Product Performance Improvement Proposal: a Multi-Methodological Approach from Design for Six Sigma and Design of Experiments

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Abstract:
This article uses the structure and elementary concepts of Design of experiments to apply to the corporate environment, as a structural basis for the stability of the manufacturing process, improvement of product performance, and, consequently, the reduction of industrial costs (a constant bottleneck in the corporate environment). Sincere the fundamental proposal used in the experimentation is the concrete understanding of the impact of the input variables (factors), as well as knowing the relationship (interaction) between them. Only that, with such knowledge, there is full mastery of the process in question. As it is a robust model, which is associated with an investment for its implementation, it is understood that, in a previous stage, the process or product that will ok analyzed is in full alignment with the strategic objectives of the business. Thus, after modeling and applying the Design For Six Sigma (DFSS) philosophy and its various methodologies, together with statistical experimentation techniques, it was concluded that it is possible to maximize the performance of a product starting from the strategic vision of the business and unfolding it into effective product (service) actions.

Keywords: Design of Experiments (DOE), Design For Six Sigma (DFSS), Product Development.

1. Introduction

Statistical experimentation was introduced by Fisher (1926) where his laboratory was the field. Due to his training, as a mathematician and biologist, at the University of Cambridge (England), he applied his specific knowledge in an agricultural station. In the term factorial, it is understood that there is a study with multiple factors simultaneously, to understand the behavior of isolated factors and their interactions.

For Petenate & Santos (2012), this agricultural research center served to introduce and validate the concepts of experimentation and, as a result, increase agricultural productivity, specifically studied by him, by using different types of fertilizers in planting.

In the understanding of Bhote (1996), Dr. Genichi Taguchi (reference in statistical experimentation), who worked directly with Dr. Fisher, when developing the method of orthogonal matrices, allowed the insertion of this concept in the industrial area and, proved that the method was more effective than the Statistical Process Control (SPC), widespread at the time. Motorola, still in the 1986s, when creating the Six Sigma philosophy, understood the effectiveness of the proposed method, and basically, the principles of performance management in the company were anchored in experimental projects. Awad & Shanshal (2017) understand that, given the effectiveness and effectiveness proven with the applicability of the method, there is great potential to minimize industrial costs. Because, with the simulation process, errors are predictable and controlled.

To Pathiratne; Khatibi & Md Johar (2018), considering the high competitiveness between major competitors, the proposal of strategic alignment applied to robust prioritization and effectiveness techniques in improvement projects as a market expansion strategy (market share). Given this, it is understood that the proposed methodology (Design For Six Sigma and the method of statistical experimentation) is a powerful strategic tool in structuring the model, as well as in decision making.

This article proposes to validate the multi-methodological approach between Design For Six Sigma and Design of Experiments to improve product performance or in the launch stage of a new product proposal. It also proposes the usability of experimental statistics concepts as an analytical element incorporating daily life.

2. Product structure

Pahl *et al.* (2005) understand that a Product Development structuring is formed by a sequence of steps/stages based on procedures that aim to transform relevant information

and opportunities demanded by the market that will be reflected in specifications (input - process - output). This is the essence of the Critical To Quality (CTQ) methodology. Jung *et al.*

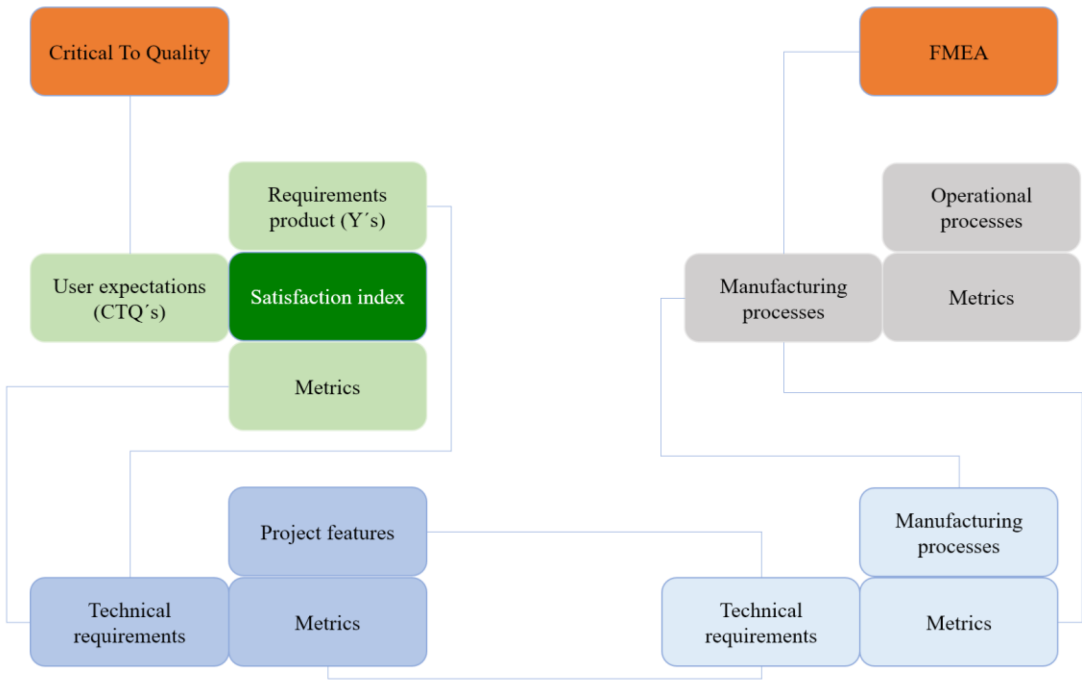
(2009) argue that it is essential, among the existing models for Product Development (DP) and Product Development Process (PDP), to consider the organizational culture formed by concepts and beliefs.

> Product Development Process Models (PDPs) are broader, start with the strategic planning of the project, determine the product management and development process and, later, propose the follow-up in the market and discontinuation of the product (CHENG, 2000).

Taguchi (1979), summarizes the QFD structure "Hinshitsu Kino Tenkai (Akao, 1972) in four steps, these fundamental ones that will cover the entire extension of the production system:

i. Product planning;
ii. component/product design;
iii. process planning;
iv. process control planning.

