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Non-quality cost optimization model in a Colombian motorcycle assembler

Modelo de optimización de costos de no calidad en una ensambladora de motocicletas colombiana

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Abstract
Non-quality costs in the motorcycle assembly process are the additional costs incurred due to defects or errors during production. These costs can significantly impact the efficiency and profitability of the assembly process. Therefore, it is essential to implement effective quality control measures to minimize costs and ensure the quality of the final product. In this paper, a multi-objective non-quality cost optimization model is developed to determine the optimal levels of process variables in a motorcycle assembly process. The methodology consists of four steps: (1) statistical analysis of the model variables, (2) transformation and modification of the variables, (3) determination of the lexicographic problem, and (4) analysis of the results. The results showed a high correlation between the variables and the determination of optimal levels of process variables resulting in a reduction of 15% of the total non-quality costs.

Keywords: Quality engineering, Process quality control, Process cost reduction, Optimization tools application.

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Resumen

Los costos de no calidad en el proceso de ensamblaje de motocicletas son los costos adicionales ocasionados por defectos o errores durante la fabricación. Estos costos pueden afectar significativamente la eficacia y rentabilidad del proceso de ensamblaje. Por lo tanto, es esencial aplicar medidas eficaces de control de calidad para minimizar los costos y garantizar la calidad del producto final. En este artículo se desarrolla un modelo multi-objetivo de optimización de costos de no calidad para determinar los niveles óptimos de las variables en el ensamblaje de motocicletas. La metodología consta de cuatro pasos: (1) análisis estadístico de las variables del modelo, (2) transformación y modificación de las variables, (3) determinación del problema lexicográfico, y (4) análisis de los resultados. Los resultados mostraron una alta correlación entre las variables y permitieron la determinación de los niveles óptimos de las variables del proceso, lo que se tradujo en una reducción del 15% de los costos totales de no calidad.

Palabras clave: Ingeniería de la calidad, Control de la calidad de procesos, reducción de costos de procesos, aplicación de herramientas de optimización.

Introduction

Motorcycle assembly processes involve a series of coordinated and sequential operations whose primary objective is to produce a motorcycle for sale and use [1]. This process involves many components and parts, ranging from the engine and chassis to the electrical system, tyres, and exterior finishes [2], and requires appropriate facilities [3], specialised tools [4,5], trained personnel [6] and quality control tools [7,8] to ensure the integrity and safety of the final product.

The motorcycle industry in Colombia has grown significantly and has become one of the main sectors contributing to industrial development [9]; in addition, Colombia has positioned itself as the second largest producer of motorcycles in Latin America, with a record of 10.344.723 motorcycles, representing 60% of the country's vehicle fleet. In the automotive industry there is a unique relationship, and it is the supplier-customer relationship where a necessary delineation is made to differentiate significant boundaries due to the non-quality faced by Tier 1 supplier companies [10]. This type of industry is trapped by the pressure of costs and innovation and is about to experience a revolutionary discontinuity in the generation of innovations [11]; therefore, it has had to adjust and improvements in its systems to guarantee the quality of the final product and avoid costs related to the lack of quality in the processes.

In general, several strategies have been implemented to increase efficiency, improve supplier-customer relationships, and optimize the types of costs identified in the motorcycle industry, including the use of technologies such as big data, total quality management, and assembly line optimization [9,12,13]. Shahi et al. in [14] mentions that the implementation of methodologies with optimization approaches allows to increase the efficiency and quality of products, and Petcharit et al. and Gaviria in [15,16] highlights the importance of innovation and technological updating as factors of industrial competitiveness.

As compliance with quality standards is critical, and the extensive testing required to ensure that each assembled motorcycle meets safety and performance requirements

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before delivery to the end customer, it is essential to plan the assembly sequence and optimise workflows in detail to ensure productivity and efficiency on the production line [17]. Recently, to improve quality and optimise costs, studies have been developed on the factors that influence the process, starting from structural models [15,18], Measurement Systems Analysis (MSA) [19], and Genetic Algorithms [20].

