**Article** **Journal of Quantitative and Statistical Analysis**
June, 2023 Vol.10 No.26 1-21

# Factors repeatability and reproducibility in the thickness of the non-magnetic coating

# Factores de repetibilidad y reproducibilidad en el espesor del recubrimiento no magnético

RAMÍREZ-ROMÁN, Adolfo†*, CHABAT-URANGA, Jacqueline, RODRÍGUEZ-RODRÍGUEZ, Luis Alberto and SUÁREZ-ÁLVAREZ, Ángel

*Universidad Veracruzana, Facultad de Ingeniería Mecánica y Ciencias Navales*

ID 1st Author: *Adolfo, Ramírez-Román* / **ORC ID**: 0000-0002-3820-8582, **Researcher ID Thomson**: S-5868-2018, **CVU CONAHCYT ID**: 244749

ID 1st Co-author: *Jacqueline, Chabat-Uranga* / **ORC ID** 0000-0003-2202-1032, **CVU CONAHCYT ID**: 464993

ID 2nd Coauthor: *Luis Alberto, Rodríguez-Rodríguez* / **ORC ID** 0000-0002-6118-040X, **CVU CONAHCYT ID**: 1011993

ID 3rd Co-author: *Ángel, Suárez-Álvarez* / **ORC ID** 0000-0002-0726-9630, **CVU CONAHCYT ID**: 946964

**DOI**: 10.35429/JQSA.2023.26.10.1.21 Received March 14, 2023; Accepted June 29, 2023

**Abstract**

The present experimental research refers to an-R&R study with the use of non-magnetic coating thickness measuring equipment on metal plate surface type analyzing the results in software that allows to demonstrate the reliability of measurements by the quality inspectors, using the intentional non-probabilistic sampling technique, choosing one piece per batch. An important study through equipment to measure non-magnetic coating on ferrous material parts, which allows to determine the effectiveness of the company through the measurement and control of specifications required by standard, detecting areas of opportunity in the process (the measurement system fails with operators or equipment failure or coating variability on the part). Therefore, each piece analyzed is described with its numerical data of thickness measurements through tables and graphs. By which, allows to compare the competencies of the staff according to the type of material and the work environment where each experimental study was developed.

**Operators, Variability, Experimental**

**Resumen**

La presente investigación experimental hace referencia a un estudio R&R con el uso de equipos de medición de espesor del recubrimiento no magnético en superficie de tipo placa metálica analizando los resultados en software que permita demostrar la confiabilidad de las mediciones por los inspectores de calidad, utilizando la técnica de muestreo no probabilístico intencional, eligiendo una pieza por lote. Un estudio importante a través de los equipos para medir el recubrimiento no magnético en piezas de material ferroso, que permite determinar la efectividad de la empresa a través de la medición y control de las especificaciones requeridas por norma, detectando áreas de oportunidad en el proceso (el sistema de medición falla con los operadores o falla de equipo o variabilidad del recubrimiento en la pieza). Por lo tanto, se describe cada pieza analizada con sus datos numéricos de medidas de espesor a través de tablas y gráficos. Por el cual, permite comparar las competencias del personal de acuerdo con el tipo de material y con el ambiente laboral donde se desarrolló cada estudio experimental.

**Operadores, Variabilidad, Experimental**

**Citation:** RAMÍREZ-ROMÁN, Adolfo, CHABAT-URANGA, Jacqueline, RODRÍGUEZ-RODRÍGUEZ, Luis Alberto and SUÁREZ-ÁLVAREZ, Ángel. Factors repeatability and reproducibility in the thickness of the non-magnetic coating. Journal of Quantitative and Statistical Analysis. 2023. 10-26: 1-21

* Correspondence to Author (e-mail: adolramirez@uv.mx)
† Researcher contributing as first author.

## 1. Introduction

An experimental study comprising ten 120-liter stationary LP gas tanks, seven steel beams and sixty-two "Y" type angles.

The thickness of the galvanized coating determines the quality of the piece, the thicker it is, the higher the quality will be, according to ASTM A123/A123M, the minimum thickness is 1.4 thousandths of an inch (the galvanized coating is usually between 1.4 and 3.9 thousandths of an inch), depending on the grade of the galvanized coating. 9 thousandths of an inch), depending on the grade of coating applied and also taking care of the customer's own specifications as some require more or less thickness; and according to ISO 2063-1:2018 for metallized coating or galvanized by thermorrhosted (thermal spraying), the recommended minimum thickness of metallized is 2.5 thousandths of an inch extending up to 14 thousandths of an inch.

The systematic measurement of coating thickness controls material costs, rework or rework of the part, manage the efficiency of the application and also the fulfillment of contracts made with customers.

## 2. Description of the research

The area of study involves the infrastructure of the Hot Dip Galvanizing production line involving Production and the head of the quality department, to select the parts to be inspected according to the batch size by number of parts.

The process consists of immersing the part in a vat-crisol with molten zinc, thus forming a protective layer of Zinc-Iron alloy, the thickness of the part depends on factors such as chemical composition, geometry, design, surface condition, and others by the zinc coating.

Also, the metallizing process, in collaboration with production and the head of the quality department, selects the parts to be inspected according to the size of the lot by number of pieces or by quantity of square meters as considered. The metallizing wire used consists of an alloy of 85% zinc and 15% aluminum.

Thermal sputter plating coats steel and other metal parts by supersonic spraying of molten microdroplets of zinc, aluminum and zinc-aluminum alloys using a gas or electric gun.

The non-magnetic coating thickness measuring equipment on ferrous substrate (Positector 6000) is used to obtain the thickness of the galvanized or metallized coating. The operators will take their respective readings on the same selected points on the part and average the measurements, and a different piece of equipment is used on each production line.

As software, Minitab, an R&R study worksheet of the measurement system is created, once the worksheet is created, the name of each operator and the number of times the measurements will be taken on the selected parts are entered. Subsequently, the thickness measurements obtained by each of the operators in charge of the measurement are recorded and the R&R study is performed, in this case the crossed system will be selected since the thickness measurements by magnetic induction will not destroy the parts and these will be used for other tests. And as a reference for coating thickness tests, we have the development of the analysis of the influence of parameters in magnetic tests (Syasko *et al.*, 2020).

A 50 cm x 50 cm steel plate of 5/16" thickness is used, metallized on one side, where half of the plate is only metallized and the other half has a sealant (vinyl epoxy coating), for its protection and to delay its reaction with the environment.

The use of this plate is for a representation of an ideal case where reference areas of 1 $dm^2$ can be traced, within each reference area five squares of 1 $cm^2$ are traced, in these squares 3 measurements are taken and the average of each of the squares is obtained, this for the thickness measurement as indicated by ISO 2063-1: 2018 (for plating application), and five circles of 4 cm in diameter where three punctual measurements will be taken and the average of each of the drawn circles is obtained as indicated in the SSPC-PA2 standard (for application of sealer type paint).

ISSN 2410-3438

As certified coated metal plates, they are used to verify the accuracy and performance of coating thickness gauges and are an important component in meeting the quality control requirements of the company's standardized requirements. These plates are DeFelsko branded and have a package of 4 round bases each coated with a different thickness, the plates are ideal for the verification of the Positector 6000, the equipment used in the project.

The sample used was a stationary LP gas tank of 120 liters, horizontal model and with an area of 1.7 $m^2$. In this tank, 20 thickness measurements were taken and the average thickness was obtained in thousandths of an inch.

As a structural sample, a "Y" type angle of ¼" x 1 ½", which will be taken to measure in a specimen according to ASTM 123/A123M-17 standard.

Also, a beam measuring 14" x 8" x 12.20 m, which will be analyzed in representation of thickness measurement for a multi-specimen item as per ASTM 123/A123M-17.

## Methodology

The stages of the R&R study for non-magnetic coating thickness gauges on ferrous substrates is indicated in Figure 1, and its respective description of each element (Otzen & Manterola, 2017), consists of:

a) Selection of two operators.
b) Determination of a significant number of pieces to be measured according to the batch size.
c) Random selection of parts from the batch.
d) Recording of galvanized and metallized thickness measurements with the measuring equipment on the selected parts.
e) Recording of the data obtained in the software.
f) Analysis of the tables and graphs.
g) Development of the conclusions of the study.

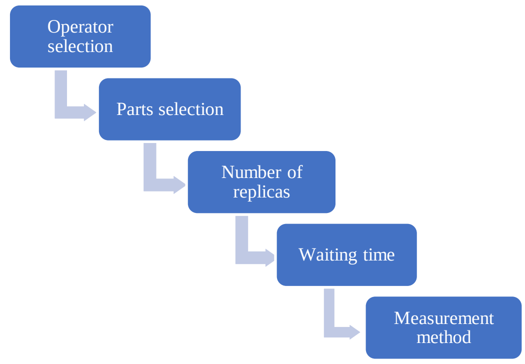



**Figure 1** Methodology scheme
*Source: Own Elaboration*

In the selection of operators, the study site has a crew of 4 quality inspectors, by production are distributed in each shift, therefore, the present study includes results of four, three or two quality inspectors, who constantly take the thickness of both the galvanized or metallized area, for the measurement of the thickness of each of the parts selected in a random order, and validation of the measurement system.

In the software "Minitab" the ANOVA method will be used for the statistical analysis of the measurement system will be executed with a total of three replicates, i.e., each operator must obtain the total thickness of the selected parts on three occasions.

The waiting time between each replicate is 20 minutes, so that the operator does not remember the previous results and generate reliable data.

Laboratory measurement: It is considered necessary to first analyze the equipment at laboratory level for the metallized area due to the conditions that present the piece and that make impossible the measurement by the method mentioned in the ISO 2063-1: 2018 and SSPC-PA2 standards, the sample is a steel plate with dimensions of 50x50 cm, metallized on one side and coated with sealant in the middle.

In the metallized area of the plate, the average thickness of each of the reference areas is analyzed and in the area with sealant, the average thickness of each reference circle is analyzed, each circle or reference area has a diameter of 4 cm, and 3 point measurements are performed for averaging.

ISSN 2410-3438

Article Journal of Quantitative and Statistical Analysis
June, 2023 Vol.10 No.26 1-21

Field measurement: In the plating production line, a stationary LP gas tank was used as a sample, with 20 thickness measurements, in 3 repetitions in the metallized section only and with sealer.

In the galvanizing production line, the measurement method is through the ASTM A123/A123M-17 specification. Pieces with an area equal to or less than 160 $in^2$ (100,000 $mm^2$) will be considered as single specimen items and items larger than 160 $in^2$ (100,000 $mm^2$) will be divided into three specimens and considered as multi-specimen.

**Representation of results**

Each R&R study contains the following tables and graphs generated by Minitab:

- Tables
- Two-factor ANOVA table with interaction.
- Two-factor ANOVA table without interaction (obtained depending on whether the interaction value is considered significant or not).
- Variance components table.
- Measurement system evaluation table.

