promote its use and propose a sustainable maintenance plan. This was carried out under a mixed approach, analyzing quantitative and qualitative parameters considering statistical and technical data, it was also necessary to assess the norm through cause-effect laws. This paper aims to promote the use of safety measures for the efficient and sustainable use of boilers to generate a culture of compliance with international standards and preserve the important factors of this sector.

Boiler, Industrial Security, Standard-Sustainable

Resumen

En la actualidad aún se presentan explosiones ocasionadas por calderas, ya sea por falta de mantenimiento o por personal poco calificado para operarlas, provocando pérdidas humanas, económicas y daños ambientales. En México, la autoridad gubernamental responsable de la protección y promoción del empleo es la Secretaría de Trabajo y Previsión Social (STPS), administra las regulaciones conocidas como Normas Oficiales Mexicanas (NOM). La normatividad que establece los requisitos de seguridad para el funcionamiento de calderas es la NOM-020-STPS-2011. El objetivo de esta investigación es analizar dicha norma, promover adecuadamente su uso y proponer un plan de mantenimiento sostenible. Esta fue realizada bajo un enfoque mixto, analizando parámetros cuantitativos y cualitativos considerando datos estadísticos y técnicos, igualmente fue necesario la apreciación de la norma mediante leyes causa-efecto. Esta investigación pretende promover el uso de medidas de seguridad para uso eficiente y sustentable de calderas para generar una cultura de cumplimiento de estándares internacionales y preservar los factores importantes de este sector.

Caldera, Seguridad Industrial, Norma-Sostenible

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Introduction

At the end of the 18th century, the first industrial boilers began to be manufactured, these operated at greater pressures than atmospheric. Therefore, when equipment failed, often, results turned catastrophic. *American Society of Mechanical Engineers [ASME]. (s.f.).*

Until the middle of the 20th century, productive aspects such as design, quality and reliability of the product and the process were considered more important than industrial safety, because it was thought that this could be achieved by being careful and that it did not require planning and design. Safety was not considered a key factor in the production process. *Asfahl, C. et.al. (2010).*

Currently, the International Labour Organization (ILO) establishes that workers must be protected against accidents caused by their work. However, for millions of workers it is far from being a reality. Global ILO estimates show that 2.78 million work-related deaths occur each year. *International Labour Organization. [ILO]. (2018).*

In Mexico, the institution in charge of complying with safety requirements is the *Secretaría de Trabajo y Previsión Social (STPS)***.** Among the standards managed by this secretariat is the Official Mexican Standard NOM-020-STPS-2011, which is focused on pressure vessels, cryogenic vessels and steam generators or boilers. *Secretaría de Trabajo y Previsión Social [STPS]. (2011).*

This paper aims to analyze the current situation of boilers in Mexico, as well as promote the proper use of the Official Mexican Standard NOM-020-STPS-2011 and propose a sustainable maintenance plan. Boilers are equipment that requires constant maintenance and monitoring, because, the explosions that can be caused by them could have important consequences in developing countries, not only destroying property and human lives, but also ruining livelihoods. This research aims to promote the use of standards and safety measures for the efficient and sustainable use of boilers. *Akshoy, P. et al. (2018).*

Methodology

This research was carried out under a mixed approach, because a quantitative and qualitative methodology was used, based on National and International Standards focused on boilers, as well as articles and books on industrial safety. Currently, there are still explosions caused by boilers, either due to lack of maintenance or because of poorly qualified personnel to operate them, causing human and economic losses and environmental damage. The quantitative approach was required to analyze statistical parameters, technical and operational data to identify the deficiencies of industrial safety in the work centers. However, the qualitative method is equally necessary for the appreciation of the normativity through cause-effect laws, providing depth to the data, interpretive richness and contextualization of the environment. Therefore, a sustainable maintenance plan is proposed to efficiently use the boilers, provide worker safety and generate a culture of compliance with international standards to preserve the important factors of this sector. *Hernández, R. (2010).*

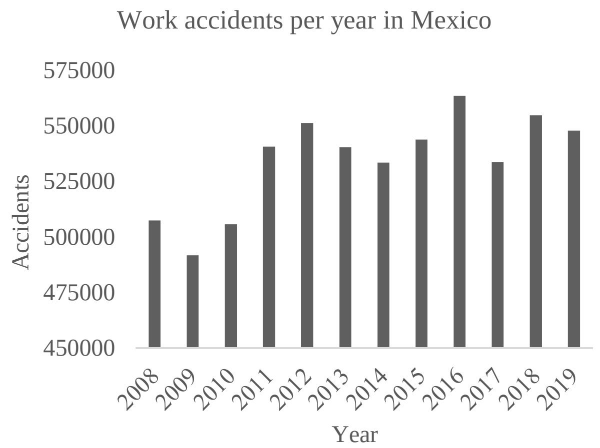
Safety and hygiene at work

The regulations define procedures and techniques that are applied in the work centers, for the recognition, evaluation and control of harmful agents that intervene in the processes and activities; with the aim of establishing measures and actions for the prevention of accidents. *Arellano, J. et al. (2013).*

Work safety in Mexico

The Mexican Institute of Social Security (IMSS) represents 79.7% of the working population with formal employment in Mexico, which is why the Database of Labor Risks that it administers is relevant for statistical purposes at the national level. *Aguilar, C. (2017).*

As can be seen in Graph 1, in Mexico there is an accident at work every minute, in the same way we can observe that from 2008 to 2019 the number of accidents remains at approximately 500,000 per year. This indicates that there is no interest in improving the labor security system in Mexico. *Instituto Mexicano del Seguro Social. [IMSS]. (2019).*



Graphic 1 Work accidents per year in Mexico
Source: IMSS. (2019)

In the case of boiler / pressure vessel explosions, statistical data is difficult to obtain, because most industries keep accident / incident data of their equipment at home and it is not reported. *Agarwal, S. et al. (2017).*

The technical-commercial magazine *"Calderas…Guía del Usuario (en la industria y comercio)"* Year 1, No. 1, pointed out that during 2019, Mexico was the Latin American country with the highest number of reported accidents, with a total of 6, reaching 34 injured. However, in Mexico there is no exact record of explosions related to boilers / pressure vessels, therefore the number of accidents may be higher. *Combustión, Energía & Ambiente, S.A. (2020).*

Audits

Inspection systems safety and health at work can provide necessary information to make decisions during the administrative process of accident prevention. *Arellano, J. et al. (2013).*