Figure 1 – Quality Function Deployment (QFD) – *Akao Model*



Source: Adapted Akao (1972)

In this alignment, Peixoto and Carpinetti (1998) understand that the Quality Function Deployment (Akao Model or QFD) thinking is directly linked to the corporate strategy. Thus, they highlight 4 pillars:

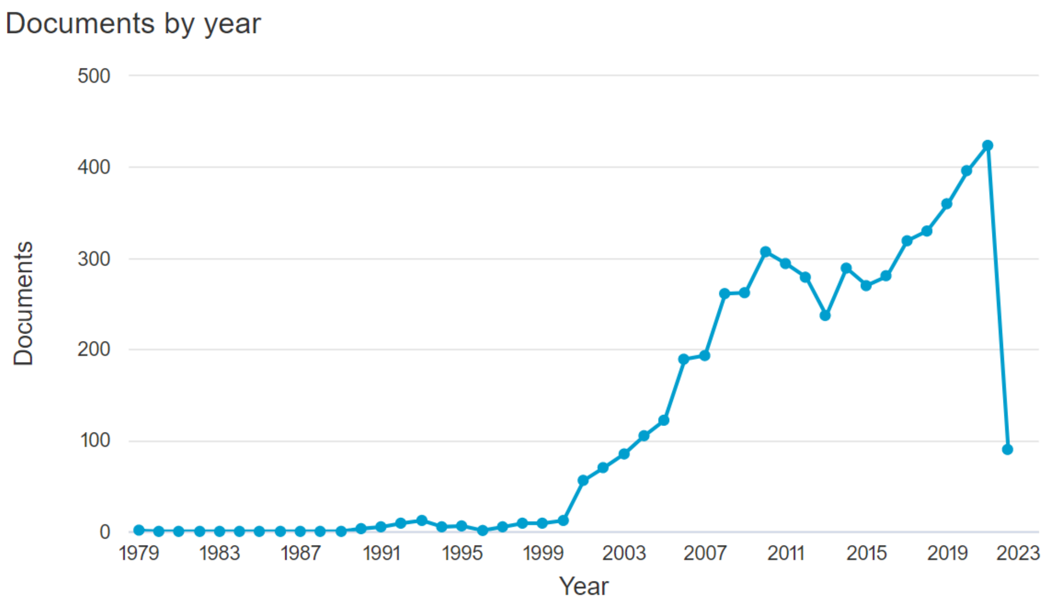
i. the unfolding of quality;
ii. the unfolding of technology;
iii. the deployment of costs;
iv. the unfolding of reliability.

This research will take a deeper approach to the planning cycle of processes as product assurance.

3. Design For Six Sigma (DFSS)

To validate the relevance of the DFSS and its respective impact on corporate strategy, a search was carried out in the Scopus database, and thus it can be seen that studies with this approach have already begun in the 1990s (figure 2). And, after 1999, there is a growing amount of production on this subject.

Figure 2 – Scopus database analysis



Source: Scopus (2022)

Approach Jenab; Wu & Moslehpour (2018), highlight the applicability of Six Sigma to minimize the defect rate and direct applications to failures in the performance of a process. Francisco; Canciglieri Junior & Sant'Anna (2020), describe an approach focused on the field of corporate strategy.

In this sense, the depth of the methodology is verified in dealing with the solution of organizational structural problems.

Considering that Design for Six Sigma's primary objective is to deliver a new product (service) conception, aligned with this purpose, some methods that are based on DFSS thinking and are validated by the market, as well as by the academy. The application of Design for Six Sigma (DFSS) concepts in the PDP is an approach that has been expanding, and the application of this methodology in new product projects is now widely defended (FRANCISCO;

CANCIGLIERI JUNIOR & SANT'ANNA, 2020). Regardless of the type of DFSS (table 1), the steps of the method follow a logical roadmap, from its conception, rationale, and purpose.

Table 1 - Structural steps DFSS

DFSS methods	Phases
DMADIC	*Define, Measure, Analyze, Design, Implement and Control*
DMADV	*Define, Measure, Analyze, Design and Verify*
DMADOV	*Define, Measure, Analyze, Design, Optimize and Verify*
DDOV	*Define, Design, Optimize and Validate*
ICOV	*Identify, Characterize, Optimize and Validate*
DMEDI	*Define, Measure, Explore, Develop and Implement*
DCCDI	*Define, Customer, Concept, Design, and Implement*
I^2DOV	*Invention and Innovation, Develop, Optimize and Verify*
PIDOV	*Plan, Identify, Design, Optimize and Validate*
IDDOV	*Identify, Define, Develop, Optimize, Verify and Validate*
DIDES	*Define, Initiate, Design, Execute and Sustain*
CDOV	*Concept development, Design development, Optimization and Verify*
DCOV	*Define, Characterize, Optimize and Verify*
IDEAS	*Identify, Design, Evaluate, Assure and Scale-up*

Source: Francisco, Canciglieri Junior & Sant'Anna (2020)

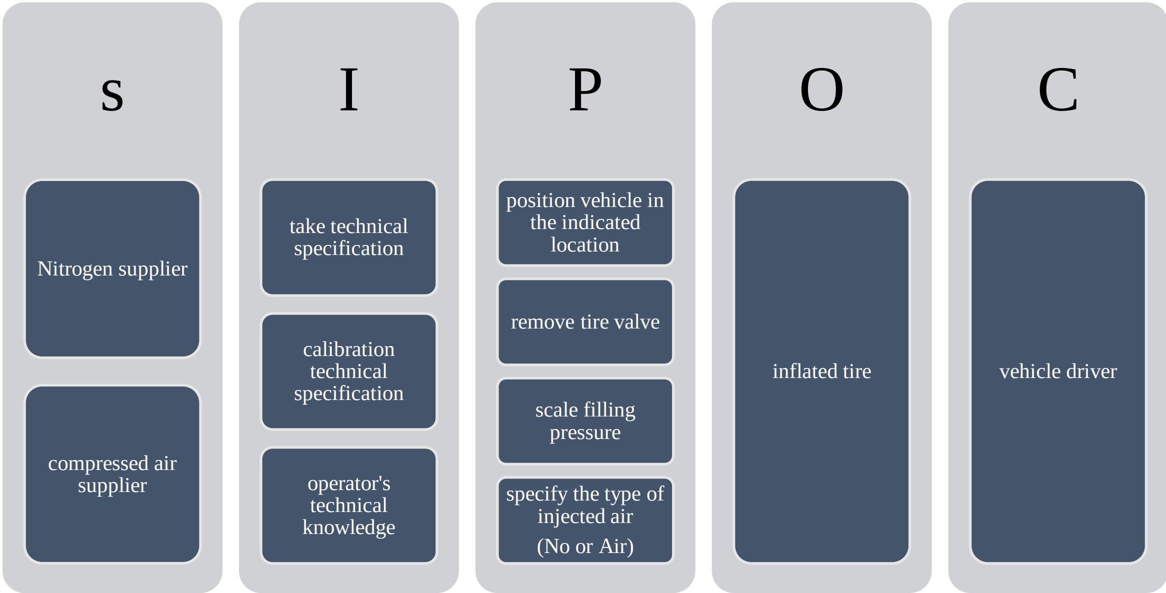
3.1. Process Mapping

The main purpose of managing a process is to ensure product quality and minimize the financial impacts on the corporation (company). The person who initiated this thought was Dr. Shewhart, with the cycle that we currently call PDCA, but literally, this cycle is known as the Shewhart cycle, still in the 1930s, with the need to insert conceptual elements of Statistics into the manufacturing process, as a way of minimizing the impacts of non-quality in the financial indices of the business.