**Graphs**

- Variance components chart
- Graph of ranges by Operators.
- Graph of x¯bar by Operators.
- Thickness plot by Parts
- Thickness plot by Operators
- Parts * Operators interaction graph

As acceptance parameters, in statistical process control (SPC), if it is a total variation of less than 10% the measurement system will be considered acceptable, between 10% and 30% can be considered acceptable and the decision to use it will depend on several factors such as the cost of the measurement instrument, cost of instrument repair, cost of training, etc., and for a percentage of more than 30% the system is unacceptable and it is required to identify and correct the problem.

**Interpretation of variables / formulas**

The sum of squares (SS) is the sum of the squared distances and represents a measure of the variability that is caused by different sources.

The $SS_{total}$ indicates the variability of the data obtained from the overall mean and is interpreted as follows:

$$SS_{total} = SS_{part} + SS_{operator} + SS_{operator\ x\ part} + SS_{equipment} \quad (1)$$

Degrees of freedom (DOF), which is used to measure how much information is available for each SC (sum of squares).

Mean squares (MS), which represents variability in the data caused by different sources and the fact that these different sources have different values.

$$CM = MS/DOF \quad (2)$$

The statistic (F), which is used to determine whether the operator, part or operator* part effects are significant. The larger the value of the F statistic the more likely the factor is to contribute to the variability in the response.

The P-value is the probability of obtaining an F-statistic.

If $P < \alpha$, then at least one mean is statistically different.

If $P > \alpha$, then the means are not significantly different.

The variance components (CompVar), obtained from each source in an ANOVA table. If the greatest amount of variation is between repeatability and/or reproducibility, the problem should be investigated and corrective action taken.

The percentage of the total variation (%Contribution (from CompVar), which corresponds to each component of the variance. If the greatest amount of variation is between repeatability and/or reproducibility, the problem should be investigated and corrective action taken.

**Standard deviation for each source of variation (Std. Dev. SD)**

The study variation (Study Var.; 6 x SD), is calculated with the standard deviation multiplied 6 times. It is usually defined as 6s denoted by σ or sigma.

ISSN 2410-3438

The percent variation (%Var. Study; %VE), of the study is calculated as the standard deviation for each variation, divided by the total variation and multiplied by one hundred.

%VS = (SD / Total variation) $x$ 100 (3)

It is used to compare the variation of the measurement system with the total variation. The number of distinct categories is a metric used in measurement system R&R studies to identify the ability of a measurement system to detect a difference in the measured characteristic, the recommended number of distinct categories is 5.

**Background of R&R studies**

The paper "Repeatability and Reproducibility in Steel Pipe Thickness Measurements for Ferroproduct" presents a cross-type R&R analysis (for non-destructive testing) to study the system used to measure the thickness of steel pipes used by the company. The objective of the study was to determine if the measurements made by the team of four inspectors were accurate.

The results obtained determined that the main source of variation was the steel pipes, and also showed that the measurement system used was unacceptable and should be corrected, since the index of the Gage R&R gauge was 31.75% when the maximum allowed is 30% (Escamilla, et al., 2020).

As in the case of measurement uncertainty in the measurement operations of a laboratory. It is indicated in literature that, under conditions of Repeatability is understood as the closeness of agreement between the results of successive measurements of the same measurand under the same measurement conditions, which include the same measurement procedure, the same observer, the same measuring instrument, used under the same conditions, the same place and with repetition in a short period of time. And, the reproducibility of the method can be estimated on the basis of results obtained when it has been used to analyze identical results when it has been used to analyze identical test portions in different laboratories using different equipment.

Internal reproducibility is then understood as the concordance of results when the analyses are carried out in the same laboratory, using the same method, but performed at different times by different analysts, using, for example, different batches or reagents (Perdomo et al., 2007).

With reference to the "Statistical model of R&R measurement in the weighing of order picking products in a distribution center", it is an article that presents the adaptation of a statistical model of R&R to measure the accuracy in weighing systems in a distribution center.

The model starts with the selection of two or more operators who will measure at least ten randomly selected orders with the scale or weighing equipment, then the number of times the order will be measured is decided and the order in which each order will be measured is randomized, and finally the model is presented (Gómez, 2013).

The study, "application of the R&R method to determine the influence of the operator in the measurements made with a coordinate measuring arm", shows the methodology required to know what influence the operators have in the measurement when using a coordinate measuring arm, also known as "CMM". A coordinate measuring arm is a device that measures the geometries of physical objects and uses a probing system to detect discrete points on the surface of objects.

The paper presents the measurements taken by three operators on ten parts. STATISTICA software was used to analyze and visualize the measurement data (Jurkowski, 2019).

The work, the "analysis of the quality of measurements in the laboratory process" is a work carried out with R&R studies for the knowledge of the quality of measurements in the quality laboratory of a cement industry. A total of two R&R studies are presented, one performed for a Blaine (measuring equipment for cement fineness) and the second for measurements for chemical analysis test. Both studies were performed by the ANOVA-crossover method (for non-destructive testing) using three operators and ten parts, repeating on three occasions, See also, the contribution of the statistical analysis of the global solar radiation in Cúcuta using the ANOVA model (Bastos, 2021).

The R&R studies performed show a favorable result for the laboratory of that cement industry since both obtained a percentage of tolerance (P/T) between 10% and 20%, so it is considered acceptable (Lopez, Mazaira et al., 2018).

The "ANOVA method used to perform the repeatability and reproducibility study within the quality control of a measurement system" is an article from the journal Scientia et Technica in which the ANOVA method is developed step by step in a Repeatability and Reproducibility (R&R) study and for a better demonstration two examples are elaborated. And, it is concluded that, in any type of process, the R&R study serves to calculate its variability and detect when it is operating in abnormal conditions and thus to carry out a corrective action plan to return the system to good conditions (Botero et al., 2007).

However, for Montgomery (2004), the variability of a process can be due to random causes and assignable causes. Random or common causes correspond to the cumulative effect of many unavoidable and small causes; they originate from raw material variability, different machinery, different labor efficiency; they define a stable system of variability causes (Orlandoni, 2012).

In "Repeatability and reproducibility in the quality assurance of measurement processes" the importance of correctly analyzing a measurement system in the measurement and manufacturing processes is taken into account. The work elaborates in detail the application of an R&R study using the method of averages and ranges to assure the quality of the measurements of gauges used in the internal diameter in articles of the Metrology Laboratory of Planta Mecánica de Camagüey.

The results of the study show a repeatability higher than the reproducibility due to the variability that exists between the pieces that were measured and that was mainly originated by the manufacturing process (Portuondo & Portuondo, 2010).

The "procedure for the analysis of repeatability and reproducibility in manufacturing processes" is an R&R study of a manufacturing system taking into account the dimensions of the manufactured parts.

The study makes use of the method of means and ranges since it is the most widely implemented in measurement systems. Therefore, the results present stability in the manufacturing system so the method of means and ranges can be used in the analysis of these systems (González & Falcón, 2015).

**Theoretical study of R&R**

The R&R is a study in which repeatability and reproducibility can be evaluated simultaneously, and evaluates that part of the total variability, which was observed during the process is related to the measurement error and is performed experimentally.

In the repeatability of measurement results, the closeness of agreement between the results of successive measurements of the same measurand (part) under the same measurement conditions.

Repeatability in the measurement system consists of the accuracy or variability under as controlled conditions as possible. It is defined as the variation with respect to the mean, this variation must be small in relation to the process specifications.

Reproducibility of measurement results: The closeness of agreement between the results of successive measurements of the same measurand (part) under changing measurement conditions (International Vocabulary of Metrology, 2012).

Such information is interpreted below in the equations:

$$\sigma^2 R\&R = \sigma^2 repeatability + \sigma^2 reproducibility \quad (1)$$

$$\sigma^2 repeatability = \sigma^2 equipment \text{ and } \sigma^2 reproducibility = \sigma^2 operator \quad (2)$$

As an application, the use of interindividual variability and reproducibility of three methods, as the purpose of the reference study, is that interindividual variability was analyzed after standardization of the results.

ISSN 2410-3438

The coefficient of variation was used to measure the variability between tests and Pearson's coefficient was used to analyze the correlation between variables (Sánchez-Garcia, 2013).

**Methods for conducting the R&R study**

The short method quickly evaluates the variability of the measurement system. With this method it is impossible to evaluate separately the repeatability and reproducibility, in this study both appear mixed or homogeneously. The steps to perform the study are as follows:

a) Select two or more operators who will perform the task of taking measurements on the object(s) with the measuring equipment to be studied.

b) Each object chosen will be measured only once by each operator.

c) Label and randomize the order in which the parts will be measured by the operators.

d) Identify the point where the object will be measured and the technique to be applied.

e) Perform the analysis of the data obtained.

The long method allows to evaluate repeatability and reproducibility separately, unlike the short method, which is unable to evaluate repeatability and reproducibility heterogeneously, to be performed it is necessary to carry out the following steps for each measuring equipment to be evaluated.

a) Select two or more operators who will perform the task of taking measurements on the object(s) with the measuring equipment to be studied.

b) Select ten or more parts for each operator, who will take the measurements repeatedly.

c) Decide the number of times each operator will measure the same part (at least two repetitions).

d) Label and randomize the order in which the parts will be measured by the operators.

e) Obtain the results of operator A and then the results of operator B, and so on until all operators have made their measurements in the first repetition.

f) Repeat the previous step until the number of repetitions is completed.

g) Perform the analysis of the data obtained.

The analysis of the measurement system by means of the long method decomposes the total variability of the system into three factors; product, instrument and operator variability. This relationship is represented as follows in the equation:

$$\sigma^2 total = \sigma^2 part + \sigma^2 operator + \sigma^2 instrument \quad (3)$$

The method of means-ranges, makes possible the analysis to the measurement system in a heterogeneous way, i.e., it is able to analyze separately reproducibility and repeatability.

This method makes it possible to pinpoint the influence of operators and equipment on the stability of the system based on a processing of data obtained and classified according to the measuring instruments, the measurements assessed and the operators executing the measurements (González & Falcón, 2015).

Gutiérrez and de la Vara (2009), mention that in order to carry out the mean-range method the following must be performed:

a) Calculate the range of the measurements taken by each operator for each piece.

b) Calculate the mean of the ranges of each operator and the mean of all the measurements taken by the same operator.

c) Obtain the mean of the mean of the ranges and the range of the means.

$$\bar{R} = ( \bar{R}_1+\bar{R}_2+\cdots+\bar{R}_n ) / n \quad (4)$$

$$R_X = X_{máx} - X_{mín} \quad (5)$$

d) Calculate the upper limit. If any range is greater than the limit, it will be a sign that the corresponding measurement is out of the usual.

e) Calculate the expanded variation of the equipment.

f) Calculate the operator's expanded variation.

g) Determine the expanded measurement error due to repeatability and reproducibility.

h) Calculate the precision/tolerance index.

i) Calculate the precision index/total variation.

j) Calculate the number of different categories.

k) Detect where the error comes from and investigate the possible causes of the error.