In addition, to validate these studies, some authors highlight the necessity to incorporate different techniques into the supply chain that help validate the information for decision making, optimise processes, avoid cost exceeds, and validate the management of defective product recalls [21,22,23]. On the other hand, in [24,25] and [26] different studies have been developed in recent years to know the trends, applications and developments in supply chains. In [27], Bal and Satoglu demonstrate and validate how strategic supply chain planning and consideration of real situations through the application of a multi-facility, multi-period and multi-product model can achieve efficient planning.

In the aerospace manufacturing industry, a major area of research has focused on clamping force during the assembly process. To this end, de Mello et al. in [28] applied Taguchi's experimental method and process capability analysis to validate these methods as effective in significantly optimising the assembly quality and geometry of manufacturing processes in the aerospace industry. Authors in [29] mentions that it is not only important to optimise the processes of the different production lines or assembly processes, but also to improve quality indicators through the implementation of Key Performance Indicators (KPIs) to facilitate decision-making.

In automotive companies it is important to reduce the number of defects per million in assembly processes, through strategies such as Kaizen [30] and Poka-Yoke [31]. These strategies can be supported by traditional approaches to compare their performance [32,33] or by techniques based on multiple targets and constraints, considering the sorting and construction of new penalties in the result analysis [34]. Thus, a cost-effective approach to optimization is obtained by ranking the constraints according to the computational cost achieving the feasibility of new penalties [35].

Despite advances in research to date, there is a gap in the development and implementation of flexible process improvement models [36]. Therefore, this paper develops a multi-objective optimisation model for non-quality costs to determine the optimal levels of process variables. The methodology is applied to a company in the automotive industry in Colombia. The main contribution of this work is to contribute to the development of new flexible quality tools for modelling complex engineering problems. The following sections describes the methodology used and then presents and discusses the results.

Methodology

The methodology used consists of four steps (Figure 1). First, the model variables are determined, and a multiple regression analysis is performed. Second, the variables are transformed, and the previously obtained regression equation is modified. Then, the penalized equation and the constraints related to the lexicographic problem are determined and, finally, the results are analyzed to identify the optimal levels of the variables to optimize the non-quality costs in the motorcycle assembly.

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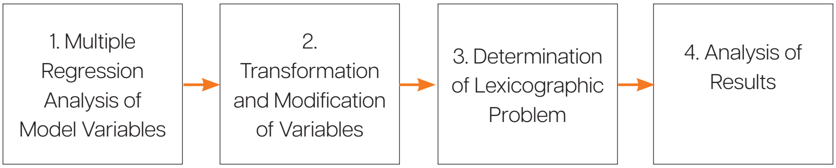

Figure 1. Methodology stages. Own elaboration.

Results

Multiple Regression Analysis of Model Variables

Identifying the key variables in motorcycle part assembly is critical to developing an effective non-quality cost model. This approach enables more efficient allocation of resources, implementation of targeted corrective and preventive actions, and continuous improvement of the production process. By understanding and addressing the root causes of defects, the company can reduce material and resource waste, and improve customer satisfaction. Data-driven decision-making, and the application of solutions focused on non-quality variables contribute to more efficient, cost-effective, quality-driven production and customer satisfaction. The analysis has been developed using a real database from a company in the automotive industry. The input, process and output variables are detailed in Table 1. Note that the variables are measured in US dollars.

Table 1. Model variables. Own elaboration.

Variable type	Variable description	Process specifications
Input variable	Total number of units per period (A)	[4,500 < 4,820 < 5,000]
Process variables	Total Unit Cost of Fairing (R1)	(1,100 < 1,180 < 1,240]
	Total Unit Chassis Costs (R2)	[400 < 420 < 460]
	Total Unit Brake Costs (R3)	[140 < 150 < 160]
	Total Unit Costs of Guayas (R4)	[12 < 13 < 14]
	Total Unit Engine Costs (R5)	(2,120 < 2,220 < 2,340]
	Total Unit Costs of General Parts (R6)	(3,760 < 3,850 < 3,940]
	Total Unit Costs of Wheels (R7)	[480 < 510 < 540]
	Total Unit Costs of Electrical Systems (R8)	(860 < 900 < 950]
	Suspension Total Unit Costs (R9)	(480 < 700 < 950]
Output variable	Total Costs (**Y**)	[42,200 < 44,400 < 46,600]

The database was within two years and classified into twenty-nine periods for each variable to know the behavior of the variables through the classifications. Figure 2 shows the behavior of the variables, where A, R_1, R_2, R_3, R_4, R_5, R_6, R_7, R_8, R_9 and Y are represented by the orange, light grey, yellow, light blue, green, purple, dark brown, dark grey, light brown, and dark blue lines, respectively.