Audits in Mexico

NOM-020-STPS-2011 establishes that audits can be done by verification units. These units (individual or legal entity) must be accredited and approved under the terms of the Federal Law on Metrology and Standardization, and they are in charge of verifying the degree of compliance with this Standard by issuing a conformity assessment opinion. *Secretaría de Trabajo y Previsión Social [STPS]. (2011).*

In Mexico, conducting audits of management systems Safety and Health at Work does not represent an attributable legal obligation to companies, however, it is an option that can adhere to ensure effective compliance with federal regulations concerning the functions and service activities Safety and Health at work. However, if they decide to carry out an audit process, they must comply with the requirements contained in Section 8 of the Official Mexican Standard NOM-030-STPS-2009 Preventive Health and Safety Services at work. *STPS. (2009).*

Boiler standards

ASME Code

A boiler explosion at the RB Grover shoe factory in Brockton near Boston in Massachusetts, USA killed 58 people and injured more than 150 in 1905. The explosion was so intense that parts of the equipment went through the floors and razed the four-story wooden building turning it into a crematorium. *Canavan, D.A. (2005).*

The Grover disaster triggered the formulation of the US National Boiler Code / Standard by the American Society of Mechanical Engineers (ASME), which governs the safe design, construction, operation, and maintenance of this equipment. Today, most national and international standards are based primarily on ASME boiler regulations. *Canavan, D.A. (2005). & Varrasi, J. (2011).*

Classification of pressure vessels according to ASME

As seen in Figure 1, according to ASME, vessels can be classified according to their intended service, service temperature and pressure, materials of construction, and geometry. *ASME. (s.f.).*

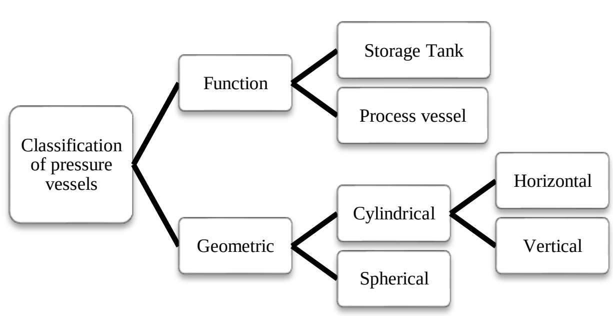


Figure 1 Classification of pressure vessels
Source: ASME. (s.f.).

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The objective of using design codes is to avoid catastrophes that can affect human beings. The main Code used in Mexico, USA and many other countries of the world, is the "CODE A.S.M.E. SECTION VIII, DIVISION 1". This Code is published on a triannual basis; 1980, 1983, 1986, 1989, 1992, 1995, etc. *León, J. M. (2001) and ASME. (s.f.).*

Official Mexican Standard NOM-020-STPS-2011

In Mexico, the Official Mexican Standard NOM-020-STPS-2011 indicates the safety conditions for pressure vessels, cryogenic vessels, and steam generators or boilers. The objective of this standard is to establish the safety requirements for the operation of said equipment in the workplace, to prevent risks to workers and damage to facilities. *STPS. (2011).*

Boiler classification according to STPS

The Official Mexican Standard NOM-020-STPS-2011 classifies the equipment depending on its capabilities, and these turn into categories (Table 1). In Mexico, it is necessary to notify the *Secretaría de Trabajo y Previsión Social* about the use of pressure vessels located in category III. *STPS. (2011).*

Categories	Pressure	Thermal capacity
II	Less than or equal to 490.33 kPa	Less than or equal to 1,674.72 MJ/hr
III	Less than or equal to 490.33 kPa	Greater than 1,674.72 MJ/hr
	Greater than 490.33 kPa	Any capacity

Table 1. Categories for steam generators or boilers
Source: STPS. (2011)

Training

The Official Mexican Standard NOM-020-STPS-2011 indicates that workers who carry out activities of operation, maintenance, repair, and pressure tests or non-destructive examinations, must receive theoretical-practical training. The boss or owner of the equipment may contract a type "C" verification unit to provide training to the personnel. *STPS. (2011).*

According to NOM-020-STPS-2011, a boiler operator must:

- Define and interpret concepts such as operating pressure, maximum allowable working pressure, calibration pressure, operating temperature, thermal capacity, drawings or plans of the equipment, the signaling system for equipment and pipes, measuring instruments, values of safe operating limits.

- Identify the characteristics of toxicity, flammability, and reactivity of the fluid or fluids handled in the equipment.

- Recognize and address the risks generated by the pressure and temperature of the fluids in the equipment.

- Maintain within the established value the operating limits of the equipment and of any pressure relief device or safety element, as well as those variables that may affect them.

- Apply the procedures for operation, review, maintenance, repair, alteration, and pressure tests or non-destructive examinations of the equipment, as applicable.

- Apply the review procedures for pressure relief devices, safety elements, and control instruments, as applicable, including emergency stop operations.

- Control changes in the operating conditions of the equipment and/or the fluids they handle.

Adequate compliance with the Mexican Official Standard NOM-020-STPS-2011, and international standards as the ASME Code, are indispensable to ensure safety in the work area. Those assigned to the boilers must be thoroughly familiar with their operations to avoid exposing themselves and others to the risk of accidents. However, these rules are often flaunted or violated while being implemented at the grassroots level. The public and private sectors using the industrial, utility, and commercial boilers must recognize that the role of these laws is not simply to regulate commercial and industrial activity but to prevent accidents, injuries, illnesses, and loss of property. *Akshoy, P. et al. (2018).*

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Accidents caused by boilers

Boiler explosions are very devastating, and many people die each year from these accidents. It occurs mainly due to the lack of training, awareness, and negligence of the industry owners, operators, and all management teams. Apart from these, there are some technical faults and over-operation in duty cycle or rated production. *Sharafat, A. et al. (2018).*

Specific reasons for boiler accidents

- Over pressurization of the equipment.
- Insufficient water in the boiler.
- Poor water treatment.
- Overheating and vessel failure.
- Improper construction or maintenance.
- Safety valve failure.
- Corrosion of critical parts of the boiler.
- Lack of trained personnel.

Recommendations for boiler safety

Proper maintenance, periodic inspection, and knowledge of boiler assistants and users make the equipment safer. In addition, managers must strictly follow the instructions below. *Akshoy, P. et al. (2018).*

- The boiler room must be surrounded by suitable fences.
- The equipment must operate with certified and efficient assistance.
- The water level in the boiler must be monitored.
- The set pressure of the safety valve must be checked periodically.
- The air-fuel ratio must remain stable.
- When starting the boiler, the greatest precautions must be taken.
- The color of the flame should be checked periodically.
- The treated water must be used as the boiler feed water.
- The equipment must be maintained periodically.
- The pressure gauge must not be defective and must be followed a periodic calibration.