The analysis of variance method (ANOVA) was designed by R.A. Fisher in the early 1920s to compare the means of two or more populations (Robles). This method consists of decomposing the variation in the data into internal or natural variation that exists within groups and the variation between groups of means (Tobarameekul et al., 2022).

The ANOVA method is considered the most accurate when performing an R&R study to the measurement system since it has advantages such as: 1) variances estimated with greater accuracy and 2) greater information obtained in the results (Escalante, 2005).

Also, it uses all the resources of the long method for an R&R study except that it considers the variance of four factors, as shown in the equation:

$$\sigma^2 total = \sigma^2 part + \sigma^2 operator + \sigma^2 operator \times part + \sigma^2 team \quad (6)$$

The factor $\sigma^2$operator × part is added to that shown in equation (2) forming part of the reproducibility and remaining as follows:

$$\sigma^2 repeatability = \sigma^2 equipment \text{ and } \sigma^2 reproducibility = \sigma^2 operator + \sigma^2 operator \times part \quad (7)$$

The R&R study by attributes, evaluates the stability of the measurement process based on evaluations already performed by inspectors where they classify parts into few categories (e.g., accepted or rejected).

The risk analysis method, in this study a given number of operators analyze the number of selected parts in turn by classifying them into a discrete binary code; 1 equals = accepted, 0 = rejected.

The signal theory method, according to Gutierrez and de la Vara (2009), the objective of signal theory is to obtain the average width of uncertainty zones that appear around each specification. Signal theory is applied to the same types of data as in the previous study. This method is used when certain parts fall close to a control limit and therefore run the risk of not being analyzed in the same way by all operators who can accept or reject the part.

With the analytical method, a certain number of parts that have been evaluated several times are studied and the number of times each part is accepted is recorded. A method that requires continuous reference values for the parts and that they cover the entire range, from the one that is rejected every time, to the one that is accepted every time, and in the intermediate zone there should be at least six parts where some are rejected and some are accepted.

The method for destructive testing refers to when the object can only be measured once, since it is somehow destroyed. In this method, what must be done is to split the part into the portions needed so that each assigned operator can measure at least two fragments of the part (Gutiérrez & de la Vara, 2009). This method makes it impossible to perform an R&R study in the traditional way because the parts are affected in the process.

According to the statistical process control (SPC), the following aspects must be taken into account when collecting data for this method (Grupo Consultor SPC, 2022):

– The pieces that represent each batch should be as similar as possible and should be at least nine consecutive pieces so that the variation is not so affected.

ISSN 2410-3438

- Collect the pieces from the different batches at different times so that the variation between the pieces in the batches is as large as possible.

- To those in charge of observing the parts, present them in random order and not in the order in which they were produced.

- Samples of parts should be taken at different times.

## 5. Results

The results comprise the evidence from the analysis of the measurements of the steel plate, stationary tank and Y-angle structure samples.

### R&R for steel plate (metallized zone only)

Study carried out on October 12, 2022 with two operators (only two of them were working in the day shift) and with the equipment internally identified as E-052, which is used for thickness measurement in the Plating Production Line.

| Source | GOF | SS | MC | F | P |
|---|---|---|---|---|---|
| Parts | 4 | 4,75301 | 1,18825 | 47,5 | 0,001 |
| Operators | 1 | 0,00065 | 0,00065 | 0,02 | 0,879 |
| Parts * Operators | 4 | 0,09995 | 0,02499 | 1,17 | 0,352 |
| Repeatability | 20 | 0,42587 | 0,02129 | | |
| Total | 29 | 5,27948 | | | |
| α to eliminate the interaction term = 0.05 | | | | | |

**Table 1** Two-factor ANOVA with interaction
*Source: Own Elaboration, Minitab 19*

| Source | GOF | SS | MC | F | P |
|---|---|---|---|---|---|
| Parts | 4 | 4,75301 | 1,18825 | 54,2 | 0,000 |
| Operators | 1 | 0,00065 | 0,00065 | 0,02 | 0,864 |
| Repeatability | 24 | 0,52581 | 0,02191 | | |
| Total | 29 | 5,27948 | | | |

**Table 2** Two-factor ANOVA without interaction
*Source: Own Elaboration, Minitab 19*

In Table 1 the interaction of Parties*Operators does not have a significant P-value (0.352) so Table 2 is created where the mentioned interaction is omitted for the study.

### R&R of the measurement system

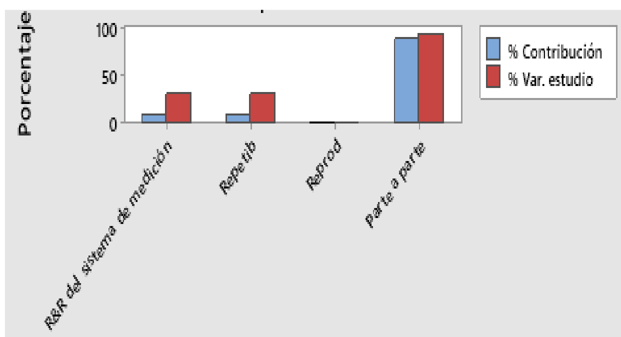
| Source | CompVar | Contribution (of CompVar) |
|---|---|---|
| Gage R&R total | 0,021909 | 10,13 |
| Repeatability | 0,021909 | 10,13 |
| Reproducibility | 0,000000 | 0,00 |
| Operators | 0,000000 | 0,00 |
| Part to Part | 0,194391 | 89,87 |
| Total variation | 0,216300 | 100,00 |

**Table 3** Variance components
*Source: Own Elaboration, Minitab 19*

| Source | Standard deviation (SD) | Study var. (6 × SD) | %Var. study (%VE) |
|---|---|---|---|
| Gage R&R total | 0,148017 | 0,88810 | 31,83 |
| Repeatability | 0,148017 | 0,88810 | 31,83 |
| Reproducibility | 0,000000 | 0,00000 | 0,00 |
| Operators | 0,000000 | 0,00000 | 0,00 |
| Part to Part | 0,440898 | 2,64539 | 94,80 |
| Total variation | 0,465080 | 2,79048 | 100,00 |
| Number of different categories = 4 | | | |

**Table 4** Evaluation of the measurement system
*Source: Own Elaboration, Minitab 19*

Table T3 shows the percentage of contribution that the variance has, in this case a total of 10.13% for the total Gage R&R, the percentage is slightly high, since the maximum recommended is 10%, after this in Table T04 it can be observed in "%Var. Study" that the total Gage R&R is 31.83%, so the measurement system used for the object is unacceptable.

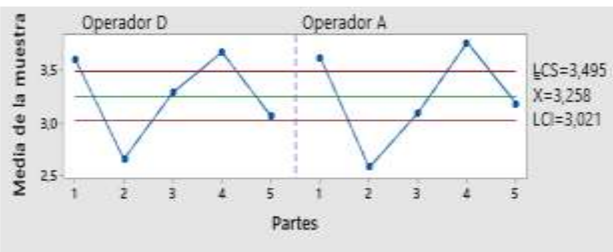



**Graph 1** Variation components
*Source: Own Elaboration, Minitab 19*

Graph 1 shows in the form of bars, the data obtained in tables 3 and 4 of the "%Contribution" and "%Var. Study".

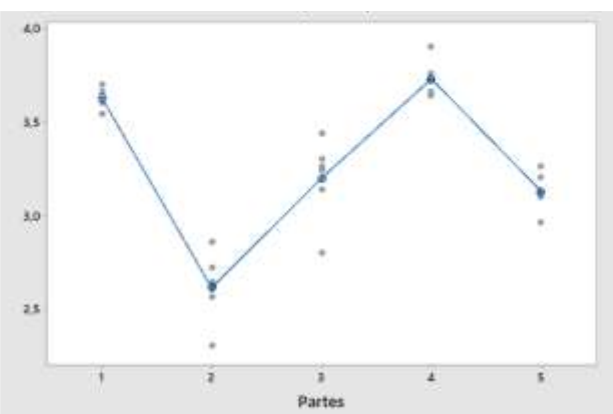

**Graph 2** Rank by operators
*Source: Own Elaboration, Minitab 19*

Graph 2 represents the ranges of the measurements obtained by the operators in the three replicates of the study where operator D has more control over its measurements with respect to operator A, since its variation in the measurement of each replicate tends to be more controlled, however, despite these variations both operators have a similar behavior in terms of the thickness of each reference area analyzed as shown in graph 3.



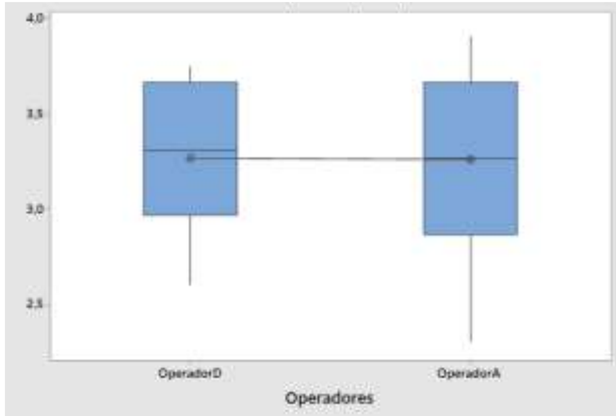

**Graph 3** Xbarra by operators
*Source: Own Elaboration, Minitab 19*

Graph 4 shows each of the measurements obtained by the operators with respect to the analyzed part. The operators had problems to measure parts 2 and 3 mainly, since the points are very dispersed with respect to the average with high and low thicknesses that start approximately from 2.1 thousandths of thickness to 2.8 thousandths of thickness for part 2 and from 2.7 to 3.3 thousandths for part 3.




**Graph 4** Thickness by parts
*Source: Own Elaboration, Minitab 19*

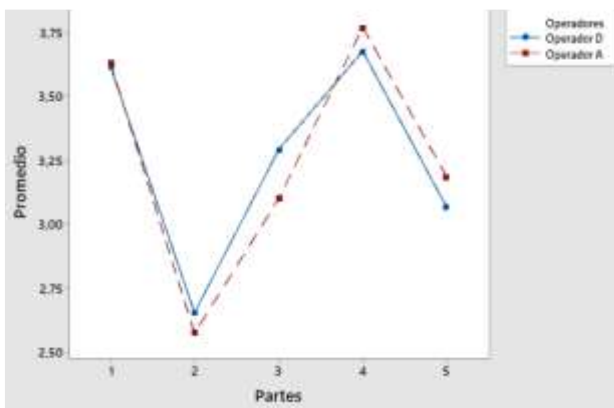
In Graph 05. Each of the obtained thicknesses is indicated, the following graphs of the same type are illustrated with a Whisker Box.