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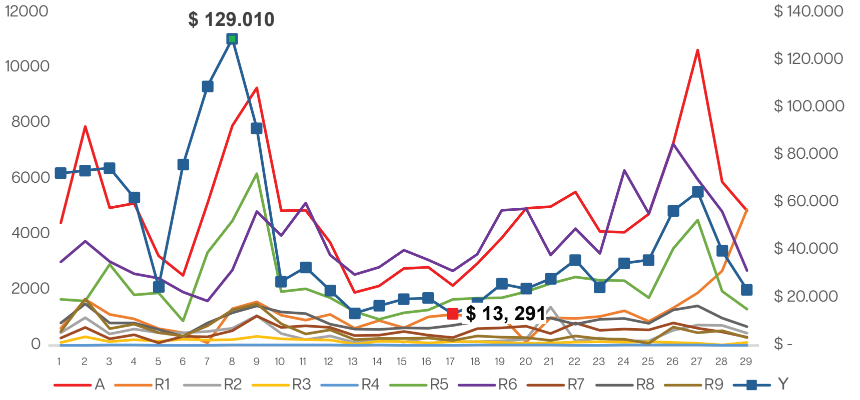

Figure 2. Oscillatory behavior of the variables over the twenty-nine periods. Own elaboration.

After analyzing the behavior of the variables in Figure 2 is notable that the lowest trend in all periods is R4, and the highest trend over the twenty-nine periods regarding Y are A, R6, and R5. In addition, the highest trend total unit of recall occurred in period eight, reaching a value of $129,010, and the lowest total unit cost of withdrawal occurred in period seventeen, reaching a value of $13,291.

On the other hand, after identifying the variables of the model and knowing the behavior of the data (see Figure 2), a correlation analysis was performed to determine the presence, direction, and external association between them. Figure 3 details the information obtained in the correlation of the model variables, where Y and R_9, Y and R_5, A and R_8, A and R_5, A and R_2, R_3 and R_9, R_4 and R_6 , R_5 and R_8, R_6 and R_7, R_7 and R_8 y R_8 and R_9.

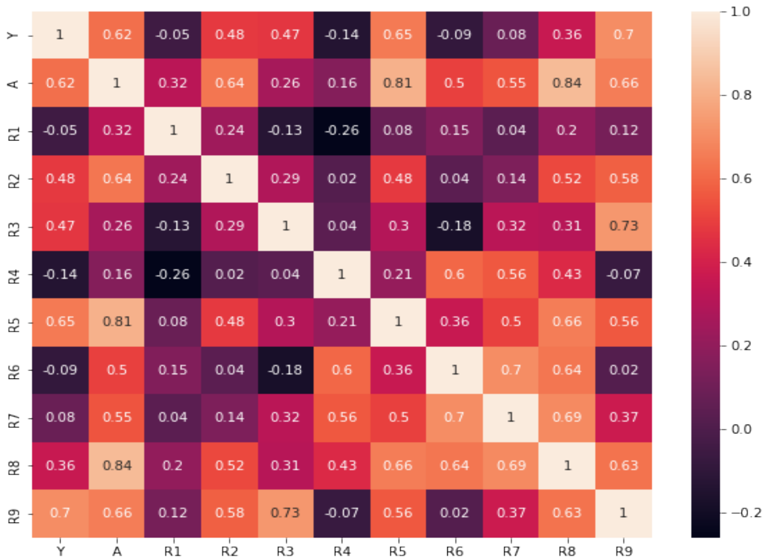

Figure 3. Correlation variable matrix. Own elaboration.