For Rontondaro (2008) process mapping is a primary model for understanding the dynamics of a given organism. And, through the Flowchart (one of the seven Quality tools) it is possible to see the relationship of interdependence between certain factors of the process in question. A very widespread method, in the corporate world as well as in the academic environment, for its ease of execution and effectiveness in the application is the SIPOC (Supply, Input, Process, Output, Customer). Through this method, it is possible to visualize the opportunities for improvement and even perceive possible incidences of variation noise generation in the process.

In the diagram (figure 3), an example of the applicability of the method can be verified and, specifically in this example, it is possible to verify the mapping of the process of calibrating the tires of a vehicle.

Figure 3 – SIPOC diagram



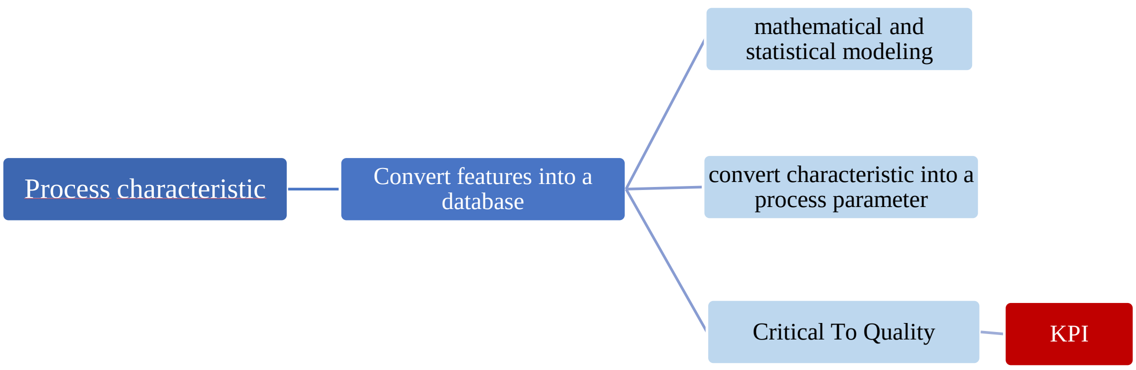
Source: Authors (2022)

Carpinetti (2012) understands that, through this macro analysis, mapping the process, it is possible to deepen an investigation, in search of the critical factors of this process; and that tools and devices allow minimizing their effects and impacts on the production chain.

3.2. Root Cause Analysis

The objective of breaking down the process into factors is to make visible the understanding of the sensitive points in the respective flow (figure 4).

Figure 4 – Critical To Quality Structure



Source: Authors (2022)

Pyzdek and Keller (2011) describe this flow in the form of a function, according to expression (1):

$$Y = f(X1, X2, X3, \dots Xn) \qquad (1)$$

Y: response variable or the dependent variable
Xn: input variables or factors

In this way, the input variables are the cause that will impact the response variable or the effect.

For Risberg Ellekjær & Bisgaard (1998), statistical experimentation is directly linked to vital variables (relevant process variables). Thus, a determining aspect to isolate such variables is through the Failure Mode Analysis (FMEA) methodology, since this is an effective device for stabilizing a process. It is assumed that the improvement process depends directly on its stability to materialize. Other tools support and guarantee this stability.

Among the seven tools, the following stand out: the flowchart and the cause-and-effect diagram. The flowchart, with visual characteristics of connections that allow a macro view of a system or subsystem, facilitates the understanding and flow of information throughout the chain. The Cause-and-Effect Diagram (Ishikawa diagram) allows relating the interference of factors (input variables) in the response variable or the final product. This structure allows, through robust techniques, to guarantee the concrete basis of a stable process.

4. Factorial Experiments

Rontondaro (2008) understands that, when approaching the theme of *Statistical Experimentation* or *Design of Experiments*, some mandatory steps were strictly adhered to earlier. Therefore, at this stage, it is elementary to understand which variable in the process under analysis is critical. Being a primary factor in decision making. To deepen the subject, it is necessary to understand some specific terms of this theme, starting from the expression of Pyzdek and Keller (2011), *Y = f(x).*

Are they:

Factors: These are the *independent variables* or the input variables $(x_1, x_2, \dots, x_n)$.
Levels: It can be understood as the value that each factor will assume in the experiment.

By definition, the *"low" and "high" levels are used* (-; +).

Answer: It is the *dependent variable* (Y) of the experiment.
Noise: These are interferences that act in the process and that there is no control over them.

To detail and improve the understanding of noise below is a breakdown.

Types of noise.

i. interns
ii. External *(environmental)*
iii. Variations

Examples:

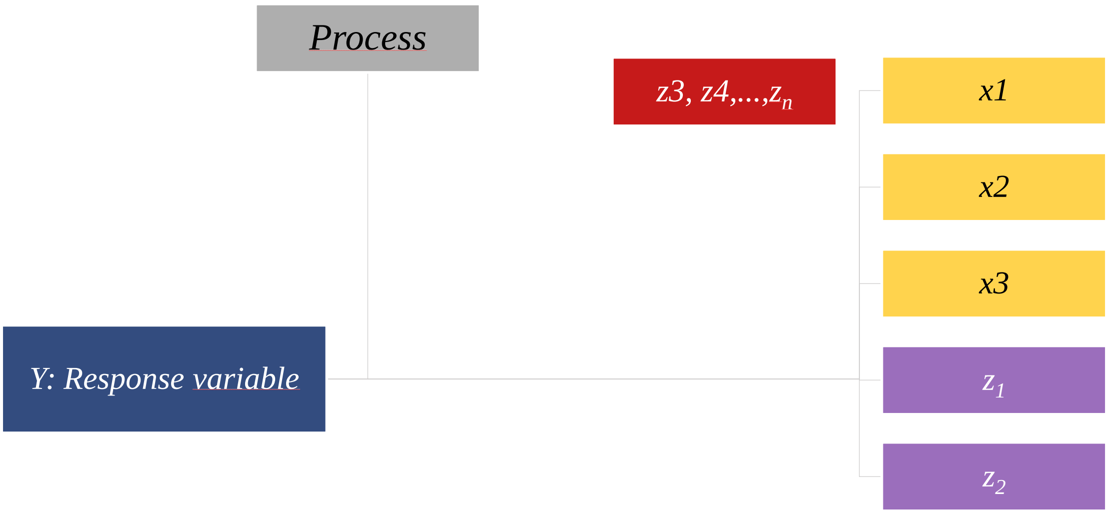
Internal: a failure in the rotor of an electric motor which, due to slack, due to wear of a belt on the pulley, will affect the performance of a characteristic of the final product.

External: A certain food that needs refrigeration, certainly, in its accommodation on the shelf of the commercial establishment, its performance will be affected.

Variational: In the metal forming process, in a manufacturing process, failure in a specific (*dimensional*) dimension, due to wear on the cutting tool, may interfere with the final product.