**Graph 5** Thicknesses by operators
*Source: Own Elaboration, Minitab 19*

Graph 5 is a Box and Whiskers plot showing the variation of the thickness of the operators. Operator A has a longer Whisker and a larger Box with respect to operator D, so operator A had a greater variation in its measurements, it is also observed that between them there is not much difference in their measurements since the line that joins the two boxes is not with much inclination.

And, in graph 6 the interaction of the operators is observed and the behavior they had with each measured part is analyzed in a better way, in this graph the operators only managed to coincide in part 1, while in the others they obtained a different measure of thickness.




**Graph 6** Interaction parts by operators
*Source: Own Elaboration, Minitab 19*

### R&R for steel plate (sealer coated area)

Study carried out on October 17, 2022 with the four available operators and with the equipment internally identified as E-052 and used for thickness measurement of the Plating Production line.

| Source | GL | SC | MC | F | P |
|---|---|---|---|---|---|
| Parts | 4 | 14,75 | 3,689 | 28,55 | 0,00 |
| Operators | 3 | 0,160 | 0,053 | 0,414 | 0,74 |
| Parts * Operators | 12 | 1,550 | 0,129 | 1,872 | 0,06 |
| Repeatability | 40 | 2,760 | 0,0690 | | |
| Total | 59 | 19,2298 | | | |
| α to eliminate the interaction term = 0.05 | | | | | |

**Table 5** Two-factor ANOVA with interaction
*Source: Own Elaboration, Minitab 19*

| Source | GL | SC | MC | F | P |
|---|---|---|---|---|---|
| Parts | 4 | 14,75 | 3,68975 | 44,51 | 0,00 |
| Operators | 3 | 0,160 | 0,05350 | 0,645 | 0,58 |
| Repeatability | 52 | 4,310 | 0,08289 | | |
| Total | 59 | 19,2298 | | | |

**Table 6** Two-factor ANOVA without interaction
*Source: Own Elaboration, Minitab 19*

In Table 05 the interaction of Parties*Operators does not have a significant P-value (0.746) so Table 06 is created where the mentioned interaction is omitted for the study.

### R&R of the measurement system

Table 07 shows the percentage of contribution that the variance has, in this case a total of 21.62% for the total Gage R&R which is too high a value, since the maximum recommended is 10%, after this in Table 08 it can be observed in "%Var. Study" that the total Gage R&R is 46.49%, so the measurement system used for the object is unacceptable.

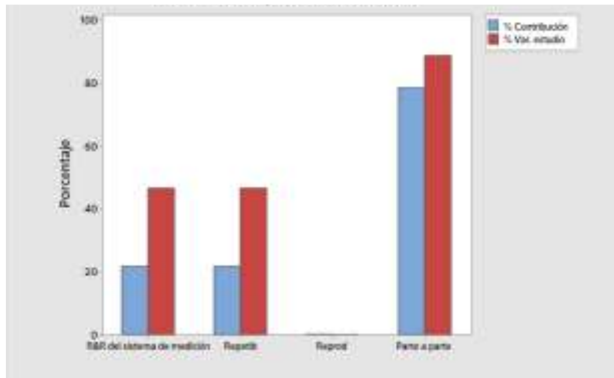
| Source | CompVar | %Contribution (of CompVar) |
|---|---|---|
| Gage R&R total | 0,082891 | 21,62 |
| Repeatability | 0,082891 | 21,62 |
| Reproducibility | 0,000000 | 0,00 |
| Operators | 0,000000 | 0,00 |
| Part to Part | 0,300572 | 78,38 |
| Total variation | 0,383463 | 100,00 |

**Table 7** Variance components
*Source: Own Elaboration, Minitab 19*

| Source | Standard deviation (SD) | Study var. (6 × SD) | %Var. study (%VE) |
|---|---|---|---|
| Gage R&R total | 0,287908 | 1,72745 | 46,49 |
| Repeatability | 0,287908 | 1,72745 | 46,49 |
| Reproducibility | 0,000000 | 0,00000 | 0,00 |
| Operators | 0,000000 | 0,00000 | 0,00 |
| Part to Part | 0,548244 | 3,28946 | 88,53 |
| Total variation | 0,619244 | 3,71546 | 100,00 |

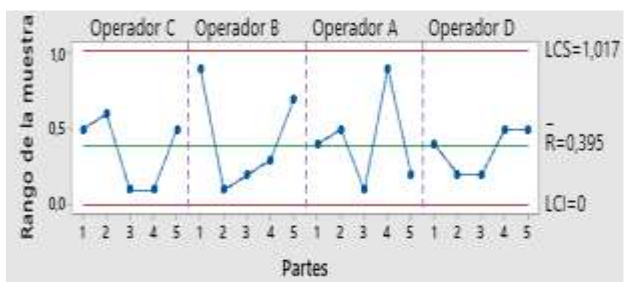
**Table 8** Evaluation of the measurement system
*Source: Own Elaboration, Minitab 19*

Graph 07 shows, in the form of bars, the data obtained in tables 03 and 04 for "%Contribution" and "%Var. Study".



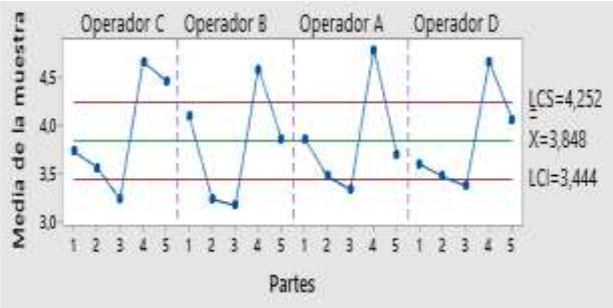

**Graph 7** Variation components
*Source: Own Elaboration, Minitab 19*

Graph 08 presents problems in the operators at the moment of repeating the thickness that they obtained previously, their ranges have a lot of variety, mainly in operators A and B, and operator D is the one that presents better results based on the ranges. Likewise, they present the same behavior with respect to the parts as detailed in graph 09.



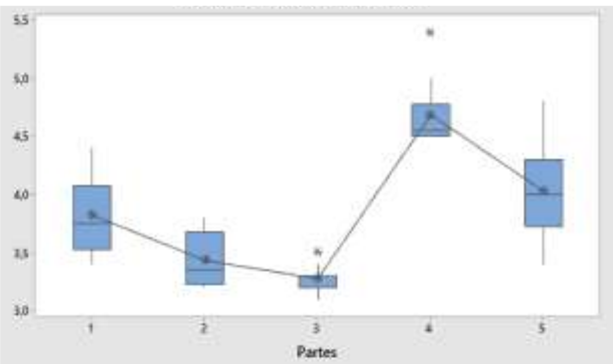

**Graph 8** Rank by operators
*Source: Own Elaboration, Minitab 19*

ISSN 2410-3438



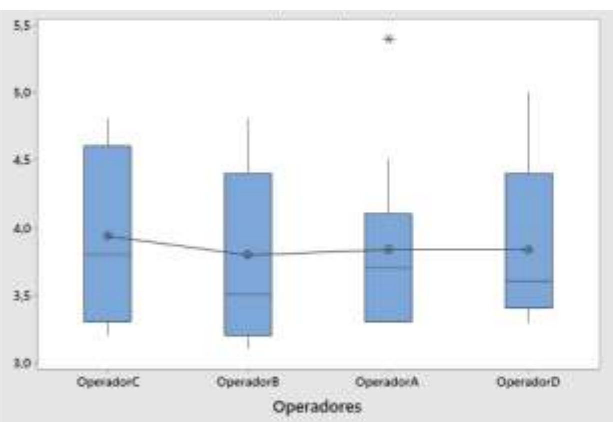

**Graph 9** Xbarra by operators
*Source: Own Elaboration, Minitab 19*

Graph 10 shows each of the measurements obtained by the operators with respect to the analyzed part. The operators presented more problems to measure parts 1 and 5, the box they present is of large size and they have a very long mustache; it can also be noted that parts 3 and 4, despite being the most controlled by the operators, each one has an atypical value with respect to the average.



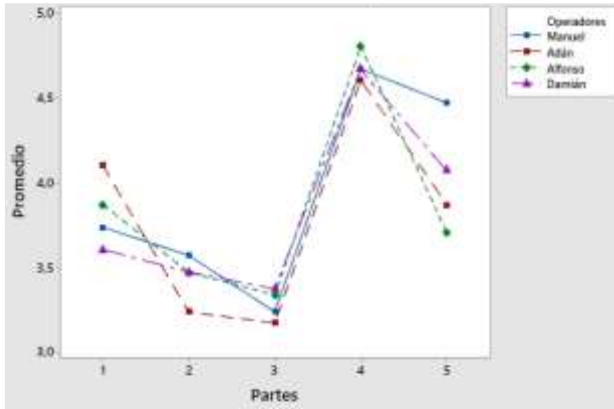

**Graph 10** Thicknesses by parts
*Source: Own Elaboration, Minitab 19*

Graph 11 is a Box and Whiskers plot showing the variation of the thickness of the operators. All the operators presented a high variation in the thicknesses obtained from the analyzed part and where the best result is obtained by Operator A.




**Graph 11** Thicknesses by operators
*Source: Own Elaboration, Minitab 19*

Graph 12 shows the interaction of the operators and analyzes in a better way the behavior they had with each measured part, in this graph confirms what was previously said, the operators present between each one of them a greater variation in their measurements in parts 1 and 5 and a small variation in parts 3 and 4.




**Graph 12** Interaction parts * operators
*Source: Own Elaboration, Minitab 19*

### R&R for stationary LP gas tank (metallized)

Study carried out on October 28, 2022 with the four available operators and with the equipment internally identified as E-052 and used for thickness measurement of the Plating Production line. In Table 9 the interaction of Parts*Operators has a P value that significant (0.00) so the table without interaction is not elaborated by Minitab 19 since it has a value less than α.

| Source | GL | SC | MC | F | P |
|---|---|---|---|---|---|
| Parts | 19 | 198,507 | 10,44 | 47,110 | 0,00 |
| Operators | 3 | 0,161 | 0,053 | 0,242 | 0,86 |
| Parts * Operators | 57 | 12,641 | 0,221 | 5,953 | 0,00 |
| Repeatability | 160 | 5,960 | 0,0372 | | |
| Total | 239 | 217,270 | | | |
| *α to eliminate the interaction term = 0.05.* | | | | | |

**Table 9** Two-factor ANOVA with interaction. *Source: Own Elaboration, Minitab 19*

### R&R of the measurement system

Table 10 shows the percentage of contribution that the variance has, in this case a total of 10.39% for the total Gage R&R which is a little high value, since the maximum recommended is 10%, after this in Table 11 it can be observed in "%Var. Study" that the total Gage R&R is 32.23%, so the measurement system used for the object is unacceptable.

