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Reliability Tests as a Strategy for the Sustainability of Products and Production Processes—A Case Study

Arturo Realyvásquez-Vargas [1], Ramón Robles-Heredia [1], Jorge Luis García-Alcaraz [2,*] and José Roberto Díaz-Reza [3]

[1] Department of Industrial Engineering, Tecnológico Nacional de México/I.T. Tijuana, Calzada del Tecnológico S/N, Tomás Aquino, Tijuana 22414, Mexico
[2] Department of Industrial Engineering and Manufacturing, Universidad Autónoma de Ciudad Juárez, 450 del Charro Avenue, Ciudad Juarez 32310, Mexico
[3] Department of Electrical Engineering and Computer Sciences, Universidad Autónoma de Ciudad Juárez, 450 del Charro Avenue, Ciudad Juarez 32310, Mexico
* Correspondence: jorge.garcia@uacj.mx; Tel.: +52-656-688-4843 (ext. 5433)

Abstract: Nowadays, manufacturing companies are looking to improve their sustainability to respond to the market and customers' demands for sustainable products. Therefore, companies must improve their production processes to increase sustainability (economic, environmental, social, technological, efficiency, energy, performance management, manufacturing, and quality). This paper presents a case study of a manufacturing company located in Tijuana (Mexico) that produces wired and wireless communication devices. Previously, this company developed four projects to produce Universal Serial Buses (USB) and their duration should have been no more than 2 weeks; however, these lasted from 2.7 to 4.5 weeks. Moreover, different types of defects were also identified and, currently, the company is carrying out a project to develop a headset model. This research aims to demonstrate the application of reliability testing for the sustainability of products and manufacturing processes by reducing project development times and defects. The failure mode and effect analysis (FMEA), design of experiments (DOE), and analysis of variance (ANOVA) techniques are applied. The results indicated that the time between the start and completion of the headset project was 1.8 weeks, which is below the company's limit of 2 weeks and, additionally, defects were reduced significantly compared to previous projects. Based on the findings, it is concluded that applying statistical tools improves the sustainability of production processes and products. This implies that manufacturing companies can increase their sustainability indexes by reducing their processes/tasks times and the number of defective parts, increasing quality and customer satisfaction.

Keywords: reliability test; headset; FMEA; ANOVA; sustainability

MSC: 60K10; 62N05; 90B25

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1. Introduction

Sustainability can be considered as the ability of a given community to create and maintain communal existence through the management of local natural resources to ensure the survival and interconnectedness of community members and the environment [1]. Traditionally, sustainability is divided into three dimensions: economic, social, and environmental [2]. However, according to Eslami et al. [3], technology [4], energy [5], efficiency [6], manufacturing [7], quality [8], and performance management [9] are also dimensions of sustainability. This research focuses only on economic, environmental, efficiency, and quality dimensions in manufacturing industries since this sector is considered as one of the sectors that most contributes to economic expansion [10] and sustainability in its environmental dimension is defined as the ability to maintain the quality and reproducibility of natural resources [11].

Regarding the economic dimension of sustainability, it is defined as the ability to efficiently use available resources to ensure profitability over time [11] and, according to Ruiz-Mercado et al. [12], the costs are the main indicator. Therefore, as the material waste is reduced, the manufacturing cost is also increased [12] and, consequently, sustainability in the economic dimension is diminished.

So, by reducing solid waste (inorganic pollutants) [12], manufacturing companies can improve environmental sustainability by minimizing pollution emissions and waste generation in their production process [13]. On the other hand, in a production process, efficiency is reflected in the resources required to generate the desired product [12]. Given that analyses of manufacturing process efficiency seek to improve productivity within a specified timeframe [14], shortening manufacturing cycles helps improve sustainability in its dimension of efficiency. Finally, the quality dimension for a product is defined as the subjective satisfaction that a consumer perceives with it [15]. This perceived product quality must satisfy consumer needs, including health and safety standards [16] and the environment [17], and the indicator for this dimension is the failure rate of a new product [8]. Therefore, reducing failures (i.e., defects) helps improve sustainability in its quality dimension.

Currently, in the manufacturing sector, companies need to rapidly aim for a higher degree of sustainability [18] since it can be considered a key factor for competitiveness [19]. However, even today, manufacturing companies face problems that negatively impact their sustainability, such as defects in their products [20]; the examples include customer complaints [21], low sales, or low productivity [22], to mention a few. As a result, manufacturing companies must implement strategies to efficiently use resources [23] and thus maintain a good level of sustainability. The literature shows several studies carried out in the manufacturing sector to assess sustainability. However, most of them have focused on assessing the sustainability of products, while efforts to assess the sustainability of production processes are relatively limited, focusing mainly on specific tasks, such as turning, milling, or grinding [24].

For more than fifty years, Mexico's economy has relied heavily on manufacturing as a prolific source of job creation and export earnings [25]. Originally, manufacturing companies were set up as industrial plants where simple tasks were performed, such as assembling manufacturing parts before exporting them to the United States of America or sewing pieces of fabric together [26]. Today, due to market demands, manufacturing companies specialize in specific areas of industrial production, such as manufacturing parts for the automotive, medical, and aerospace industries, among other niches [27].