New Technologies for accident prevention

The technical-commercial magazine *"Calderas…Guía del Usuario (en la industria y comercio)"* Year 1, No. 2, says it is currently developing the Caldera 4.0, named for the fourth industrial revolution (also called the intelligent revolution). The equipment consists of modern combustion control, which allows us to be expanded in stages and in which the boiler controls are included, incorporating measurements, calculations, and alarms. This will result in a high availability and security benefit. Teams are increasingly automated, and some tasks depend little on people, so human errors are reduced. It is difficult for accidents to disappear in their entirety, however, technology offers us advantages to prevent them. *Combustión, Energía & Ambiente, S.A. (2020).*

Sustainable Maintenance Plan

The Government of Mexico recognizes that climate change represents the main global environmental challenge of this century and has been a leader among developing countries with its progressive goals, objectives, and regulatory actions at the national and international levels. *Climate Action Reserve. (2016).*

A sustainable maintenance plan successfully implemented can help improve the efficiency of a boiler, in addition to supporting the fight against global warming. *Behzad M. et al. (2018).*

Before making a sustainable maintenance plan, it is necessary to carry out a sustainability assessment (Figure 2), which is an appropriate method that simultaneously integrates the economic, social, environmental, and technical aspects of a system throughout its life cycle.
Sala, S. et al. (2015). & Santoyo, E. et al. (2014).

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Selection of Indicators and Criteria

There are several indicators and criteria to assess sustainability. However, not all indicators may apply to a particular topic. Indicators must have meaning in the study area and must be measurable, reliable, and easy to understand by stakeholders. *Long, Y. et al. (2016).*

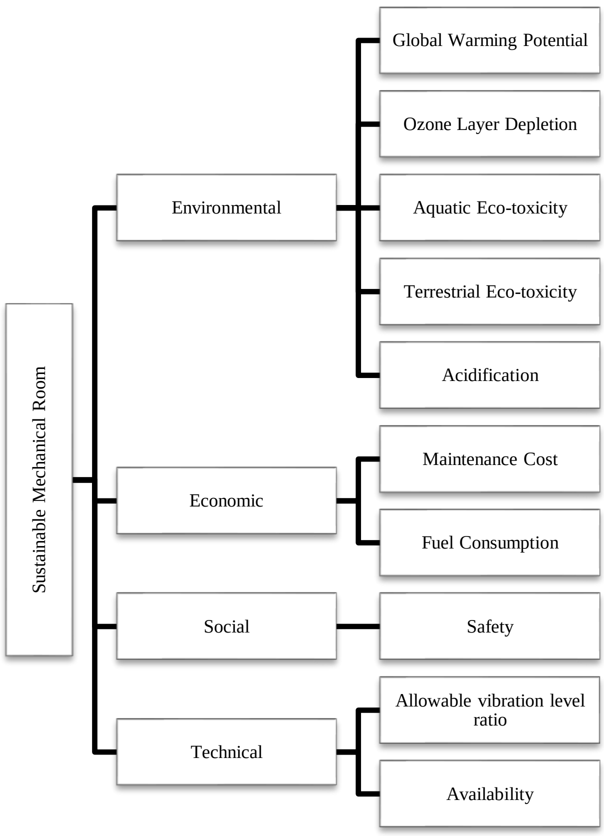

Figure 2 The general framework of indicators and criteria for evaluating sustainability
Source: Sala, S. et al. (2015). & Santoyo, E. et al. (2014)

Environmental Indicator

A boiler must comply with the established standards to avoid significantly damaging the environment because the energy inefficiency of the equipment can cause an additional amount of emissions of polluting substances such as Sulfur Dioxide (SO_2), Carbon Monoxide (CO), or Soot (C). *Uribazo, P. et al. (2006).*

Economic Indicator

In the economic indicator, two criteria must be considered, first, the cost of maintenance, which will depend on the company and the conditions in which it works. Second, the cost of fuel, in the case of boilers the best option is natural gas, which guarantees a cleaner ecosystem and lengthens the maintenance periods and useful life of this equipment, which also provides economic savings. *Colás, J. (2005).*

Social Indicator

In this indicator, social security stands out, to guarantee it, the established regulations must be complied with; In the case of Mexico, the Official Mexican Standard NOM-020-STPS-2011 indicates the safety conditions for the proper operation of pressure vessels. Personnel must be trained to carry out proper maintenance and this will ensure greater safety in the workplace. *STPS. (2011).*

Technical Indicator

The percentage of availability of the equipment is an indicator of the evaluation of the performance. Following formula (1) the availability of the system is obtained. *Mobley, R.K. (2002).*

$$Availability = \frac{\text{Required Availability} - \text{Downtime}}{\text{Required Availability}} \times 100 \qquad (1)$$

Few sustainability evaluation studies introduce the vibration index as one of the indicators. In the case of vibrations in the boiler, these can be caused by several possible reasons, which can be divided between chemical and mechanical factors. *Jasiński et al. (2016). & Mayyas et al. (2013).*

Results

A study by Behzad, M. et al. conducted in 2018 investigated the impact of such a modern program on various parameters for forms of sustainability in a boiler room, using methods such as monitoring and predictive maintenance. The evaluation consisted of four criteria, such as environmental, economic, social, and technical. The improvement of the indicators led to a positive change in sustainability during the period of operation. It was shown that the program can be successful in improving the performance of all criteria, especially, the social and technical aspects. The results were also promising for the overall evaluation. Monitoring techniques and predictive maintenance led to an improvement of at least 28% in the sustainability performance of the boiler room during use. *Masoud Behzad et al. (2018).*

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Discussion of results

According to the study by Behzad, M. et al. to implement a sustainable maintenance plan, based on social, environmental, technical, and economic aspects; it can be an alternative to increase the overall performance of the boilers, as well as to ensure the well-being of the personnel in the work centers. However, we should not underestimate other methods such as auditing to improve sustainability performance.