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A multiple linear regression analysis was then performed to obtain the equation presented in (1). For this purpose, as developed for Morán-Zabala and Cogollo-Flórez in [36], the assumptions of linearity, independence, homoscedasticity, normality, and non-collinearity of the models were validated by calculating the correlation coefficient, the Durbin-Watson statistic, the Levene statistic, the Anderson-Darling statistic, and the variance inflation factor, respectively.

$$\boldsymbol{Y} = 27.258 + 59.6282A - 6R_1 - 13R_2 + 35R_3 + 991R_4 + 7R_5 - R_6 - 50R_7 - 59R_8 + 41R_9 \quad (1)$$

Transformation and Modification of Variables

Transformation of variables to obtain one-side specifications and modify the constant terms in the regression equations applying $x_k = x_i - LSL \leq (USL\text{-}LSL)$ is shown from (2) to (11). Then, the modified regression equation considering that $Y_n' = C + R' + x_1' - x_2' + x_3' + \ldots + x_m'$ are presented in (12).

$$A' = A - 4.500 \leq 500 \quad (2)$$

$$R_1' = R_1 - 1.100 \leq 140 \quad (3)$$

$$R_2' = R_2 - 400 \leq 60 \quad (4)$$

$$R_3' = R_3 - 140 \leq 20 \quad (5)$$

$$R_4' = R_4 - 12 \leq 2 \quad (6)$$

$$R_5' = R_5 - 2.120 \leq 220 \quad (7)$$

$$R_6' = R_6 - 3.760 \leq 180 \quad (8)$$

$$R_7' = R_7 - 480 \leq 60 \quad (9)$$

$$R_8' = R_8 - 860 \leq 90 \quad (10)$$

$$R_9' = R_9 - 480 \leq 470 \quad (11)$$

$$Y' = 74.317 + 56.714A' - 6.675R_1' - 5.231R_2' + 4.915R_3' + 11.889R_4' + 14.960R_5' - 3.760R_6' - 23.835R_7' - 50.563R_8' + 19.540R_9' \quad (12)$$

Determination of Lexicographic Problem

The GP Lexicographic problem determination is reduced to minimizing the sum of the deviation variables from the constrained goal, considering the priority of factors [37]. Thus, Cherif et al. and Morán-Zabala and Cogollo-Flórez in [36] and [38] poses the process control problem as a GP Lexicographic problem, as follows:

$$Min\ P_{Y_i} \sum_{i=0}^{l} (\delta_{Y'}^{+} + \delta_{Y'}^{-}) + P_{A_k} \sum_{j=0}^{k} (\delta_{A'}^{+} + \delta_{A'}^{-}) + P_{R_i} \sum_{t=0}^{r} (\delta_{R'}^{+} + \delta_{R'}^{-}) \quad (13)$$

The penalized equation considering the goal ponderations and the variables model minimization are detailed in (14). Here is important to highlight that there are some variables only with negative penalization and other with both, negative and positive. When the penalized variable considers both is due to the needed of being strict with

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the fulfillment of the process specification. On the other hand, as the objective is to minimize the total cost, when variables are only penalized in a negative way it is only as those variables can decrease more than the others without causing errors into the model solutions.

$$\boldsymbol{Min\ m}: P_Y(\delta_Y^-) + P_{R_1}(\delta_{R_1}^-) + P_{R_2}(\delta_{R_2}^- + \delta_{R_2}^+) + P_{R_3}(\delta_{R_3}^- + \delta_{R_3}^+) + P_{R_4}(\delta_{R_4}^- + \delta_{R_4}^+) + P_{R_5}(\delta_{R_5}^-) + P_{R_6}(\delta_{R_6}^-) + P_{R_7}(\delta_{R_7}^- + \delta_{R_7}^+) + P_{R_8}(\delta_{R_8}^-) + P_{R_9}(\delta_{R_9}^-) + P_A(\delta_A^-) \quad (14)$$

Subject to:

Input Constraints:

$$A' + \delta_D^- = 500 \quad (15)$$

Process Constraints:

$$R_1' + \delta_D^- = 140 \quad (16)$$

$$R_2' + \delta_D^- - \delta_D^+ = 60 \quad (17)$$

$$R_3' + \delta_D^- - \delta_D^+ = 20 \quad (18)$$

$$R_4' + \delta_D^- - \delta_D^+ = 2 \quad (19)$$

$$R_5' + \delta_D^- = 220 \quad (20)$$

$$R_6' + \delta_D^- = 180 \quad (21)$$

$$R_7' + \delta_D^- - \delta_D^+ = 60 \quad (22)$$

$$R_8' + \delta_D^- = 90 \quad (23)$$

$$R_9' + \delta_D^- = 470 \quad (24)$$

Output Constraints:

$$Y' + \delta_{Y'}^- = 4{,}000; \quad i.e.$$

$$56{,}714A' - 6.{,}75R_1' - 5{,}231R_2' + 4{,}915R_3' + 11{,}889R_4' + 14{,}960R_5' - 3{,}760R_6' - 23{,}835R_7' - 50{,}563R_8' + 19{,}540R_9' = 42{,}190 \quad (25)$$