Costa (2019) understands that the objective of any experiment is to identify the components active in each process and to measure the impact of each factor and level on the response variable. And, in this way, structure its processes and products, considering this interaction (figure 5), between the control factors (x_1, x_2, x_3, ..., x_n), as well as the performance of noise (z_1, z_2, z_3, ..., z_n).

Figure 5 – Performance of control factors and process noise



Source: Adapted Costa *et al*. (2021)

According to Antony *et al*., (2006), experiments can be classified as **complete**, where at least one observation is analyzed among all possible combinations. Check the example below:

4 factors (x_1, x_2, x_3, x_4)
x_1: 2 levels
x_2: 2 levels
x_3: 2 levels
x_4: 2 levels

The applicable notation is 2^k
k: number of factors
2: signals the number of levels.

Thus, the total number of experiments is 16 (2^4).

For **fractional experiments**, still, according to, some observations will not be considered, but even with such restrictions, it is possible to conclude. According to Uluskan and Oda (2020), this experimental model is applied to meet possible cost constraints or, due to technical infeasibility. According to Sin *et al.* (2015), regardless of the classification of the experiment, the objective remains: To know the effect of varying the factors on the final response (*Y*). To detail and establish the understanding of the practice of experimentation, a *cross table was structured* (table 2) to highlight the factors and the respective levels, which will be considered in this example.

Table 2 - Effect of varying levels and interaction

# experiment	test sequence	*A*	*B*	*C*	result/effect
1	2	-1	-1	-1	Y1
2	5	1	-1	-1	Y2
3	7	-1	1	-1	Y3
4	1	1	1	-1	Y4
5	6	-1	-1	1	Y5
6	4	1	-1	1	Y6
7	8	-1	1	1	Y7
8	3	1	1	1	Y8

Source: Authors (2022)

To consider the levels ("low" - ; "high" +), the following logic was applied (highlighted in red), for the respective columns:

A: 2^0 (- + - + - + - +)
B: 2^1 (- - + + - - + +)
C: 2^2 (- - - - + + + +)

According to, the notation for calculating the main effect, as well as its interactions, follows the second-order interaction (more applied to reality).

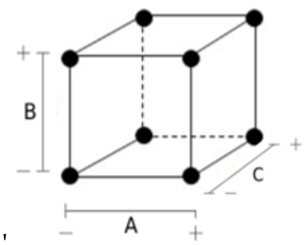
$$\binom{k}{2}\frac{k!}{2!(k-2)} = \frac{k(k-1)(k-2)}{2!(k-2)} = \frac{k(k-1)}{2} \quad \textit{(Second order interaction effects)}$$

$$\binom{k}{3}\ third\ order\ interaction\ effects$$

$$\binom{k}{k}\ k\ order\ interaction\ effects: main\ effects$$

The experiment is represented by a cube (figure 6), where each edge is a response, resulting from the combination between level and factor.

Figure 6 – Geometric notation of this experiment



Source: Authors (2022)

Result prediction with predicted error, according to regression equation (2);

$$\hat{y} = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_{12} x_1 x_2 + \beta_{13} x_1 x_3 + \beta_{23} x_2 x_3 + \beta_{123} x_1 x_2 x_3 \quad (2)$$

Where each term can be understood:

β_0: *constant*

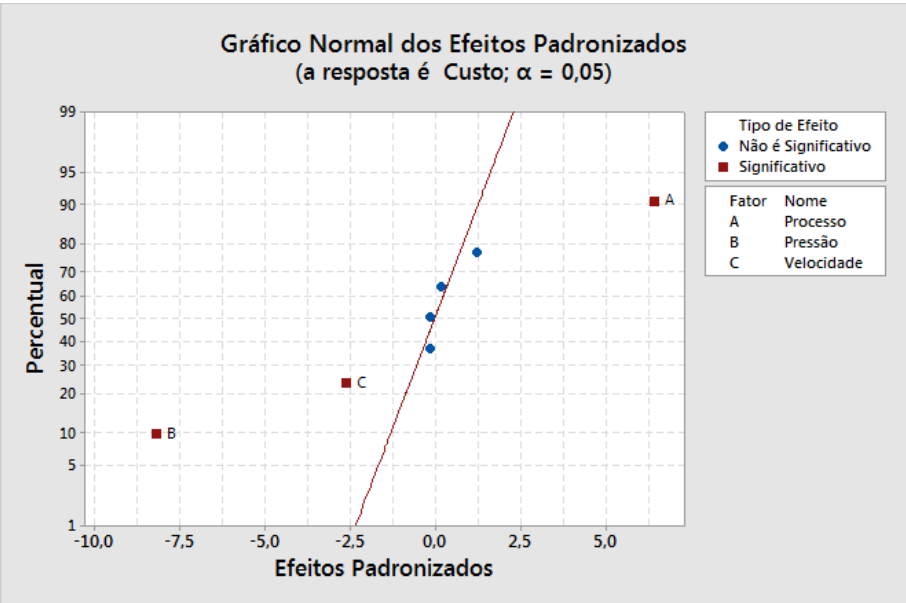
$\beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3$: *linear terms*

$\beta_{12} x_1 x_2 + \beta_{13} x_1 x_3 + \beta_{23} x_2 x_3$: *second order interaction*

$\beta_{123} x_1 x_2 x_3$: *third order interaction*

Schnitzler; Grassi and Quinaia (2009) emphasize that the graph of standardized effects (figure 7) presents the effects for each response of interest and that the effects of lesser magnitude, for those that **are not representative**, have a normal distribution with a mean of zero and the variance is constant. These points tend to be distributed along the line. The **representative effects, on the** other hand, have means different from zero and, therefore, stand out from the respective line.

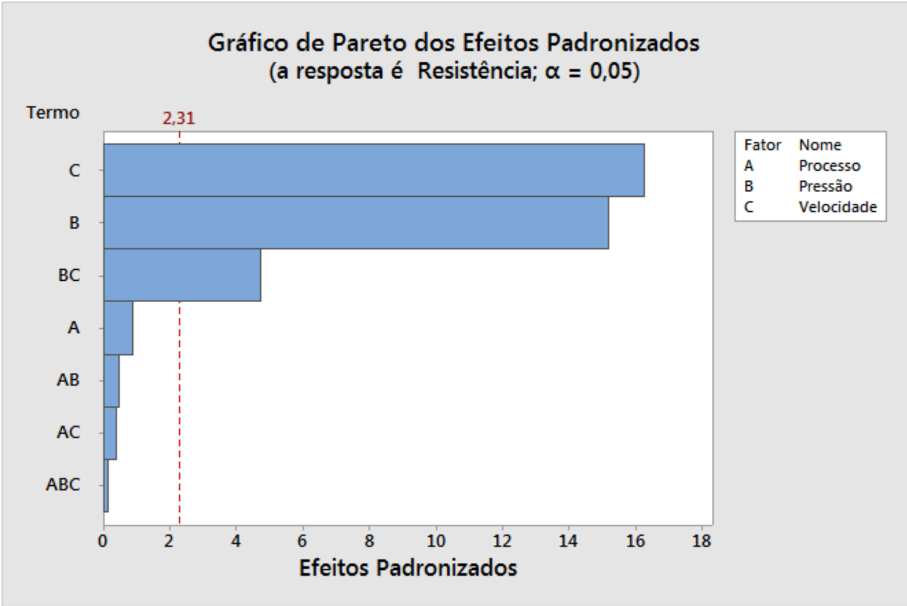
Figure 7 – Effects Graph (*Normality Straight)*



Source: Minitab Support (2022)

The points of greatest impact and relevance (figure 8), to the process in question, will be highlighted according to the order of magnitude in the Pareto chart of the effects.