On the other hand, priority should be given to those methods that result in more improvement in the performance of the boiler, allow more safety, and reduce the emissions of polluting substances. Comparing these solutions could be a potential topic for further investigation. *Masoud Behzad et al. (2018).*

Conclusions

Industrial safety is very important, but it has clear deficiencies in Mexico, and it is evident with the number of annual accidents (approximately 500,000 since 2008). Mexico was the Latin American country with the most registered boiler explosions (6 in total) in 2019, even so, there is no exact statistical data in the country on explosions or accidents related to pressure vessels, because the majority of the industries keep the referred data and are not reported, therefore the number of accidents is higher than indicated. *IMSS. (2019). & Combustión, Energía & Ambiente, S.A. (2020).*

Safety Standards such as the ASME code or the Official Mexican Standard NOM-020-STPS-2011 particularly cover the performance of exams and the awarding of certificates of competence to boiler assistants and engineers. However, these rules are often ignored or violated while being implemented at the grassroots level. The function of these laws is not simply to regulate commercial and industrial activity but to prevent accidents in the workplace. *STPS. (2011). & Akshoy, P. et al. (2018).*

To carry out full compliance with national and international standards, the user of the boiler must have qualified personnel to manage the equipment, carry out regular checks on it and carry out predictive maintenance programs. *Akshoy, P. et al. (2018).*

An efficient way of working with boilers is through the implementation of sustainable maintenance, in which aspects such as environmental, economic, social, and technical impact must be considered. Operation and maintenance strategies help improve employee health and safety, protect the environment, and improve productivity. *Masoud Behzad et al. (2018).*

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Fault diagnostic proposal for an induction motor using combined models of parity equations

Propuesta de diagnóstico de fallas para un motor de inducción utilizando modelos combinados de ecuaciones de paridad

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Abstract

This work consists of a combined technique of two residual arrays for additive and parametric detection faults in a three-phase induction motor based on parity equations applied through a hybrid model with stable state behavior in the DQ reference frame. The main idea of this technique is to approximate the nonlinear model of induction motor to the linear model of DC motor, during the synchronous reference frame, with the intention of generating a significant change in the residues obtained by the combinations of parity equations in presence of faults. On the other hand, a more simplified and reliable analysis is used in the detection of the fault. Final mathematical analysis can be validated using a reliable simulation environment that enables interaction with power electronics, motor control, data analysis, numerical calculation, and dynamic system model design such as the software of PSIM or MATLAB.

Diagnostic, Fault detection, Induction motor

Resumen

Este trabajo consiste en una técnica combinada de dos matrices residuales para la detección de fallas aditivas y fallas paramétricas en un motor de inducción trifásico basadas en ecuaciones de paridad aplicada a través de un modelo hibrido con comportamiento en estado estable en el marco de referencia DQ. La idea principal de esta técnica es aproximar el modelo no lineal del motor de inducción al modelo lineal del motor de CD durante el marco de referencia sincrónico, con la intención de generar un cambio significativo en los residuos obtenidos mediante las combinaciones de las ecuaciones de paridad obtenidas en presencia de fallas, por otro lado, se utiliza un análisis más simplificado y confiable para la detección de la falla. El análisis matemático final se podrá validar utilizando un entorno de simulación confiable que permite la interacción con la electrónica de potencia, control de motores, análisis de datos, calculo numéricos y diseño de modelos de sistemas dinámicos como lo es PSIM o Matlab.

Diagnóstico, Detección de fallas, Motor de inducción

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Introducción

The induction motor IM is well known as the labor force in the industry. It is and will continue to be widely used in a great variety of application due to a great variety of factors such as low costs, simple construction, robustness and reliability (Kosow, 1993) Unlike the DC motor, the IM can be utilized in volatile or aggressive environments since sparks and corrosion pose no trouble at all respectively, although the degree of reliability tends to diminish under extreme working environment conditions which are greatly magnified when the IM operates with a critical load, a situation which could be a risk for the safety of the personnel, the environment and economy. Its use varies in industrial processes, and it can be frequently seen integrated in many critical processes (Krishnan, 2001).One way to raise the degree of reliability is through maintenance programs and specific attention by means of constant monitoring of the motor, with the objective of detecting faults and avoiding errors in the process (Isermann T. H., 1996).

Generally, the most frequent IM faults are of mechanical nature, and these are related with the electrical operation of the motor, such as overheating and inter-turn short circuit in stator winding (Chen, 2012). A fault in the motor components cause a waste of resources, materials and time, in addition it may turn into a risk of damage to other elements of the process, not to mention the possible effects on the integrity of the staff that coexists with the equipment (Isermann R. , 1995). The most common basic faults in IM are rotor faults, stator faults, and bearing faults to name a few, the latter is the most recurrent and carries with it the eccentricity effect that consists of the misalignment of the axis of rotation with respect to the axis of the machine (Loparo, 2000).

The relevance of motors in industrial processes has prompted a fairly broad field of research in the diagnostic area (Benbouzid, 1999), (Bachir, 2001). Various studies have sought a way to increase the reliability of the object of study from preventive maintenance using criteria and methodologies for control and supervision (Krause, 2002). A starting point to begin any type of study inherent to IM is to understand their operation and the elements that comprise it.

Currently, two main fault detection and diagnosis methods are used in induction motors; one is the method based on signal analysis and the other is the method based on parameter estimation (Krause, 2002). The merit of the parameter estimation method is that it is easier to identify or isolate faults; if the necessary parameters can be estimated online, then fault detection and diagnosis can be easily achieved. The merit of the method based on signal analysis proposed by Schoen (Schoen, 1995) is that it can be easily used for fault detection, but it is difficult to use for the isolation of faults in IM. Current spectrum analysis has gained more prominence in its use in the last few decades due to its low cost in comparison with the other two methods above mentioned (Loparo, 2000), (Mohamed El, 2000).

Vibration analysis is the most widely studied technique to detect faults in IM (Nandi, 2002) due to its significant magnitudes and the immunity to external phenomena such as electromagnetic interference in sensors like accelerometers, although the problem is the very limited operating range.

Another technique based in the model is the use of parity equations (Bouattour, 2000), (Isermann T. H., 1996) which can be adequate for the detection of a wide variety of faults, but for calculating the residuals of the general parity equation it is necessary to first obtain an accurate mathematical model of the system (Chen, 2012). This is mostly performed on linear systems, where precise model is more easily available.

The most susceptible part to faults are bearings, stator winding, engine bar and the axis. Faults can be classified as follows *electrical faults, mechanical faults, and environmentally-related faults* (Kosow, 1993).

A simple way to detect faults is to compare the behavior of the process signals to the signals of the model in its ideal state. Any existing differences between the process and the model are detected through a residual series in such a way that residuals oversee detecting faults that may exist during the process. The parity equation method goes after the probability with the formulation of the model in state-spaces.