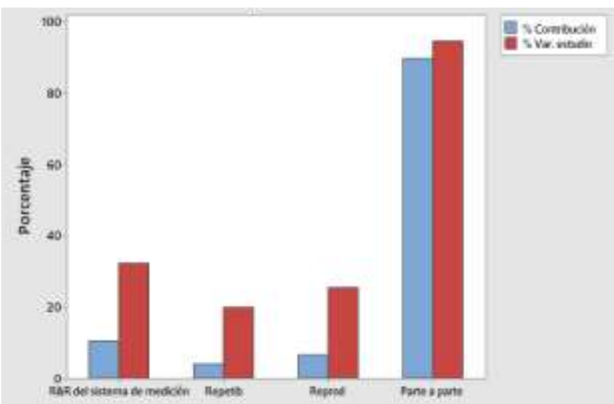
| Source | CompVar | %Contribución (de CompVar) |
|---|---|---|
| Gage R&R total | 0,098758 | 10,39 |
| Repeatability | 0,037250 | 3,92 |
| Reproducibility | 0,061508 | 6,47 |
| Operators | 0,000000 | 0,00 |
| Operators*Parts | 0,061508 | 6,47 |
| Part to Part | 0,852166 | 89,61 |
| Total variation | 0,950923 | 100,00 |

**Table 10** Variance components
*Source: Own Elaboration, Minitab 19*

| Source | SD (SD) | Var. study (6 × SD) | %Var. study (%SV) |
|---|---|---|---|
| Gage R&R total | 0,314257 | 1,88554 | 32,23 |
| Repeatability | 0,193003 | 1,15802 | 19,79 |
| Reproducibility | 0,248007 | 1,48804 | 25,43 |
| Operators | 0,000000 | 0,00000 | 0,00 |
| Operators*Parts | 0,248007 | 1,48804 | 25,43 |
| Part to Part | 0,923128 | 5,53877 | 94,66 |
| Total variation | 0,975153 | 5,85092 | 100,00 |
| Number of different categories = 4 | | | |

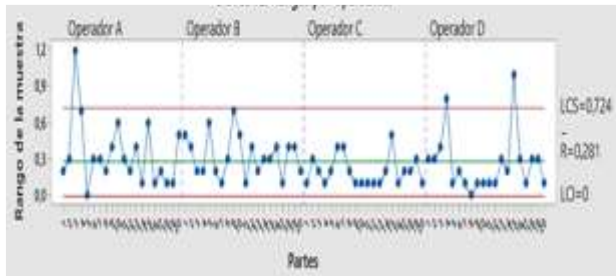
**Table 11** Evaluation of the measurement system
*Source: Own Elaboration, Minitab 19*

Graph 13 shows, in the form of bars, the data obtained in Tables 03 and 04 for "%Contribution" and "%Var. Study".



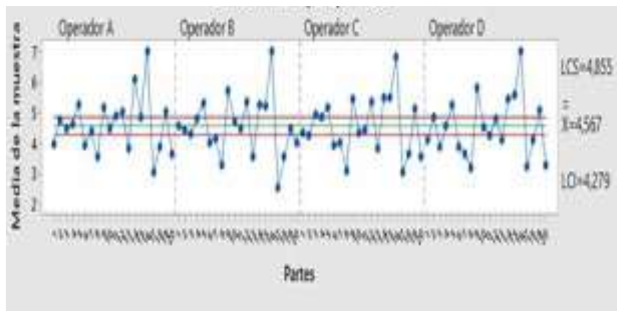

**Graph 13** Variation components
*Source: Own Elaboration, Minitab 19*

Graph 14 shows problems in the operators at the moment of repeating the thickness obtained previously, their ranges have a lot of amplitude, mainly in operators A and D that even have data outside the upper control limit and operator C is the one that presents better results based on the ranges since a better control is observed in its measurements.



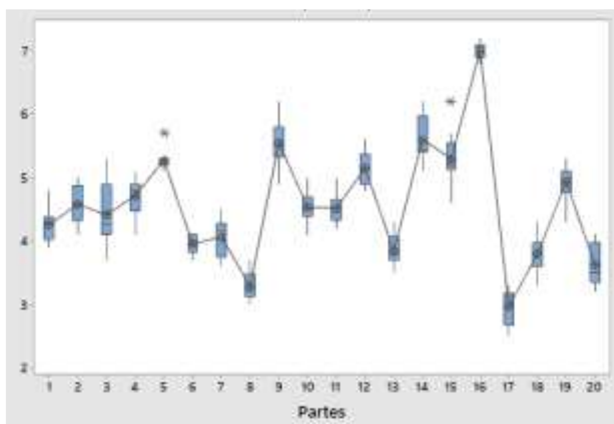

**Graph 14** Range by operators
*Source: Own Elaboration, Minitab 19*

Graph 15 shows the different values obtained by each of the operators in the three replicates carried out, where very varied values ranging from 2.5 to 7.0 thousandths of the plating thickness are found.




**Graph 15** Xbarra by operators
*Source: Own Elaboration, Minitab 19*

Graph 16 shows each of the measurements obtained by the operators with respect to the part analyzed.

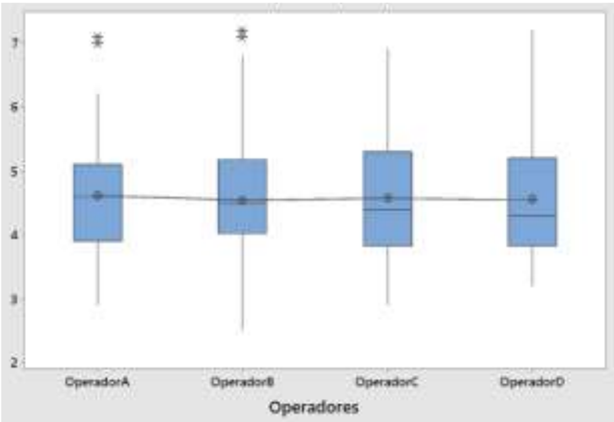



**Graph 16** Thicknesses per part
*Source: Own Elaboration, Minitab 19*

The operators presented greater difficulty in measuring parts 3 and 9 since the box they present is of large size and they have a very long mustache; it can also be noted that parts 5 and 17 were those with the least variation among all the measurements of the operators and that in spite of this, part 5 obtained an outlier value with respect to the mean which was 5.2 thousandths of an inch.

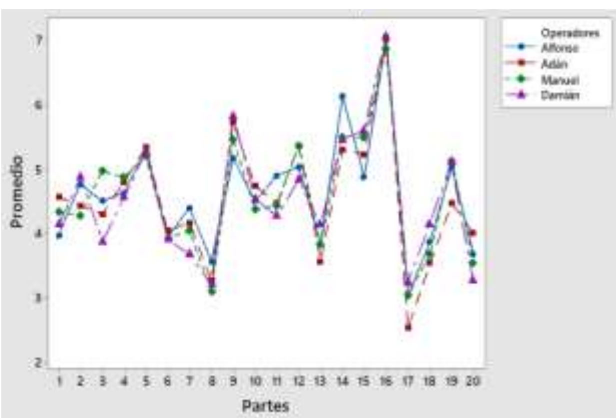
ISSN 2410-3438

Figure 17 is a Box and Whiskers plot showing the variation in operator thickness.




**Graph 17** Thicknesses by operators
*Source: Own Elaboration, Minitab 19*

All operators presented a high variation in the thicknesses obtained from the analyzed part and where the best result is obtained by Operator B since it has a smaller box than the rest, however it obtained two outliers to the average, also the graph shows that there is high variation in the measurement of thicknesses in all operators because the whiskers presented are of large size, finally the operators do not have much variation between them because the line that joins with the average of each operator does not have great inclination.




**Graph 18** Interaction Parts * Operators
*Source: Own Elaboration, Minitab 19*

In graph 18 the interaction of the operators is observed and the behavior they had with each measured part is analyzed in a better way, parts 4, 5, 16 and 19 were the ones with less variation among the average thicknesses of each operator, while those with more variation were parts 3, 7 and 20, it can also be seen that operator D tends to obtain lower thicknesses than the rest of the operators.

**R&R for stationary LP gas tank (coated with sealant)**

Study carried out on October 28, 2022 with the four available operators and with the equipment internally identified as E-052, which is used to measure the thicknesses of the plating production line.

| Source | GL | SC | MC | F | P |
|---|---|---|---|---|---|
| Parts | 19 | 211,989 | 11,1573 | 228,9 | 0,00 |
| Operators | 3 | 0,253 | 0,0845 | 1,734 | 0,17 |
| Parts * Operators | 57 | 2,777 | 0,0487 | 3,152 | 0,00 |
| Repeatability | 160 | 2,473 | 0,0155 | | |
| Total | 239 | 217,493 | | | |
| α to eliminate the interaction term = 0.05 | | | | | |

**Table 12** Two-factor ANOVA with interaction
*Source: Own Elaboration, Minitab 19*

In Table 12 the interaction of Parties*Operators has a P-value that significant (0.00) so the table without interaction is not elaborated by Minitab 19 since it has a value less than α.

**R&R of the measurement system**

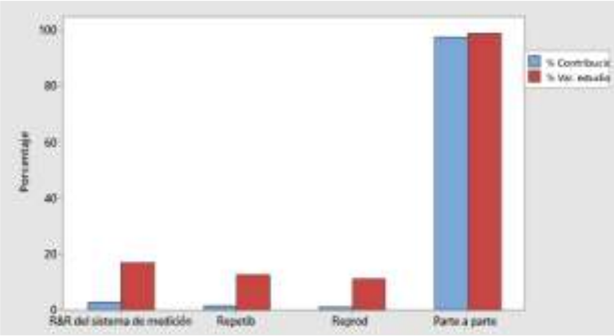
For this stage of the coating, Table 13 shows a total of 2.85% for the Gage R&R which is a value that is within the acceptable and in Table 14 it can be observed in "%Var. Study" that the total Gage R&R is 16.88% so the measurement system used is acceptable, but requires improvement.

| Source | CompVar | % Contribution (from CompVar) |
|---|---|---|
| Gage R&R total | 0,027144 | 2,85 |
| Repeatability | 0,015458 | 1,62 |
| Reproducibility | 0,011685 | 1,23 |
| Operators | 0,000596 | 0,06 |
| Operators*Parts | 0,011089 | 1,16 |
| Part to Part | 0,925715 | 97,15 |
| Total variation | 0,952858 | 100,00 |