There are currently 5195 manufacturing and export service industries in Mexico nationwide. Of these, 383 are in Baja California state (7.4% of the national total) and 240 are located in Tijuana (62.7% of the state total and 4.6% of the national total). These companies generate 2,895,151 direct jobs nationwide and 389,459 in the state of Baja California (13.5% of the national total) and 269,575 in Tijuana (9.3% of the national total and 69.2% of the state total) [28], which demonstrates the importance of studying this sector from the economic, social, and environmental dimensions of sustainability.

Based on previous backgrounds, this paper presents a case study of a Mexican manufacturing company that, on previous projects, had low sustainability levels in its products and production processes. This was due to failures in its manufactured products, high material-use costs, solid waste (inorganic contaminants), high material consumption, and delays in project completion. Then, this research aims to show the application of reliability tests as a strategy to increase manufacturing companies' sustainability. To achieve that goal, different useful tools are applied, such as analysis of variance (ANOVA) [29], design of experiments (DOE) [30], and failure mode and effect analysis (FMEA) [31].

The rest of the document is as follows: the following subsection presents the research problem context for the case study. Section 2 presents the theoretical foundations of the ANOVA, DOE, and FMEA. Similarly, Section 3 shows the methodology applied to solve the problem for the case study, whereas Section 4 comprises the results derived from the methodology. Finally, Section 5 includes the conclusions for this research.

Research Problem

The current research is carried out in a manufacturing company that produces wired and wireless communication devices, including Bluetooth and digital enhanced cordless telecommunications devices. This company has several plants worldwide; however, the research is performed in a plant located in Tijuana, Mexico. This plant produces a family of products focused on various headsets, telephones, and conference equipment. In the case of headsets, this plant manufactures and distributes 77% of the headsets produced in all the company plants in 150 countries and currently has 2200 employees distributed in a direct workforce, a design center, an international distribution center, and a technical support call center.

The company's design center's main function is designing and introducing new products to the market and it has six departments to develop projects. One is the design quality department, which verifies that the product complies with internal company, customer, and governmental requirements. For this purpose, reliability tests are developed to subject the product to mechanical stress that simulates the conditions of use during its useful life to verify its quality. The quality laboratory receives the samples and performs the required tests and, once they are completed, a report is created and the design quality engineer is notified about the result.

Previously, the company has carried out several projects to develop USB A, USB B, USB C, and USB D products. Table 1 shows that the average delivery time for these four developed projects was 3.5 weeks; however, the required delivery time is 2 weeks from when the laboratory receives the product until the results are delivered.

Table 1. Average delivery time in previous projects.

Project	Average Delivery Time Per Run (Weeks)	Difference with the Required Time
Project USB A	4.5	+2.5
Project USB B	3.5	+1.5
Project USB C	2.7	+0.7
Project USB D	3.7	+1.7

Currently, within the families of headphones produced, the company is carrying out a project to develop several products within the family that, in this research, are called AA. The products in this series are headsets designed for office use and are called AAXXX model from here.

Included in the delivery time is an environmental test, which was implemented due to a failure found in a previous project carried out in the company. Currently, this test is required for developing all office products in the reliability tests and its duration is 3 days, which increases the test duration time. This test requires three different environmental cycles in a temperature chamber and Table 2 shows these requirements.

Table 2. Environmental test requirements.

Cycle	Temperature Range and Relative Humidity (R.H.)	Duration (Hours)
Storage temperature	From −30 °C to 85 °C	9
Storage temperature and humidity	From 10 °C to 85 °C, 92% R.H.	48
	−40 °C	3
Temperature/humidity cycle	32 °C, 85% + 5% R.H.	3
	85 °C, 15% + 3% R.H.	3

During this test, it was observed that most of the failures were mechanical and Table 3 shows their frequency. These types of failures are identified during the product verification stage, which causes new iterations to the design that impacts the release of the product, delaying the mass production beginning and shipments to the customer, failing in the delivery date promised, causing some fines or penalties from customers due delays in delivering. Additionally, this delay and production problem has resulted in a low sustainability level regarding the quality, economy, environment, and efficiency of those last four projects.

Table 3. Frequency of the different types of faults found in the last four projects.

Failure Type	Project USB A	Project USB B	Project USB C	Project USB D	Total
Acoustic	15	8	4	14	41
Electric	5	7	16	20	48
Mechanical	45	60	67	72	244
Manufacturing	4	10	8	10	32
Packaging	2	7	3	3	15
Testing	1	4	12	4	21
User	3	2	15	8	28
Total	75	98	125	131	429

Based on the problems mentioned above, this research aims to show that reliability tests are an effective strategy to increase manufacturing companies' sustainability in terms of quality, economy, environment, and efficiency. Figure 1 shows the steps to perform the microphone reliability test (microphone cycling) of the AAXXX headset.