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The proposal is to design and perform the physical modelling for the detection of faults in a three phase IM using a combination of the parity equations proposed in (Rodríguez, 2011) and (Chulines, 2018) and considering sensors to determine changes in the current, voltage and positioning in the IM. The residuals obtained through the parity equations will be implemented by using a test bank and the faults will be simulated through PSIM software.

In the Introduction section of this paper, it is highlighted the importance of IM in the industry, in addition to being the very core of the industry until today, it is also mentioned that there are techniques and methods for the detection of faults for preventive and corrective maintenance, to extend the lifetime of the IM. The current paper is developed based on one of the methods already described.

The Methodology section presents the IM modelling under the reference frame DQ, which describe the mechanical and electrical equations. The section continues to describe the residuals generation through the selected parity equations technique, as well as the operation thresholds in which these operate in fault-free conditions alongside the fault detection matrix for the DQ model. Next, it moves on to present the equations and residuals in the case of the stator model and the model combination is made to generate a combined detection table which gives as a result a better detection.

In the Conclusion section, considerations for the detection are presented as well as the references studied for this article.

Methodology

Fault diagnostic for the induction motor under the DQ reference frame

Usually, an IM is connected to an inverter to control the speed in various applications. However, there exists 'non-critical' applications in which it is only necessary to have a constant functioning in stationary state. In this sense, it is important to have a constant monitoring for a fault diagnostic in a synchronous IM.

Modelling of the induction motor under the DQ reference frame

The starting point for the analysis of the IM model under the synchronous reference frame is to initially deduce the transfer functions in the electrical and mechanical subsystem. For the electrical and mechanical pieces to be coupled, there exists a link between the current produced by torque and the induced magnetic force. This link is implicit in total current loop of IM and is independent from the mechanical part in the transfer function (Krishnan, 2001). The supposition for the deductions of the transfer functions applied to the IM is to consider constant the flux linkages in the rotor ψ_ry $p\psi_r = 0$.

Next, the stator equations are:

$$V_{qs} = (R_s + L_s\rho)i_{qs} + \omega_s L_s \rho i_{ds} + L_m \rho i_{qr} + \omega_s L_m i_{dr} \quad (1)$$

$$V_{ds} = (R_s + L_s\rho)i_{ds} - \omega_s L_s \rho i_{qs} + L_m \rho i_{dr} - \omega_s L_m i_{qr} \quad (2)$$

From these equations related to the rotor in the DQ axis from the flux linkages, the following equations in the stator currents are obtained.

$$i_{qr} = -\frac{L_m}{L_r} i_{qs} \quad (3)$$

$$i_{dr} = \frac{\psi_r}{L_r} - \frac{L_m}{L_r} i_{ds} \quad (4)$$

Substituting the rotor currents (3) and (4) in (1) and (2) the following expressions are obtained.

$$V_{qs} = (R_s + \sigma L_s \rho)i_{qs} + \sigma\omega_s L_s i_{ds} + \omega_s \frac{L_m}{L_r}\psi_r \quad (5)$$

$$V_{ds} = (R_s + \sigma L_s \rho)i_{ds} - \sigma\omega_s L_s i_{qs} + \frac{L_m}{L_r}\rho\psi_r \quad (6)$$

Where σ is the leakage coefficient and it is obtained when the flux component produced by the stator current is constant in steady state, so that the derivatives of the stator current in the *d* axis in the synchronous frame are:

$$i_f = i_{ds}$$

$$pi_{ds} = 0$$

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The total torque component produced by the stator current is the current in the q axis in the synchronous frame.

$$i_T = i_{qs}$$

It is also known that the rotor flux is given by:

$$\psi_r = L_m i_f$$

Substituting the values above in the stator voltage equation.

$$V_{qs} = (R_s + L_s\rho)i_T + \omega_s L_a i_f + \omega_s \frac{Lm^2}{L_r} i_f$$
$$= (R_s + L_s\rho)i_T + \omega_s L_a i_f \quad (7)$$

Where L_a is:

$$L_a = \sigma L_s = \left(L_s - \frac{Lm^2}{L_r}\right) \quad (8)$$

Now, the stator frequency is represented by:

$$\omega_{s1} = \frac{i_T}{i_f}\left(\frac{R_r}{L_r}\right)$$

$$\omega_s = \omega_r + \omega_{s1} = \omega_r + \frac{i_T}{i_f}\left(\frac{R_r}{L_r}\right) \quad (9)$$

The equation for the motor electrical part can be obtained substituting ω_s in (2).

$$V_{qs} = \left(R_s + \frac{R_r L_s}{Lr} + R_a\rho\right) i_T + \omega_r L_s i_f \quad (10)$$

When the torque is produced by the stator current it can be derived from the following equation.

$$I_T = \frac{V_{qs} - \omega_r L_s i_f}{R_s + \frac{R_r L_s}{L_r} + L_a\rho} = \frac{K_a}{1 + sT_a}\left(V_{qs} - \omega_r L_s i_f\right) \quad (11)$$

Where:

$$R_a = R_s + \frac{L_s}{L_r} R_r \qquad K_a = \frac{1}{R_a} \qquad T_a = \frac{L_a}{R_a}$$

For this section, the feedback voltage is converts to the torque current, then the electromagnetic torque is written:

$$\tau_e = K_f i_T \quad (12)$$

Where the torque constant is defined by

$$K_f = \frac{3}{2}\frac{P}{2}\frac{Lm^2}{L_r} i_f \quad (13)$$

Dynamic loads can be represented taking the electromagnetic torque and the load torque that is considered friction, in this particular case.

$$j\frac{d\omega_m}{dt} + B\omega_m = \tau_e - \tau_L = K_f i_T - B_l \omega_m \quad (14)$$

When in terms of the electric velocity of the rotor, it is derived from the multiplication of both sides by the pair of poles

$$j\frac{d\omega_r}{dt} + B\omega_r = \frac{P}{2} K_f i_T - B_l \omega_r \quad (15)$$

Next, the transfer function between velocity and produced torque.

$$\frac{\omega_r(s)}{I_T(s)} = \frac{K_a}{1 + sT_a} \quad (16)$$

Where

$$K_a = \frac{P}{2}\frac{K_f}{B_t}, \qquad B_t = B + B_l, \qquad T_a = \frac{J}{B_t}$$

Once the electrical and mechanical parts of the IM are solved from equations (7) and (8), the block diagram is obtained in the following drawn:

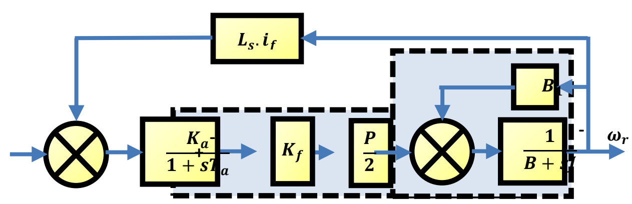

Figure 1 Block diagram of the IM model with rotor flux constant linkage
Source: R. Krishnan, Electric Motor Drives Modeling, Analysis and Control. Prentice Hall, 2001

This model is like the DC motor model shown in (Chan, 2006) and (Isermann T. H., 1996), the main difference is that this model takes V_{qs} as input parameter rather than the armature current I_A.