**Table 13** Variance components
*Source: Own Elaboration, Minitab 19*

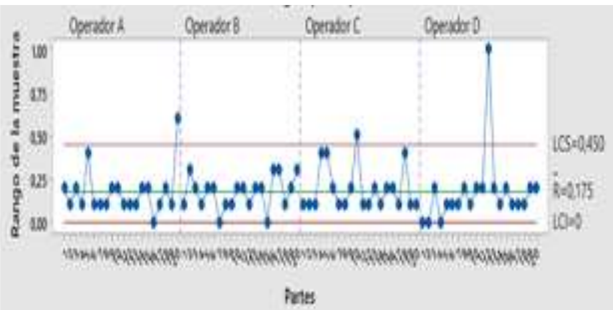
| Source | Desv.Est. (DE) | Var. study (6 × DE) | %Var. study (%VE) |
|---|---|---|---|
| Gage R&R total | 0,164753 | 0,98852 | 16,88 |
| Repeatability | 0,124332 | 0,74599 | 12,74 |
| Reproducibility | 0,108098 | 0,64859 | 11,07 |
| Operators | 0,024413 | 0,14648 | 2,50 |
| Operators*Parts | 0,105305 | 0,63183 | 10,79 |
| Part to Part | 0,962141 | 5,77284 | 98,57 |
| Total variation | 0,976145 | 5,85687 | 100,00 |
| Number of different categories = 8 | | | |

**Table 14** Evaluation of the measurement system
*Source: Own Elaboration, Minitab 19*



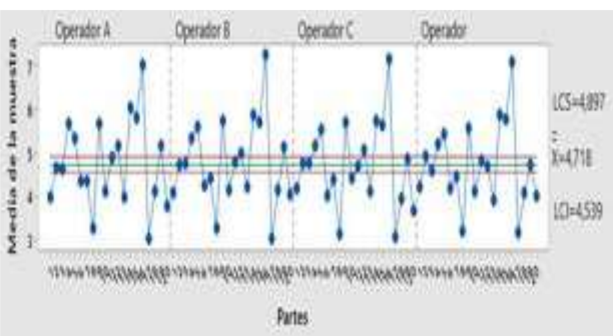

**Graph 19** Variation components
*Source: Own Elaboration, Minitab 19*

Graph 19 shows, in the form of bars, the data obtained in tables 03 and 04 for "%Contribution" and "%Var. Study".



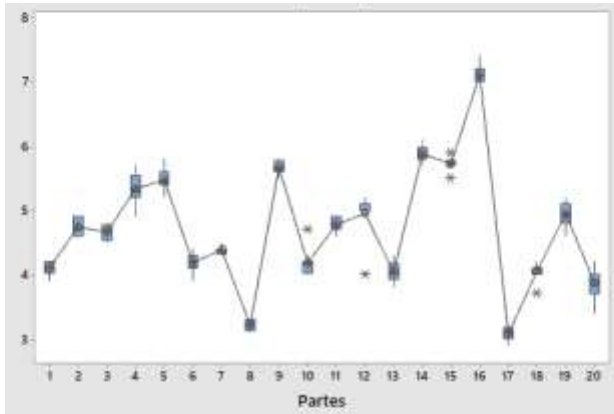

**Graph 20** Rank by operators
*Source: Own Elaboration, Minitab 19*

Graph 20 shows a quite acceptable control in the operators at the moment of repeating the thickness obtained previously, mainly in operators B and D a good control is observed in general with their measurements, despite the fact that operator D had a range well above the control limit in general presents a great behavior at the time of performing their measurements.



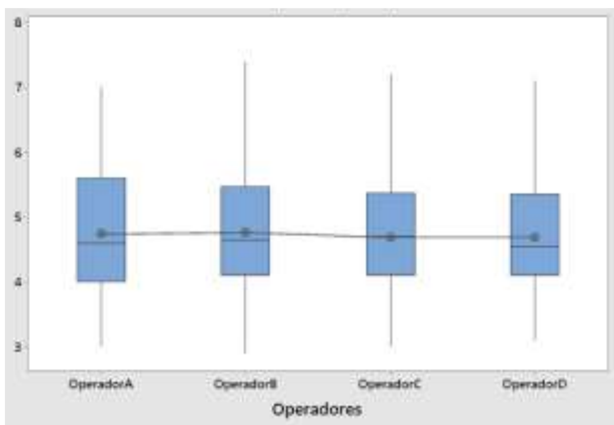

**Graph 21** Xbarra by operators
*Source: Own Elaboration, Minitab 19*

Graph 21 shows the different values obtained by each of the operators in the three replicates performed, where very varied values ranging from 3.0 to 7.2 thousandths of the plating thickness are found, and at a glance it can be seen that their graphs show a similar amount of thickness.




**Graph 22** Thicknesses by parts
*Source: Own Elaboration, Minitab 19*

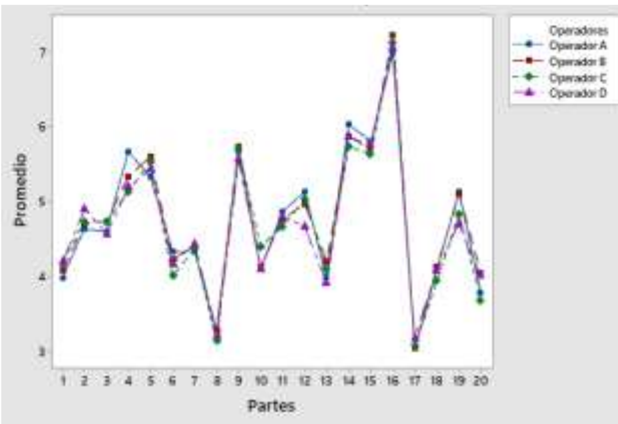
Graph 22 shows the thicknesses obtained by the operators with respect to the part analyzed. In this graph it can be seen that parts 10, 12, 15 and 18 presented atypical values and that the thicknesses of each part analyzed do not present much variation, the parts with a larger box size and a more extensive whisker were points 3 and 20.




**Graph 23** Thicknesses by operators
*Source: Own Elaboration, Minitab 19*

Graph 23 is a Box and Whiskers diagram demonstrating the variation in thickness of the operators. All operators presented a high variation in the thicknesses obtained from the analyzed part with a box and whisker of very similar sizes between them and observing that operator B has a higher average than the rest of operators.

**Article** **Journal of Quantitative and Statistical Analysis**
June, 2023 Vol.10 No.26 1-21




**Graph 24** Interaction Parts * Operators
*Source: Own Elaboration, Minitab 19*

Graph 24 shows the interaction of the operators and analyzes in a better way the behavior they had with each measured part, the parts with a higher variation were parts 4 and 12 and in general there is a good behavior between the measurements of each operator since many of their measurements are similar.

## R&R for galvanized Y-angle (one specimen)

Study carried out on November 07, 2022 with the four available operators and with the equipment internally identified as E-044 and used for thickness measurement in the Galvanizing Production line.

| Source | GL | SC | MC | F | P |
|---|---|---|---|---|---|
| Parts | 4 | 3,09 | 0,7726 | 114,0 | 0,00 |
| Operators | 3 | 0,062 | 0,0206 | 3,049 | 0,07 |
| Parts * Operators | 12 | 0,081 | 0,00677 | 1,043 | 0,43 |
| Repeatability | 40 | 0,260 | 0,00650 | | |
| Total | 59 | 3,494 | | | |
| to eliminate the interaction term = 0.05 | | | | | |

**Table 15** Two-factor ANOVA with interaction
*Source: Own Elaboration, Minitab 19*

| Source | GL | SC | MC | F | P |
|---|---|---|---|---|---|
| Parts | 4 | 3,090 | 0,7726 | 117,7 | 0,00 |
| Operators | 3 | 0,062 | 0,0206 | 3,148 | 0,03 |
| Repeatability | 52 | 0,341 | 0,0065 | | |
| **Total** | 59 | 3,4940 | | | |

**Table 16** Two-factor ANOVA without interaction
*Source: Own Elaboration, Minitab 19*

In Table 16 the interaction of Parties*Operators has a P-value that is not significant (0.431) so Table 4.6.2 is generated where this interaction is omitted.

## R&R of the measurement system

In the analysis of the Y type angle, Table 17 shows a total of 10.52% for the total Gage R&R, it is a little high value, since the maximum recommended is 10%, and in Table 18 it can be observed in "%Var. Study" that the total Gage R&R is 32.43%, so the measurement system used is unacceptable.

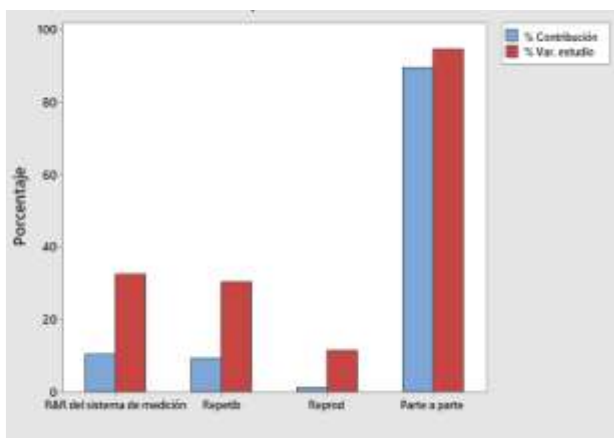
| Source | CompVar | %Contribution (of CompVar) |
|---|---|---|
| Gage R&R total | 0,0075043 | 10,52 |
| Repeatability | 0,0065641 | 9,20 |
| Reproducibility | 0,0009402 | 1,32 |
| Operators | 0,0009402 | 1,32 |
| Part to Part | 0,0638419 | 89,48 |
| Total variation | 0,0713462 | 100,00 |

**Table 17** Variance components
*Source: Own Elaboration, Minitab 19*

| Source | Standard deviation (SD) | Study var. (6 × SD) | %Study var. |
|---|---|---|---|
| Gage R&R total | 0,086627 | 0,51976 | 32,43 |
| Repeatability | 0,081019 | 0,48611 | 30,33 |
| Reproducibility | 0,030662 | 0,18397 | 11,48 |
| Operators | 0,030662 | 0,18397 | 11,48 |
| Part to Part | 0,252670 | 1,51602 | 94,59 |
| Total variation | 0,267107 | 1,60264 | 100,00 |
| Number of different categories = 4 | | | |

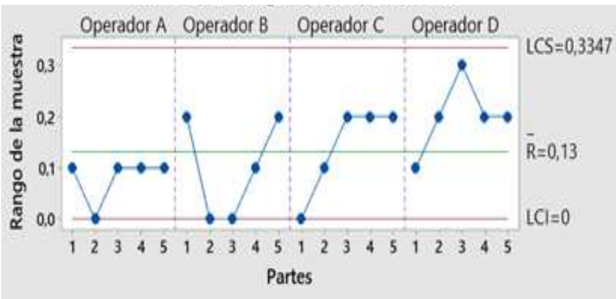
**Table 18** Evaluation of the measurement system
*Source: Own Elaboration, Minitab 19*

Graph 25 shows, in the form of bars, the data obtained in Tables 03 and 04 for "%Contribution" and "%Var. Study".