The constraints (16) to (24) guarantees the fulfillment of targets R1 to R9, as since the positive (δ^+) and negative (δ^-) deviations from the minimization of the penalized equation of the response variable are equal to zero, there is a satisfactory solution in Y = $30.006. Failure to meet specifications under the non-quality cost control model can result in increased expenses due to returns, warranty claims, and rework, which directly affects the company's operational efficiency and increases production costs. In addition, poor product quality can result in the loss of customers and damage the company's reputation in the marketplace.

The solution presented above corresponds to a 15% reduction in the total cost of assembling the motorcycles without quality, therefore, Figure 4 shows the percentage

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reduction obtained for each of the variables of the model after its application, where the variables with the greatest impact on the total reduction of 15% were R6 and R5, with 48% and 17%, respectively.

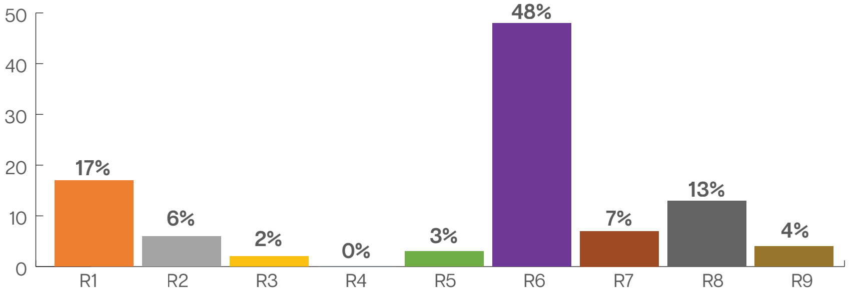

Figure 4: Percentage reduction of each model variable. Own elaboration.

Conclusions

Controlling non-quality costs has a wide positive impact on cost reduction by reducing the costs associated with non-quality, such as rework and returns. The improvement in product quality that results from addressing the variables considered for this study increases productivity by optimizing processes and minimizing the time spent correcting defects in motorcycle assembly.

The approach presented is flexible and adaptable to different industries, so it is not limited to the automotive assembly line. Its usefulness can be extended to cost reduction, resource optimization, and delivery time; to logistics and supply chain for efficient route and inventory management; and to energy and environment for minimizing emissions and production costs. Its versatility makes it a valuable decision-making tool in any industry where multiple objectives must be considered simultaneously.

Non-quality costs reflect quality performance in assembly and other stages of the motorcycle supply chain. Although non-quality costs can occur in any organization, their reduction should be the primary objective. The approach presented helps decision makers improve quality decisions on the assembly line. Although this approach allowed a 15% reduction in the total non-quality costs of the data analyzed in the motorcycle assembly line, tests and methods are needed to strengthen and improve the robustness of the model's application in the future. Future work will focus on the comparison of other optimisation approaches and complementary tools to validate the information obtained through optimisation, such as simulation models, artificial intelligence, heuristics, and metaheuristics.

Authors contribution

Yesenia Mejía contributed to the methodology design, data curation, data analysis, validation and verification of results, writing, critical revision of the intellectual content of the manuscript and production of tables, figures or supplementary material; Jean P. Morán-Zabala contributed to the methodology design, data curation, data analysis, software development, validation and verification of results, writing, critical revision

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of the intellectual content of the manuscript and production of tables, figures or supplementary material; Andrea L. Flórez-Rendón contributed to the methodology design, validation and verification of results, writing, critical revision of the intellectual content of the manuscript and production of tables, figures or supplementary material; Juan M. Cogollo-Flórez contributed to the methodology design, data curation, data analysis, software development, validation and verification of results, writing, critical revision of the intellectual content of the manuscript and production of tables, figures or supplementary material.

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