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Residuals generation through parity equations

The present work makes use of a simple model of instantaneous computation in steady state mode which has little similarity to the DC motor (Krishnan, 2001) since the fault detection based on parity equations for this type of model is the availability to detect various parameters (Chan, 2006).

Based on known ways of theoretically modeling the structure of a linear mathematical model in continuous time without taking into account the perturbations (17) and (18), the representation of the state-space model obtained for the IM is shown in (19) and (20).

$$\dot{\mathbb{x}}(t) = \boldsymbol{A}\mathbb{x}(t)\mathbb{u}(t) \quad (17)$$

$$\mathbb{y}(t) = \boldsymbol{C}\mathbb{x}(t) \quad (18)$$

$$\begin{bmatrix} \dot{I_{qs}} \\ \dot{\omega_r} \end{bmatrix} = \begin{bmatrix} \frac{-R_a}{L_a} & \frac{-\psi}{L_a} \\ \frac{K_t N_p}{J} & \frac{-(B+B_1)}{J} \end{bmatrix} \begin{bmatrix} I_{qs} \\ \omega_r \end{bmatrix} + \begin{bmatrix} \frac{1}{L_a} & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} V_{qs} \\ 0 \end{bmatrix} \quad (19)$$

$$\mathbb{y}(t) = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} I_{qs} \\ \omega_r \end{bmatrix} \quad (20)$$

Where:

$$\psi = L_s I_{ds}, \qquad N_p = \frac{P}{2} \quad (21)$$

It should be taken into account that the structure obtained in (19) is similar to the DC motor model shown in (Chan, 2006) and (Isermann T. H., 1996) but it is not the same. An important difference is that the second input term $\dot{I_{qs}}$ in (19), the magnetic flux is defined as the relationship between the stator inductance and the stator current $\psi_s L$ of the D axis in the I_{ds} synchronous frames. Another important difference is that the first term of ω_r, the magnetic flux ψ, the motor model is defined as the ratio between the number of poles P, the magnetic inductance L_m, the rotor inductance L_r and the current flux producing component of the stator I_f.

One way to add redundancy in the equations in the instant t is introducing (17) in (18) with their respective derivatives as:

$$\boldsymbol{Y}(t) = \boldsymbol{T}\mathbb{x}(t) + \boldsymbol{QU}(t) \quad (22)$$

Where:

$$\begin{bmatrix} y(t) \\ \dot{y}(t) \\ \ddot{y}(t) \\ \vdots \\ y^q(t) \end{bmatrix} = \begin{bmatrix} \boldsymbol{C} \\ \boldsymbol{CA} \\ \boldsymbol{CA^2} \\ \vdots \\ \boldsymbol{CA^q} \end{bmatrix} \mathbb{x}(t) + \begin{bmatrix} 0 & 0 & 0 & \dots & 0 \\ \boldsymbol{CB} & 0 & 0 & \dots & 0 \\ \boldsymbol{CAB} & \boldsymbol{CB} & \boldsymbol{CB} & \dots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ \boldsymbol{CA^{q-1}B} & \boldsymbol{CA^{q-2}B} & \dots & \boldsymbol{CB} & \boldsymbol{0} \end{bmatrix} \begin{bmatrix} u(t) \\ \dot{u}(t) \\ \ddot{u}(t) \\ \vdots \\ u^q(t) \end{bmatrix} (t) \quad (23)$$

Now the residual vector based on the state-space model for continuous time is given in (24), which is deduced in (Isermann T. H., 1996) from the residual generation with parity equations for the MIMO process with transfer functions and polynomial error.

$$\boldsymbol{r}(t) = \boldsymbol{WY}(t) - \boldsymbol{WQU}(t) \quad (24)$$

An important condition to satisfy both the first and second terms of (24) is that the sum is equal to zero, then $\boldsymbol{W}T = 0$ (Isermann T. H., 1996), where $\boldsymbol{W}$ is called the null space of T and can be obtained by proposing as many zeros as possible in the rows, taking into account that the lines are linearly independent. In our case study the matrix W obtained by the induction motor is (25):

$$\boldsymbol{W} = \begin{bmatrix} R_a & \psi & L_a & 0 & 0 & 0 \\ -\alpha & \beta & 0 & J & 0 & 0 \\ \gamma & 0 & \delta & 0 & JL_a & 0 \\ 0 & \gamma & 0 & \delta & 0 & JL_a \end{bmatrix} \quad (25)$$

Where:

$$\alpha = K_t N_p, \qquad \beta = B + B_1 \quad (26)$$

$$\gamma = \psi\alpha + R_a\beta, \qquad \delta = L_a\beta + JR_a$$

By the assumption in the operation in healthy state the parameter does not change, $r(t) = 0$, then, a fault is detected when $r(t) \neq 0$. The residuals obtained by the MI are:

$$r_1(t) = R_a I_{qs}(t) + \psi\omega_r(t) + L_a \dot{I_{qs}}(t) - V_{qs}t$$
$$r_2(t) = -\alpha I_{qs}(t) + \beta\omega_r(t) + J\dot{\omega_r}(t)$$
$$r_3(t) = \gamma I_{qs}(t) + (L_a\beta + JR_a)\dot{I_{qs}}(t) + JL_a\ddot{I_{qs}}(t) - \beta V_{qs}t - J\dot{V_{qs}}(t) \quad (27)$$

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It must be taken into account that during the operation on steady-state the derivative of $x(t)$ is zero, and $V_{qs}t = V_{qs}$, therefore, the residual can be simplified, this is suitable when the type of fault is incipient; taking into account that it is the most common fault in electrical machines, then residual equations can be reduced in the following way:

$$
\begin{aligned}
r_4(t) &= \gamma\omega_r(t) + [L_a\beta + JR_a]\dot{\omega_r}(t) \\
&\quad + JL_a\ddot{\omega_r}(t) - \alpha V_{qs} \\
r_1(t) &= R_a I_{qs}(t) + \psi\omega_r(t) - V_{qs} \\
r_2(t) &= -\alpha I_{qs}(t) + \beta\omega_r(t) \\
r_3(t) &= \gamma I_{qs}(t) - \beta V_{qs} \\
r_4(t) &= \gamma\omega_r(t) - \alpha V_{qs}
\end{aligned} \tag{28}
$$

Likewise, like the D.C motor (Isermann, 1996), if an additive fault occurs, all the residuals except decoupling are diverted as shown in table 1. This is compatible to locate faults in the sensor and therefore this type of fault is easily detectable. When a parametric error occurs in R_s or R_r there is no considerable increase in $R3$, therefore, a null value can be considered to simplify the error detection matrix. In the other hand, a simple way to distinguish the fault is by using classic current detectors in the stator current, with limit values with an adequate tuning, considering the behavior in the Fig. 2.