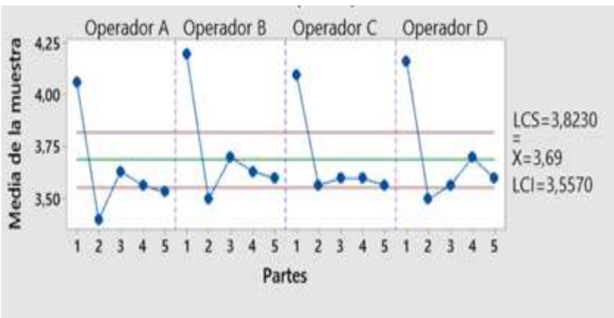

**Graph 25** Variation components
*Source: Own Elaboration, Minitab 19*

ISSN 2410-3438




**Graph 26** Rank by operators
*Source: Own Elaboration, Minitab 19*

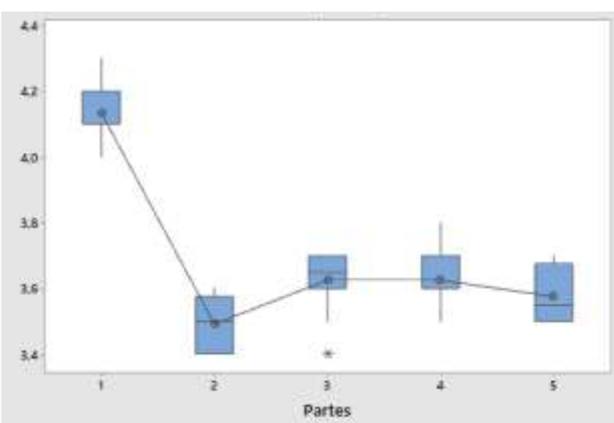
In graph 26 it can be seen that the operators have a lot of control over the measurements that each one obtains, since their ranges are within the limits.




**Graph 27** Xbarra by operators
*Source: Own Elaboration, Minitab 19*

Graph 27 shows the behavior of the measurements of each operator and at a glance it can be said that the operators tend to have the same sequence in their data.

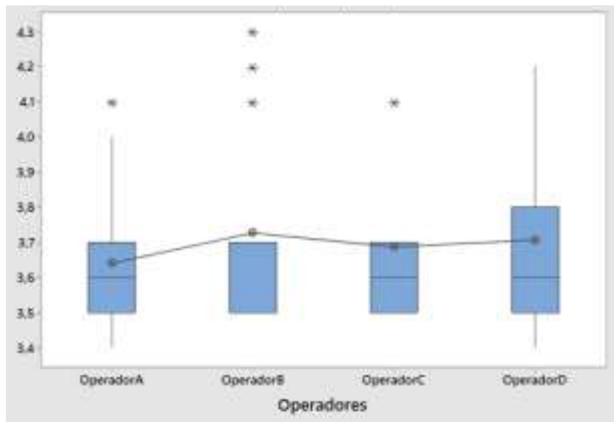
Graph 28 shows the thicknesses obtained by the operators with respect to the analyzed part. In this graph it can be seen that parts 1 and 4 present longer whiskers than the rest, so there was more complication when measuring the thickness of these points, likewise part 3 presents a long whisker towards the bottom and with an atypical value.




**Graph 28** Thicknesses by parts
*Source: Own Elaboration, Minitab 19*

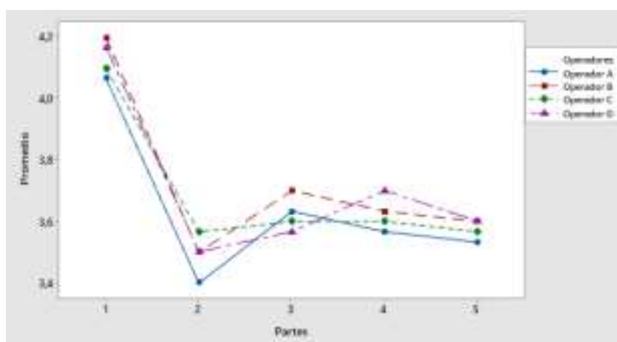
**Operators in general show a regular behavior during thickness measurements**

Figure 29 is a Box and Whiskers plot showing the variation of the thickness of the operators. Operator D presents a box of greater size than the rest as well as its whisker that has a greater length, the other three operators have a box of similar size so that between them mainly, there is little variation in their measurements, however, operator B presents problems since its mean is higher compared to the rest presenting three outliers with respect to the mean of its values.




**Graph 29** Thicknesses by operators
*Source: Own Elaboration, Minitab 19*

Figure 30 shows that part 5 is the most controlled with only 0.1 thousandths of an inch in the variation of its measurements and that in none of the parts the operators were able to obtain the same result between them with respect to the parts..



**Graph 30** Interaction Parties * Operators
*Source: Own Elaboration, Minitab 19*

ISSN 2410-3438

**R&R for galvanized steel beam (multi-specimen)**

Study carried out on November 11, 2022 with the four available operators and with the equipment internally identified as E-044, used for thickness measurement of the Galvanized Production line.

In Table 19 the interaction of Parts*Operators has a P-value that is significant (0.00) so the table without interaction is not generated by Minitab 19 since it has a value less than α.

| Source | GL | SC | MC | F | P |
|---|---|---|---|---|---|
| Parts | 14 | 118,1 | 8,43732 | 139,0 | 0,00 |
| Operators | 3 | 0,112 | 0,03739 | 0,616 | 0,60 |
| Parts * Operators | 42 | 2,549 | 0,06068 | 4,334 | 0,00 |
| Repeatability | 120 | 1,680 | 0,01400 | | |
| Total | 179 | 122,463 | | | |
| α to eliminate the interaction term = 0.05 | | | | | |

Table 19 Two-factor ANOVA with interaction
*Source: Own Elaboration, Minitab 19*

**R&R of the measurement system**

| Source | CompVar | % Contribution (from CompVar) |
|---|---|---|
| Gage R&R total | 0,029561 | 4,06 |
| Repeatability | 0,014000 | 1,92 |
| Reproducibility | 0,015561 | 2,14 |
| Operators | 0,000000 | 0,00 |
| Operators*Parts | 0,015561 | 2,14 |
| Part to Part | 0,698053 | 95,94 |
| Total variation | 0,727614 | 100,00 |

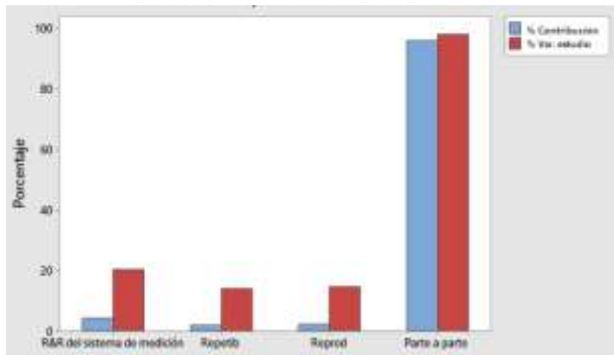
**Table 20** Two-factor ANOVA with interaction
*Source: Own Elaboration, Minitab 19*

| Source | Standard deviation (SD) | Study var. (6 × SD) | %Var. study (%VE) |
|---|---|---|---|
| Gage R&R total | 0,171933 | 1,03160 | 20,16 |
| Repeatability | 0,118322 | 0,70993 | 13,87 |
| Reproducibility | 0,124743 | 0,74846 | 14,62 |
| Operators | 0,000000 | 0,00000 | 0,00 |
| Operators*Parts | 0,124743 | 0,74846 | 14,62 |
| Part to Part | 0,835496 | 5,01297 | 97,95 |
| Total variation | 0,853003 | 5,11802 | 100,00 |
| Number of different categories = 6 | | | |

**Table 21** Evaluation of the measurement system
*Source: Own Elaboration, Minitab 19*

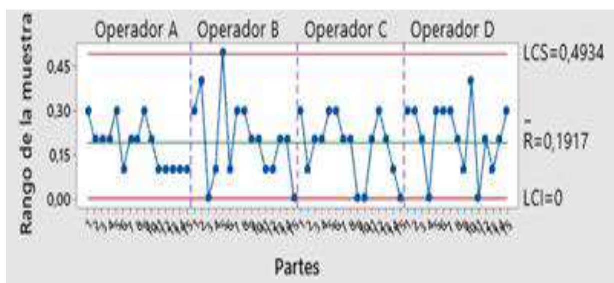
Table 20 shows a total of 4.06% for the total Gage R&R, a value within the acceptable range, and in Table 21 it can be observed in "%Var. Study" that the total Gage R&R is 20.16% so the measurement system used is acceptable, but requires improvement.

Graph 31 shows in the form of bars, the data obtained in Tables 03 and 04 of "%Contribution" and "%Var. Study".

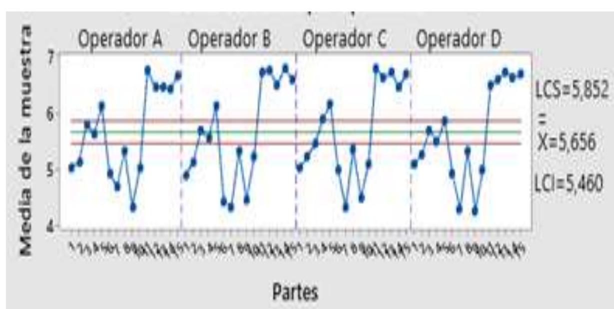



**Graph 31** Variation components
*Source: Own Elaboration, Minitab 19*

Graph 32 shows the behavior that the operators had in their three replicates, operator B obtained a value outside the upper control limit, but in general the four operators keep their measurements controlled and in graph 33 the behavior of the measurements of each operator is observed and at a glance it can be said that the operators tend to have the same sequence in their data.

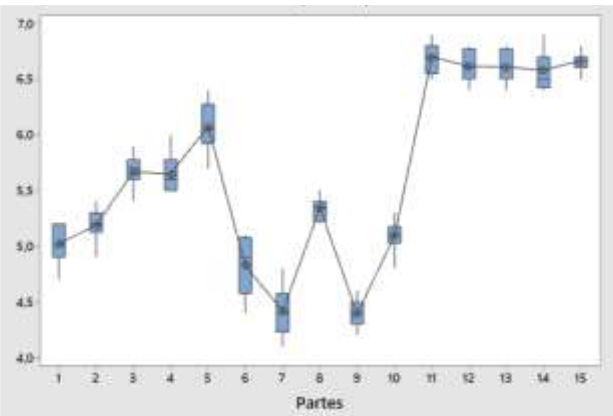



**Graph 32** Ranges by operators
*Source: Own Elaboration, Minitab 19*




**Graph 33** Xbarra by operators
*Source: Own Elaboration, Minitab 19*

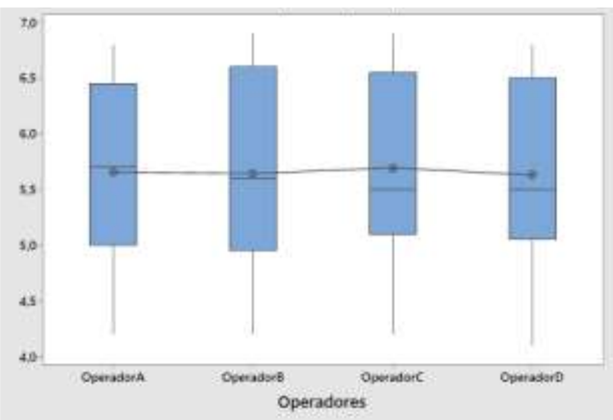
Graph 34 shows the thicknesses obtained by the operators with respect to the analyzed part. In this graph it can be seen that parts 5, 6 and 7 present a greater variation compared to the other parts of the piece.