Figure 8 – Effects Graph (Pareto)

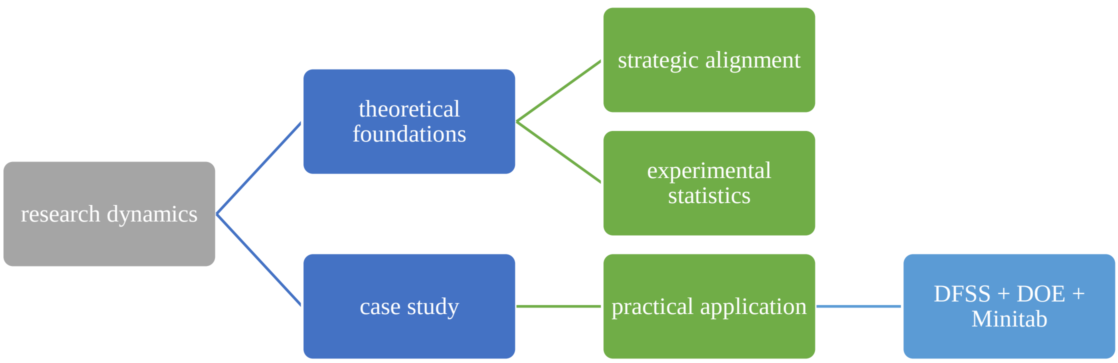


Source: Minitab Support (2022)

5. Method and Results

This work is the result of field research (figure 9), with *on-site visits* to collect data, process analysis, and carry out the test rounds, together with the specialized technical team from the areas of production, maintenance, and processes, to understand which *factors* contribute and directly impact the structure of the final product, plastic caps with *liner* (seal). With this knowledge, it is possible to reformulate process parameters and specifications (process window for each parameter) as a basis for continuous improvement and process stabilization. For data analysis and statistics, the *Minitab software was used*, which was designed with this objective in mind.

Figure 9 – Research structure



Source: Authors (2022)

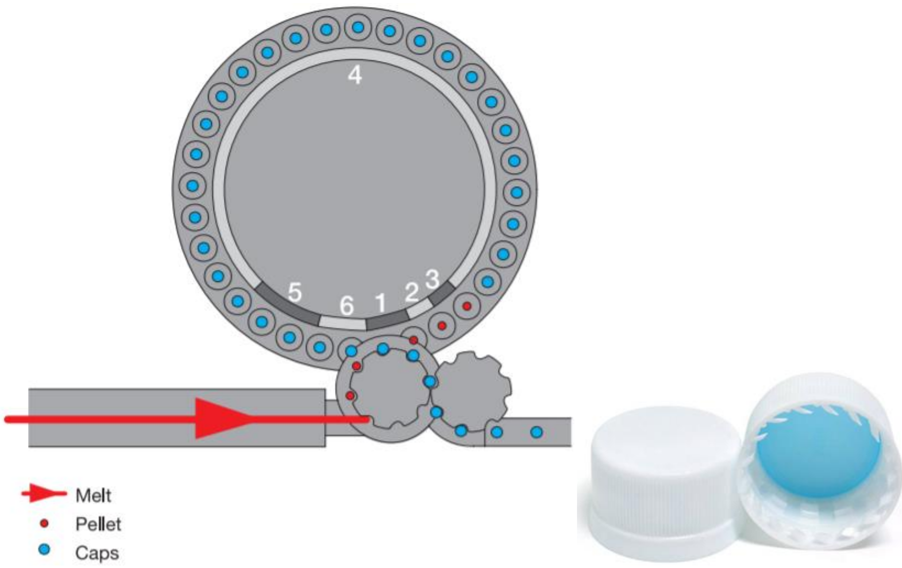
Specifically, the study was developed in a multinational industry, a reference in the plastic caps segment, and the purpose of this study was given by the need to find the best process window and guarantee a competitive performance and stand out in the competition. For this, given the elements, the statistical experimentation techniques were applied in a production line of lids with liner, which uses this PMV224 equipment (figure 10).

Figure 10 – Specific equipment for manufacturing plastic caps

Source: Manufacturer's Manual (2022)

According to the present study, a list of relevant technical attributes *(critical factors) was elaborated* to analyze and understand the best final composition and, then, make a decision based on this proposed structure. The factors and their weights were defined by specialists from the areas of process engineering and maintenance, who detailed the mapping of this process. The focus of this study, according to the mapping carried out, points out that this component, of conformation of the *liner* and junction to the lid, has a significant impact on the response variable (figure 11).

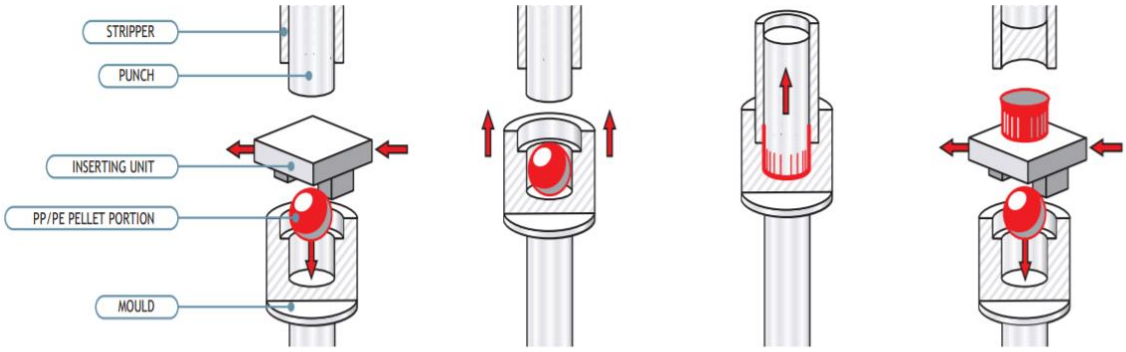
Figure 11 – Detail of the liner applicator component



Source: Manufacturer's Manual (2022)

It can be seen in the detail of the application of the sealing component (figure 12), after going through the process of heating the *polyvinyl chloride* (PVC) to then be shaped together in the lid. This study addressed the factors (variables) that are relevant to such an application.