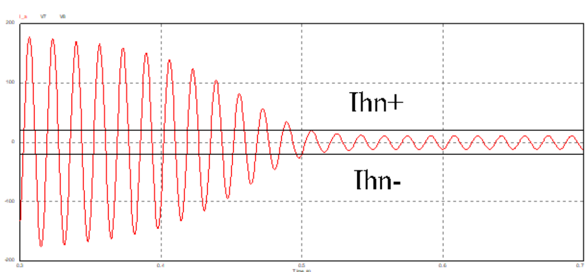

Figure 2 *Limit thresholds in IM nominal current.*
Source: Own design

The limit values of the thresholds are tuning by the “health condition” of the induction motor, the threshold is set close to the nominal current.

$$
f_n = \begin{cases} 1 \rightarrow & I_n > Ih_{n+} \\ 1 \rightarrow & I_n < Ih_{n-} \\ 0 \rightarrow & Ih_{n-} > I_n > Ih_{n+} \end{cases}
$$

Where:

n represents the phases a, b, or c.

f_n represents the faults in phases a, b, or c.

I_n is the current in phases a, b, or c.

$Ih_n +$ is the threshold of the current in phases a, b, or c.

$Ih_n -$ is the threshold of the current in phases a, b, or c.

Table 1 shows the parameters associated with the diagnosis of electrical faults in the induction motor model using the parity equations based on the DQ reference frame for their linearization. However, this information does not identify the damaged phase, associated with the electrical parameter.

Faults		R_1	R_2	R_3	R_4
parametrical	R_s	I	0	0	I
	R_r	I	0	0	I
	L_s	I	0	I	I
	L_r	I	I	I	I
	B	0	I	I	I
	B_l	0	I	I	I
Additi ve	$i_{qs}{}^e$	I	I	I	0
	ω_r	I	I	0	I
	$V_{qs}{}^e$	I	0	I	I

Table 1 Fault detection matrix on DQ reference frame
Source: Own design

Where “I” represents a significant change which can be positive or negative.

An easy way to validate the good performance of the fault detection technique proposed as the simplified IM model during steady state is through simulations software PSIM, which contains availability for parametric variation of the IM model (Rodríguez, 2011).

Since there is a relatively large change in the residual set obtained when an additive or incipient fault occurs, it is not necessary to use diagnostic methods to locate the fault, which simplifies the IM supervision, since the MI model is like the DC model, the analysis makes it possible to ensure the existence of a parity space, and therefore, obtain the advantages of fault detection for this type of system.

In order to interpret I_{qs} and a simple algebraic equation, The Park transform is sufficient to develop the mathematical algorithm for the fault detection system.

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The technique proposed by (Hernández López, junio 2011) considers that the V_{qs} value is equal to the RMS value of the stator voltage V_s. In this way, only the current and speed sensors are used.

Although this information does not identify the damaged phase associated with the electrical parameter, it tends to analyze the stator currents phase to accurately identify the damaged parameter (Chulines, 2018).

Parity in the three-phase induction motor model.

The state space representations from the electrical equations of the IM are:

$$\dot{x}(t) = Ax(t) + Bu(t) \quad (29)$$

$$y(t) = Cx(t) \quad (30)$$

$$\begin{bmatrix} \dot{I}_s \\ \dot{I}_r \end{bmatrix} \begin{bmatrix} -L_s^{-1}R_s & -L_s^{-1}\dot{M} \\ -L_r^{-1}\dot{M}^T & -L_r^{-1}R_r \end{bmatrix} \begin{bmatrix} I_s \\ I_r \end{bmatrix} \begin{bmatrix} L_s^{-1} & 0 \\ 0 & L_r^{-1} \end{bmatrix} \begin{bmatrix} V_s \\ V_r \end{bmatrix} + \begin{bmatrix} -L_s^{-1}M & 0 \\ 0 & -L_r^{-1}M^T \end{bmatrix} \begin{bmatrix} \dot{I}_r \\ \dot{I}_s \end{bmatrix} \quad (31)$$

In extended form

$$\dot{I}_s = -L_s^{-1}R_sI_s - L_s^{-1}\dot{M}I_r + L_s^{-1}V_s - L_s^{-1}M\dot{I}_r \quad (32)$$

$$\dot{I}_r = -L_r^{-1}\dot{M}^TI_s - L_r^{-1}R_rI_r + L_r^{-1}V_r - L_r^{-1}\dot{M}^T\dot{I}_s \quad (33)$$

Assuming only the behavior in steady state, it can be considered that $I_r = 0$, so the previous expressions are reduced to the following equations:

$$\dot{I}_s = -L_s^{-1}R_sI_s + L_s^{-1}V_s \quad (34)$$

$$0 = -L_s^{-1}\dot{M}^TI_s - L_r^{-1}M^T\dot{I}_s \quad (35)$$

Therefore, the equations affect the stator as follows:

$$\dot{x} = \dot{I}_s = \begin{bmatrix} \dot{I}_{sa} \\ \dot{I}_{sb} \\ \dot{I}_{sc} \end{bmatrix} \quad (36)$$

$$A = -[L_s]^{-1}[R_s] \quad (37)$$

$$B = [L_s]^{-1}$$

And the output of the system is $y = C_x$:

$$y = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \dot{I}_{sa} \\ \dot{I}_{sb} \\ \dot{I}_{sc} \end{bmatrix} \quad (38)$$

applying parity, a ω^T must be determined that satisfies the isolation of parameters of the equation

$$r(t) = \omega^T Y(t) - \omega^T Q_u U(t)$$

$$[\omega_{i1}^T \quad \omega_{i2}^T \quad \omega_{i3}^T] \begin{bmatrix} C \\ CA \\ CA^2 \end{bmatrix} = 0 \quad (39)$$