**Graph 34** Thicknesses by parts
*Source: Own Elaboration, Minitab 19*

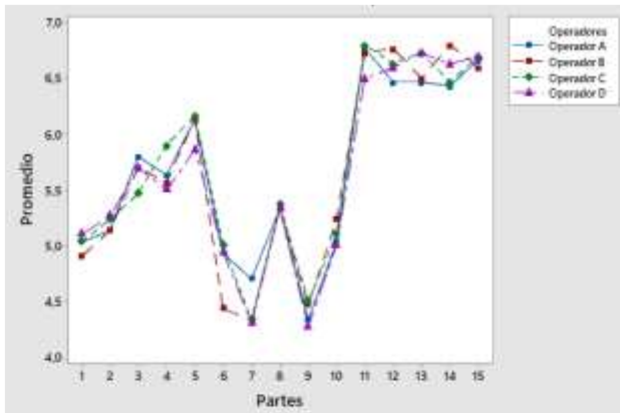
The operators in general show a regular behavior when taking thickness measurements.

Graph 35 shows a similar amount of variation among the operators, where operator B was the one who had more complications when measuring the part, since he has a larger box size and a more extensive mustache.




**Graph 35** Thicknesses by Operators
*Source: Own Elaboration, Minitab 19*

And, in graph 36 it is observed that in parts 4, 5, 12, 13 and 14 there was a greater complexity for the thickness measurement since the measurements obtained by each operator are different and that in parts 8, 10 and 15 there is greater ease for the operators to obtain similar results.




**Graph 36** Interaction Parts * Operators
*Source: Own Elaboration, Minitab 19*

**Acknowledgement**

For the development of the experiments in the operations, we thank the laboratory and quality personnel of the company Metalyzinc, S.A. de C.V., for the use of their internal resources, as well as the thesis student Elías del Ángel García Eng (zS18001567), for his practical contribution, and the members of the Academic Body UV-CA-470 Innovation in Management Systems for the development and analysis of the evidence of the study.

**Conclusions**

In the two studies that were carried out at laboratory level, a certain discomfort was observed on the part of the operator, since they were not in their work area and therefore did not take the necessary time to measure the part correctly.

The surfaces of the parts when they are galvanized or metallized do not have a uniform surface, although they may seem so, they have different thicknesses, so most of the error in the R&R studies performed is caused by the variation of thickness in the part, therefore, the equipment used to obtain thicknesses in both production lines (galvanized and metallized) are in good condition and can continue to be used for their proper functions.

The unfavorable results that were obtained in the parts that had only the metallized coating (steel plate and stationary gas tank), is due to the type of surface that the part has that involves roughness, which complicates the obtaining of the thickness to be reliable.

The operators are more confident in their measurements when measuring on a smoother surface, for example, comparing the two R&R studies performed on the stationary gas tank, the first shows an error of 32.23% while, in the same tank, but already sealed, presents an error of 16.88% where the measurement system is already acceptable.


**Figure 2** Individual readings on Coated Plate (28945) located in the Coating Thickness Standards
*Source: Own Elaboration*

To better corroborate that the error obtained in the studies that were considered unacceptable, it is recommended to increase the accuracy of the equipment to at least two figures after zero.

## References

Botero Arbeláez, Marcela; Arbeláez Salazar, Osiel; Mendoza Vargas, Jairo A. (2007). Método ANOVA utilizado para realizar el estudio de repetibilidad y reproducibilidad dentro del control de calidad del sistema de medición. Ciencia y Técnica, XIII (37), 533-537. Recuperado a partir de http://www.redalyc.org/articulo.oa?id=84903792.

DeFelsko. (2019). PosiTector6000 - Guía rápida del medidor de espesor de recubrimiento v.7.9. Estados Unidos. Recuperado a partir de https://es.defelsko.com/resources/measurement-terms-coating-thickness-gages

Escalante Vazquez, Edgardo J. (2005). Seis-Sigma. Metodología y Técnicas. ISBN-13 978-6070504488 Editorial Limusa.

Escamilla, M., Tejeda, J. F., Yáñez, R., Mejías, J., Meza, J., Macedo, A., & Ochoa, M. (2020). Repetibilidad y Reproducibilidad en las Mediciones del Espesor de Tubos de Acero para Ferroducto. Aguascalientes. Recuperado el 30 de octubre de 2022 en https://www.redalyc.org/articulo.oa?id=94463783003.

Gómez Montoya, R. A. (2013). Modelo estadístico de medición R&R en el pesaje de productos de la preparación de pedidos en un centro de distribución. Revista Soluciones de Postgrado, 5(10), 45–64. Recuperado a partir de https://revista.eia.edu.co/index.php/SDP/article/view/45-64.

González, G., & Falcón, C. (septiembre de 2015). Revista Cubana de Ingeniería. Procedimiento para el análisis de repetibilidad y reproducibilidad en procesos de manufactura, pp. 53-59. Cuba. Recuperado el 22 de octubre de 2015 a partir de https://www.researchgate.net/publication/289380451_Procedimiento_para_el_analisis_de_repetibilidad_y_reproducibilidad_en_procesos_de_manufactura.

Grupo Consultor SPC (2022). Control Estadístico de Proceso - SPC. Recuperado el 25 de octubre de 2022, de Estudios de MSA para pruebas destructivas: https://spcgroup.com.mx/estudios-de-msa-para-pruebas-destructivas/

Gutiérrez, H., & de la Vara, R. (2009). Calidad de Mediciones (Repetibilidad y Reproducibilidad). En H. Gutiérrez, & R. de la Vara, Control Estadístico de Calidad y Seis Sigma (págs. 278-309). Editorial Mc Graw Hill.

Jurkowski, Sławomir. (2019). Aplicación del método R&R para determinar la influencia del operador en las mediciones realizadas con un brazo de medición de coordenadas. Archivo de Ingeniería Mecánica. 66. 73-81. 10.24425/ame.2019.126372.

López Calvajar, G., Mazaira Rodríguez, Z., Hernández, I. A., & Cabrera, H. R. (2018) Análisis de la calidad de las mediciones en el proceso de laboratorio. Espacios, 39(6), pp. 18-29. Recuperado a partir de https://revistaespacios.com/a18v39n06/18390618.html.

Minitab (2022). Soporte de Minitab 20. Recuperado el 3 de noviembre de 2022, de Todos los estadísticos y gráficas para Estudio R&R cruzado del sistema de medición: https://support.minitab.com/es-mx/minitab/20/help-and-how-to/quality-and-process-improvement/measurement-system-analysis/how-to/gage-study/expanded-gage-r-r-study/interpret-the-results/key-results/

Orlandoni Merli, Giampaolo (2012) Gestión de la Calidad: Control Estadístico y Seis Sigma. TELOS. Revista de Estudios Interdisciplinarios en Ciencias Sociales. Recuperado a partir de https://www.redalyc.org/pdf/993/99323311008.pdf

Otzen, Tamara, & Manterola, Carlos (2017). Técnicas de muestreo sobre una población a estudio. Revista Internacional de Morfología, 35(1): 227-232. DOI: 10.4067/S0717-95022017000100037 Recuperado el 28 de octubre de 2022 en https://scielo.conicyt.cl/pdf/ijmorphol/v35n1/art37.pdf

Perdomo Morales, A. J.; Rodríguez López, J.; Fernández Álvarez, F.; Rodríguez Mambuca, R.; Torres Ponce, B.; Casanova Cabezas, C. E.; Borges Gómez, Y.; Maseda Maestre, E.; López Tito, N.; Álvarez Chibás, M.; Ramos Miranda, C.; Solís Marín, Y.; Piovet Viamonte, A. P.; Trujillo Cárdenas, N.; Sánchez Herrera, A.; Sánchez Expósito, F. (2007) Incertidumbre de la medición, repetibilidad y reproductibilidad interna en el laboratorio de ensayos y calibraciones azucareras (leycaz) durante el quinquenio 2002-2006 Recuperado a partir de http://www.redalyc.org/articulo.oa?id=223014972004.

Portuondo, Y., & Portuondo, J. (2010). Tecnología Química. La repetibilidad y reproducibilidad en el aseguramiento de la calidad de los procesos de medición, 30. Recuperado el 24 de octubre de 2022 a partir de https://www.redalyc.org/pdf/4455/445543770014.pdf

Sánchez-Garcia, Mariel & Rodríguez de la Vega, Ricardo & Gonzalez-Hernandez, Marta & Rosa, M. (2013). Variabilidad y reproducibilidad de 3 métodos para medir el grosor de la capa de fibras del nervio. Archivos de la Sociedad Española de Oftalmología. 88(10). 393-397. DOI: 10.1016/j.oftale.2013.01.012.

Sepúlveda Mora, S. B., Bastos Guerrero, D. C., & Illera Bustos, M. J. (2021). Análisis estadístico de la radiación solar global en Cúcuta utilizando el modelo ANOVA. Tecnura, 25(70), 16–31. https://doi.org/10.14483/22487638.17595

Syasko, V. A., Vasilev, A. Y., & Ivkin, A. E. (2020). Análisis de la influencia de parámetros de interferencia controlados durante las pruebas magnéticas del espesor del recubrimiento. En Revista de Física: Serie de conferencias (Vol. 1636). IOP Editorial Ltd. https://doi.org/10.1088/1742-6596/1636/1/012015

Tobarameekul, Patchaya, Sangsuradet, Supawon, & Worathanakul, Patcharin. (2022). Estudio comparativo de la carga de Zn en Zeolita Funcional Avanzada NaY de ceniza de bagazo y ceniza de cáscara de arroz para la adsorción sostenible de CO2 con ANOVA y diseño factorial. Atmósfera, 13(2). https://doi.org/10.3390/atmos13020314

VIM. (2012). Vocabulario Internacional de Metrología - Conceptos fundamentales y generales, y términos asociados. Organización Internacional para la estandarización. Geneva. 3a Edición (Vim), 104. Recuperado a partir de http://www.cem.es/sites/default/files/vim-cem-2012web.pdf