Figure 12 – Detail of the liner applicator component



Source: Manufacturer's Manual (2022)

Based on the process mapping, the critical factors related to experimentation are:

x_1: *forming pressure*

x_2: *compression spring*

x_3: *spindle rotation*

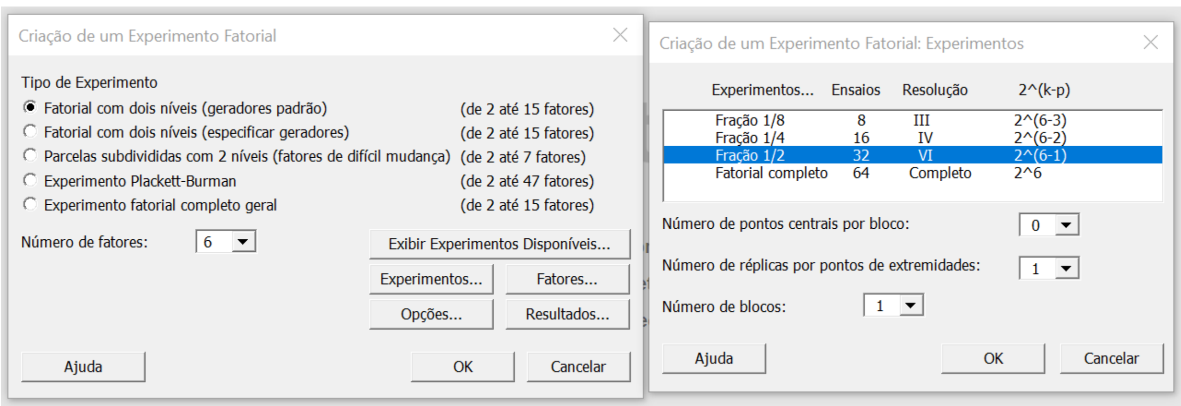
x_4: *injection temperature (spindle)*

x_5: *puncture temperature x die*

x_6: *pellet hardness and geometry (PVC)*

According to this relationship, there is an experimental basis of 2^6 (64 trials). But considering the base of the fractional experiment, 32 trials will be needed, generated by the *Minitab statistical software* (figure 13). Understanding that there is an inherent cost in performing each experiment, without losing the level of significance, the feature of fractional experiments is applied.

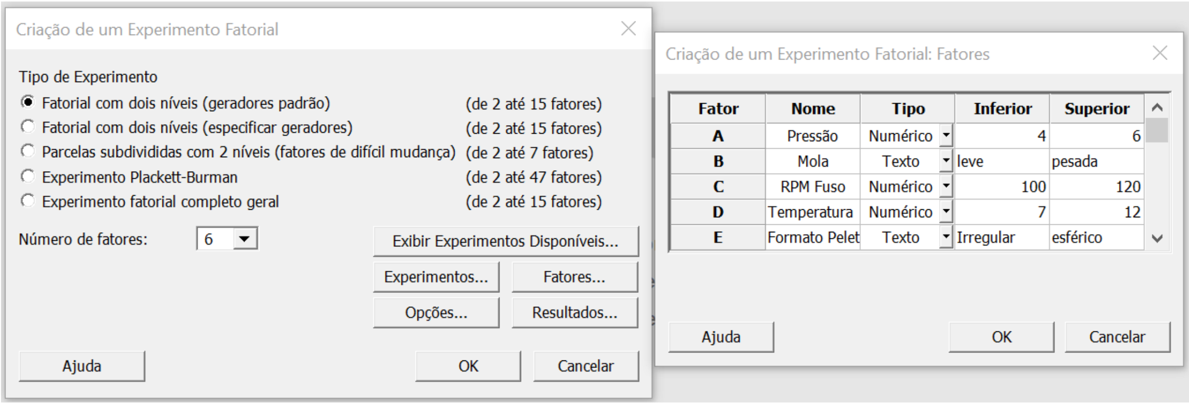
Figure 13 – Trial setup experiment



Source: Authors (2022)

Then, it was followed with the *inputs* of the factors and their corresponding levels (figure 14).

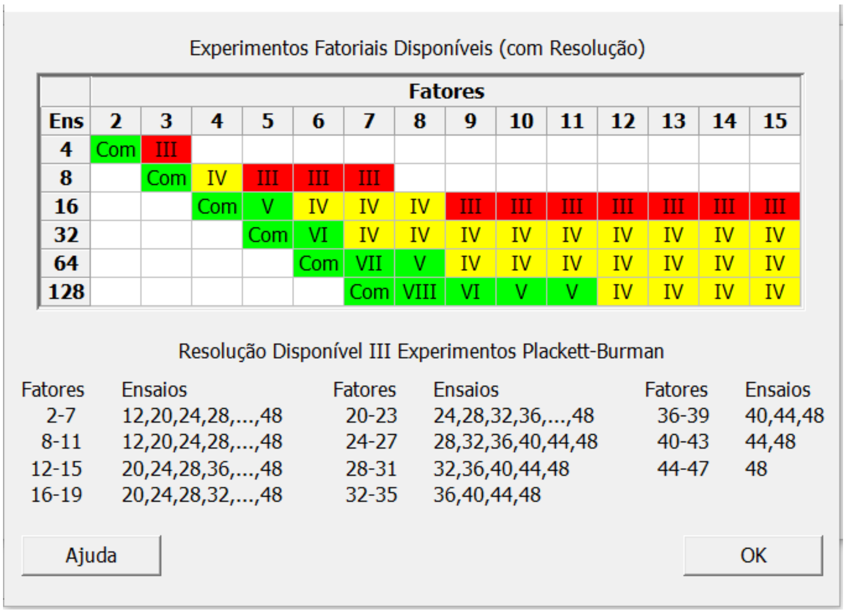
Figure 14 – Input factors and levels



Source: Authors (2022)

It is important to note that, depending on the number of factors, there is a minimum limit of tests, which should be considered. This threshold will express the level of confidence in the response of this experiment. Minitab makes this information available for consideration when performing the study (figure 15). In this specific case, the minimum number is 32 trials (configuration of experiments).

Figure 15 – Input factors and levels



Experimentos Fatoriais Disponíveis (com Resolução)

	Fatores													
Ens	2	3	4	5	6	7	8	9	10	11	12	13	14	15
4	Com	III												
8		Com	IV	III	III	III								
16			Com	V	IV	IV	IV	III	III	III	III	III	III	III
32				Com	VI	IV	IV	IV	IV	IV	IV	IV	IV	IV
64					Com	VII	V	IV	IV	IV	IV	IV	IV	IV
128						Com	VIII	VI	V	V	IV	IV	IV	IV

Resolução Disponível III Experimentos Plackett-Burman

Fatores	Ensaios	Fatores	Ensaios	Fatores	Ensaios
2-7	12,20,24,28,...,48	20-23	24,28,32,36,...,48	36-39	40,44,48
8-11	12,20,24,28,...,48	24-27	28,32,36,40,44,48	40-43	44,48
12-15	20,24,28,36,...,48	28-31	32,36,40,44,48	44-47	48
16-19	20,24,28,32,...,48	32-35	36,40,44,48		

Source: Authors (2022)

Based on this orientation, the experiment was assigned the equivalent fractional base, without replicas (figure 16).