To search for vectors that satisfy the desired structure, the following must be fulfilled:

$$\omega_{i1}^T C \quad \omega_{i2}^T CA \quad \omega_{i3}^T CA^2 = 0 \quad (40)$$

As the matrix C is equal to an identity in order to take physical measurements directly from the stator currents, then the equations of the residuals are as follows:

$$\omega_{i1}^T C = \omega_{i2}^T CA + \omega_{i3}^T CA^2 \quad (41)$$

$$\omega_{i2}^T C = \omega_{i1}^T C + \omega_{i3}^T CA^2 \quad (42)$$

$$\omega_{i3}^T CA^2 = \omega_{i1}^T C + \omega_{i2}^T C2 \quad (43)$$

To find each of the residuals, the ω^T of the equations was proposed to be insensitive to the changes in the associated parameters for each of the phases of the stator in the IM, the results of the behavior of the residuals for each of the stator phases can be seen in table 2.

Parametric faults	R_1	R_2	R_3
R_{sa}	I	0	0
R_{sb}	0	I	0
R_{sc}	0	0	I
L_{sa}	I	0	0
L_{sb}	0	I	0
L_{sc}	0	0	I

Table 2 Fault detection matrix limited to IM stator phases
Source: (Chulines, 2018)

For the diagnosis of the DQ model, as it is like the electrical model of the MI, it provides a system similar to DC motor. Once a W matrix is obtained, it is possible to determine the residuals and check its insulation flexibility.

Full fault detection

To carry out a more complete fault diagnosis for a particular object of study, it is important to correctly detect the symptoms that the system is possibly presenting.

In this sense, after a detailed analysis of the IM fault detection system in (Rodríguez, 2011) and (Chulines, 2018) both techniques can be combined to be more accurate about the type of fault in the system therefore improving the life cycle of the motor.

As mentioned before, the combination of these two techniques complements each other since in (Rodríguez, 2011) faults have a 50 % margin of error in the DQ model in which the faults of the margin of error were parametric, (Chulines, 2018) does the same to determine the faults, but in each phase of stator currents and thus complement the detection of parametric faults in the MI of this combined system, resulting in a more complete detection system.

Table 3 shows the residuals obtained through the parity equations based on DQ model. In this matrix the failures in R_s and L_s are highlighted because the damaging phase cannot be identified. In this sense, table 4 shown the residues corresponding to the damaged phases related to the failures of R_s and L_s obtained through the parity equations based on stator model. So, the system provides us with better detection, and it is known exactly the damaged phase, giving the opportunity to apply preventive or corrective maintenance post-fault.

DQ model					
	Faults	r_1	r_2	r_3	r_4
Parametric	R_s	I	0	0	I
	R_r	I	0	0	I
	L_s	I	0	I	I
	L_r	I	I	I	I
	B	0	I	I	I
	B_l	0	I	I	I
Additive	i_{qs}^e	I	I	I	0
	ω_r	I	I	0	I
	V_{qs}^e	I	0	I	I

Table 3 Fault detection matrix with parity equations witch DQ models.
Source: Own design

Stator model				
Faults	r_1	r_2	r_3	Insolation Faults
R_s	I	0	0	R_{sa}
	0	I	0	R_{sb}
	0	0	I	R_{sc}
	I	I	0	R_{sa}, R_{sb}
	I	0	I	R_{sa}, R_{sc}
	0	I	I	R_{sb}, R_{sc}
	I	I	I	R_{sa}, R_{sb}, R_{sc}
L_s	I	0	0	L_{sa}
	0	I	0	L_{sb}
	0	0	I	L_{sc}
	I	I	0	L_{sa}, L_{sb}
	I	0	I	L_{sa}, L_{sc}
	0	I	I	L_{sb}, L_{sc}
	I	I	I	L_{sa}, L_{sb}, L_{sc}

Table 4 Fault detection matrix with parity equations with stator models bases on faults in R_s and L_s
Source: Own design

The result presented in table 3, clearly show that detection is now capable of identifying the damaged phase unlike the model based on the DQ reference frame. In addition, the residuals obtained through the stator model add additional symptoms which enhance the detection of other parameters such as current and voltage in each of the IM phases. So, now you can have simultaneous multiple fault detection of R_s and L_s as shown in table 4.

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Conclusions

Since the induction motor model can be matched with the DC motor model, the analysis makes it possible to ensure the existence of the parity space and, therefore, obtain the advantages of the fault detection for this type of system. In this way, it is convenient to heuristically consider a diagnostic dead time from the beginning and fixed current thresholds, according to the stabilization time and from the input nominal current respectively. By adding a pair of fixed thresholds to the residual of stator and using table 3, it is possible to detect the parametric and additive faults, as well as the insolation of each of the affected phases for L_s and R_s respectively.

The Park transform and simple algebraic equations it is enough to develop the mathematical algorithm of proposed detection system which can be easily implemented in any digital processor since the operators are addition, subtraction, and multiplication. This combined detection system is the most feasible option due to its short response time and at the same time the system can be improved for greater precision in the future.

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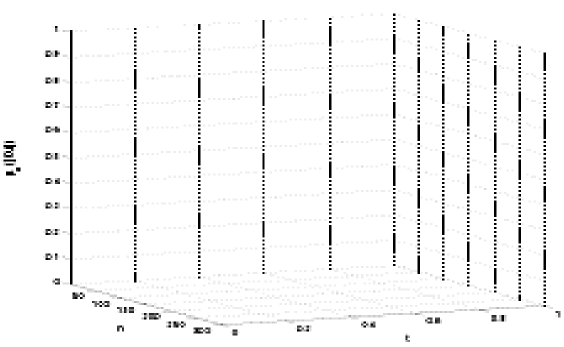

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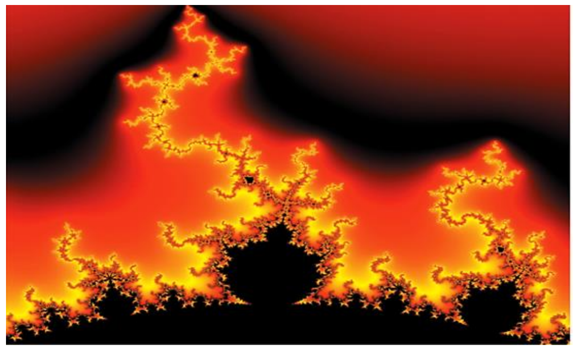

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