Figure 16 – Experiment classification

Experimento Fatorial Fracionado

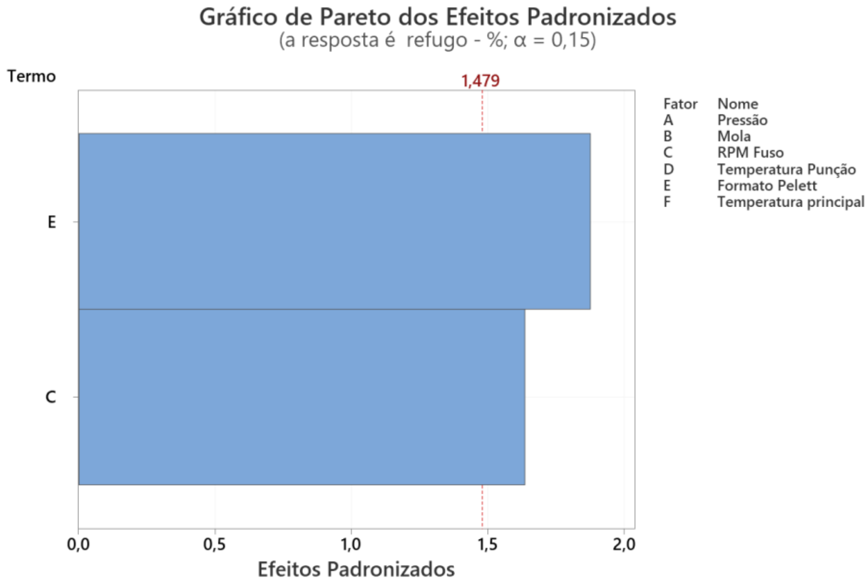
Resumo do experimento

Fatores:	6	Experimento Base:	6; 32	Resolução:	VI
Ensaios:	32	Réplicas:	1	Fração:	1/2
Blocos:	1	Pts centrais (total):	0		

Source: Authors (2022)

After testing wheels and *input* of the observed data, it can be inferred that, for the generation of scrap (covers out of specification, two factors are relevant: the *format of the* heated pellet (PVC) and the *rotation of the spindle*, which is responsible for the PVC heating process (figure 17).

Figure 17 – Critical factors in the generation of out-of-spec caps



Source: Authors (2022)

Given this result, it is possible to generate the predictability of the rejection rate, through *linear regression* (figure 18), according to these critical factors.

Figure 18 – Linear regression of this process

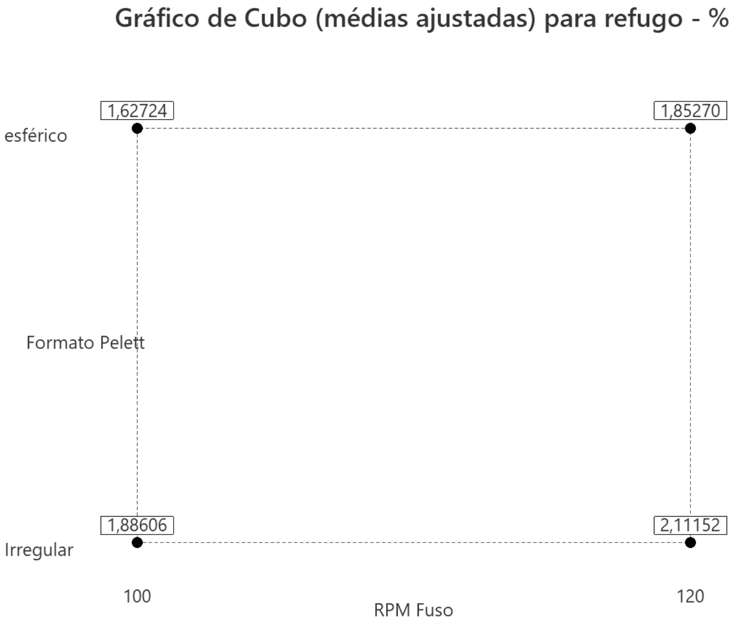
Equação de Regressão em Unidades Não codificadas

$$\text{refugo - \%} = 0{,}629 + 0{,}01127\ \text{RPM Fuso} - 0{,}1294\ \text{Formato Pelett}$$

Source: Authors (2022)

As in this experiment, only two factors were significant, for this observation, the cube graph (figure 19), has only one face of the cube. This face will have the spindle rotation factor at its base and the PVC format factor on its side. As in this experiment, the objective is to minimize the failure rate, one should look for the smallest value between them, which is on the upper-left edge, of each edge. In this way, it is evident that the appropriate factors and levels are *(spindle rotation: 100 and PVC format: spherical).*

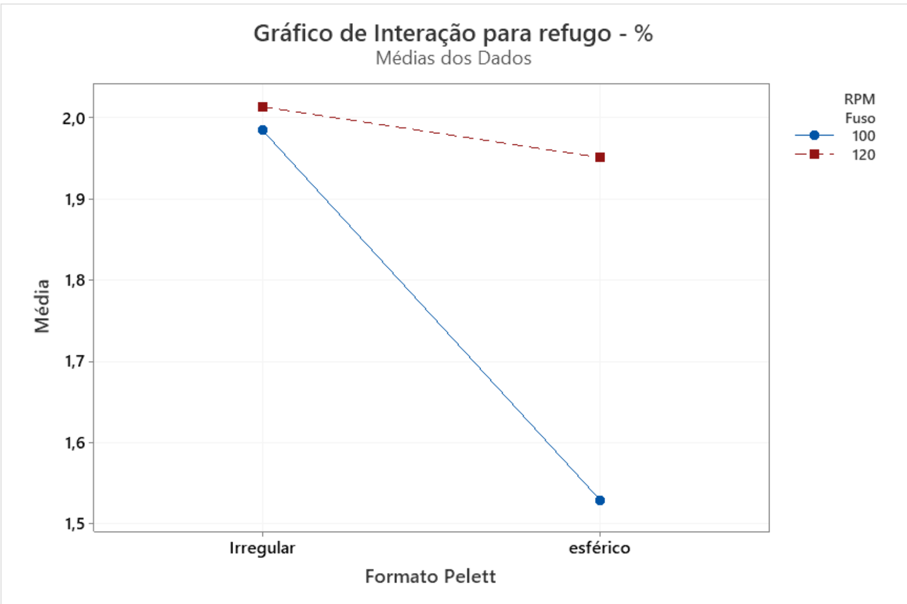
Figure 19 – Experiment cube graph



Source: Authors (2022)

As can be seen (figure 20) in the respective graph of the interaction of critical factors, aiming to minimize the rejection and failure rate, it is noted that in the Spindle Rotation factor, the lowest value found corresponds to 100 RPM. And for the PVC Shape factor, the smallest value corresponds to the spherical shape. Therefore, it is stated that the best configuration for this result is the combination of Spindle Rotation at 100 RPM and the spherical and regular shape of the Pellet.

Figure 20 – Main effects interaction graph



Source: Authors (2022)

6. Discussions and Final Considerations

Given the result, it is evident that decision-making based on concrete analysis, considering the problem modeling stage as a vital item, facilitates the necessary actions with a focus on optimizing investments and allocating resources and adding value to the business. Process mapping is fundamental to understanding what are the relevant factors that impact the expected response, and, through this mapping, it is possible to generate analyzes and validations in stages, so that the experiment is suitable for the corporate environment.

It is evident that in the corporate environment there is space to implement scientifically based actions and avoid the traditional models of implementing actions (trials and errors). Because, depending on the frequency and impact, this can reflect abruptly on the financial results of the business. Thus, it is understood that this work contributes in a relevant way to the difficulties of corporate daily life.

References

Antony, J. et al. An application of Taguchi method of experimental design for new product design and development process. Assembly Automation, v. 26, no. 1, p. 18–24, 1 Jan. 2006.

Awad, M., Shanshal, Y.A., Utilizing Kaizen process and DFSS methodology for new product development. International Journal of Quality & Reliability Management, v. 34, no. 3, p. 378–394, 1 Jan. 2017.

Akao Yoji. 1972. "New Product Development and Quality Assurance – Quality Deployment System." (Japanese) Standardization and Quality Control. Vol. 25, No. 4. pp. 7-14.

Bhote K. Qualidade de classe mundial. Rio de Janeiro. Qualitymark, 1996.

Carpinetti, L. Quality Management: Concepts and Techniques. 2nd ed. Atlas Publisher, 2012.

Cheng, L.C. Caracterização da gestão de desenvolvimento do produto: Delineando o seu contorno e dimensões básicas. In: CONGRESSO DE GESTÃO E DESENVOLVIMENTO DE PRODUTO, 2, 2000.

Costa, N. Design of experiments – overcome hindrances and bad practices. *The TQM Journal*, v. 31, no. 5, p. 772–789, 1 Jan. 2019.

Costa, D.O., Santos, M., Pereira. D.A.M., Aplicação da Filosofia Six Sigma para Melhoria da Performance numa Indústria de Embalagens Metálicas para Bebidas. *Revista SIMEP*, João Pessoa, v1, n.1, p. 4-21 jun 2021.

Francisco, M.G., Canciglieri Junior, O., Sant'Anna, Â.M.O. Design for six sigma integrated product development reference model through a systematic review. *International Journal of Lean Six Sigma*, v. 11, no. 4, p. 767–795, 1 Jan. 2020.

Fisher, R.A. The arrangement of field experiments. *Journal of the Ministry of Agriculture*, London, 1926.

Jenab, K., Wu, C., Moslehpour, S. Design for six sigma: A review. *Management Science Letters*, vol. 8, no. 1, p. 1–18, 2018.

Jung, C.F., Caten, C.S.T., Echeveste, M.E.S., Ribeiro, J.L.D. Análise estrutural e síntese das características lineares e sistêmicas de modelos de desenvolvimento de produto. Anais. VIII

SEPROSUL – Semana de Engenharia de Produção Sul-Americana. *Revista Liberato*, Novo Hamburgo, v.9, n. 12, p 108-109. Jan./jun. 2009.

Oshiumi Kiyotaka. 1966. *Perfecting Quality Assurance System in Plants*, (Japanese) Quality Control Vol. 17 (May 1966): 62-67 (supp.).

Pahl, G., Beitz, W., Feldhusen, J., Grote, K. *Projeto na engenharia: Fundamentos do desenvolvimento eficaz de produtos, métodos e aplicações*. Trad. Werner, H. A., 6 ed. São Paulo: Editora Edgar Blücher, 2005.

Pathiratne, S.U., Khatibi, A.M.D., JOHAR, M.G. (2018). CSFs for Six Sigma in service and manufacturing companies: an insight on literature. International Journal of Lean Six Sigma, v. 9, no. 4, p. 543–561, 1 Jan. 2018.

Peixoto, M.O.C., Carpinetti, L.C.R. Aplicação de QFD integrando o modelo de akao e o modelo QFD estendido. Gestão & Produção [online]. 1998, v. 5, n. 3 [Acessado 23 Abril 2022], pp. 221-238. Disponível em: <https://doi.org/10.1590/S0104-530X1998000300005>. Epub 06 Maio 2010. ISSN 1806-9649. https://doi.org/10.1590/S0104-530X1998000300005.

Perecin, D., Son, A. Effects by comparisons and by experiment in Factorial Experiments interactions; Science Magazine Agrotec ., Lavras, v. 32, no. 1, p. 68-72, Jan./Feb., 2008.

Petenate, A., Santos, V. Factorial Experiments: improving processes and products through statistical experimentation. Campinas. 2012. *Anais XVIII Regional Meeting of Mathematics Teachers – LEM/IMECC/UNICAMP*.

Pyzdek, T., Keller, P. Six Sigma: *The Professional's Guide, A Complete Guide for Green Belts, Black Belts, and Managers at All Levels*. 3 ed. Rio de Janeiro. Alta Books, 2011.

Rashed, K., et al. Fused filament fabrication of nylon 6/66 copolymer: a parametric study comparing full factorial and Taguchi design of experiments. *Rapid Prototyping Journal*, v. ahead-of-print, n. ahead-of-print, 1 Jan. 2022

Rotondaro, R.G., *Six Sigma: a management strategy for the improvement of processes, products, and services.* Sao Paulo: Atlas, 2008.

Risberg Ellekjær, M., Bisgaard, S. The use of experimental design in the development of new products. *International Journal of Quality Science*, v. 3, no. 3, p. 254–274, 1 Jan. 1998

Silva, A. Statistics applied with Minitab. Rio de Janeiro; Editora Moderna Ltd., 2015.

Schnitzleri, D., Grassi, M., Quinaia, S. Application of factorial design to a protocol for extraction and fixation of sulfides volatilizable by acidification (SVA) in sediment samples; *New Chemical Magazine.*

Sin, A.B., Zailani, S., Iranmanesh M., Ramayah, T. (2015). Structural equation modeling on knowledge creation in Six Sigma DMAIC project and its impact on organizational performance. *International Journal of Production Economics*, Volume 168, 2015, Pages 105-117, ISSN 0925-5273, https://doi.org/10.1016/j.ijpe.2015.06.007.

Taguchi, G., Wu, YU-IN. *Introduction to off-Line Quality Control*. Central Japan Quality Control Association. Meieki Nakamura-Ku Magaya, Japan, 1979.

Uluskan, M., Oda, E.P. (2020), *A thorough Six Sigma DMAIC application for household appliance manufacturing systems: Oven door-panel alignment case*, Vol. 32 No. 6, pp. 1683-1714.

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