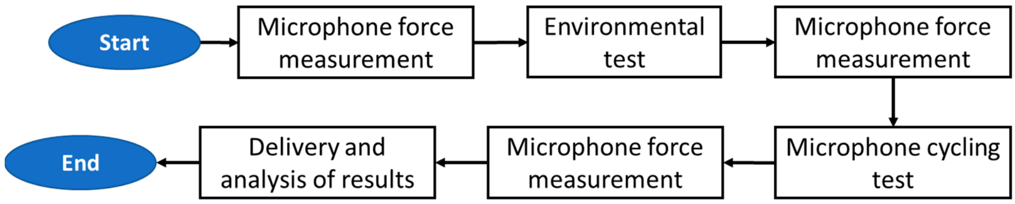

Figure 1. Microphone cycling test process diagram.

2. Literature Review

2.1. DOE

The design of experiments (DOE) is a powerful tool for optimizing processes [32]. It is widely used to apply Quality by Design (QbD) in research and industrial settings [33]. In QbD, the quality should be built into the product/process [34]. Therefore, to guarantee the final product's quality, understanding the product and its manufacturing process represents a key factor [33]. As a part of process validation, DOE plays a central role in defining the acceptable ranges for the critical process parameters [32]. Knowledge is achieved by establishing models that correlate process inputs with process outputs [33]. The ultimate DOE objective is twofold and comprises process characterization and optimization carried out sequentially [35].

According to Jones and Montgomery [36], the implementation of DOE comprises the following seven steps:

1. Setting solid objectives;
2. Selection of process variables (factors) and responses (critical quality attributes);
3. Selection of an experimental design;
4. Execution of the design;
5. Checking that the data are consistent with the experimental assumptions;
6. Analyzing the results;
7. Use and interpretation of the results.

For a more detailed explanation of these steps, read Jones and Montgomery [36] or Politis et al. [33].

According to the literature, there are three main categories of experimental designs, depending on the parameters under study. Such categories are mixture design [37], process or factorial designs [38], and mixture-process designs [39].

2.2. ANOVA

According to several authors, ANOVA is the most efficient method to analyze the data from experimental designs [40], comparing two or more groups or treatments simultaneously, and it is the most effective tool for analyzing more complex data sets with different sources of variations [41]. Mathematically speaking, ANOVA measures the relationship between an independent variable and a dependent variable based on linear regression [42]. It is considered that an independent variable has a significant impact on the dependent variable when the p-value is lower than 0.05 [42]; moreover, ANOVA can be used to analyze the differences between variables since it provides statistical evidence of whether the variances are equal or not [43].

In ANOVA, the one-way fixed effects analysis of a variance F-test is commonly used to compare the effects of k-independent group means [44]. Additionally, the F value is used to test the null hypothesis where all the means are equal, i.e., $H_0 = \mu_1 = \mu_2 = \ldots \mu_k$ versus the alternative hypothesis, i.e., H_1: at least one of the μi is different [45]. The critical statistic F-value is obtained from the F-distribution with $k - 1$ and $N - k$ degrees of freedom. When the F-ratio is equal to or greater than the critical F-value, H_0 is rejected; otherwise, it is accepted [44].

ANOVA has been applied to experiments with different processes. For instance, several authors have applied ANOVA in different desalination processes [46]. Similarly, other authors have applied ANOVA in clinical experiments in optometry [47]. Moreover, Niedoba and Pięta mention [48] that ANOVA has been successfully applied in experiments to study the flotation process and properties of three types of coal. In the manufacturing industry, ANOVA has been applied by Equbal et al. [49] to perform a study to determine optimum cutting parameters to achieve optimum machining performance on turning of glass fiber-reinforced polymer (GFRP) composites that yield the optimum output responses and they find the statistical significance of the cutting parameters and their interactions.

In another study, Jin and Guo [50] applied the ANOVA method to analyze and reduce the natural variations inherent in batch manufacturing processes, specifically in the printing process of screening conductive grids to manufacture solar batteries. Similarly, Upadhyay et al. [51] studied several elements of vendor-managed inventory that are critical to both the customer and the manufacturer (supplier) in the Indian context and they determined the relative importance and difficulties in the implementation of vendor-managed inventory elements.

2.3. FMEA

A failure mode and effect analysis (FMEA) is a fundamental engineering and reliability technique used to define, identify, and eliminate known and potential failure modes, errors, problems, and the effects of the items of interest from a process, design, service, or system before they are delivered to the customer [52]. Moreover, it allows finding critical failure causes and failure mechanisms used to diagnose possible failure and dissatisfactions of functions for any items in a system before they occur, so it also helps to reduce these potential failure risks [53]. Several authors mention that FMEA is a systematized and logical methodology that detects, analyzes, and ranks estimated risk with several potential failure modes [52]. Moreover, it is useful to improve the manufacturing processes; for instance, control tests or design changes can help engineers avoid failures and reduce their effects [54].

The FMEA focuses on three risk factors of a potential failure: (1) occurrence, (2) detection, and (3) severity [55]. They are ranked from 1 to 10 on a discrete ordinal scale [56]. Multiplying the degree of risk factor occurrence, severity, and detection of a potential problem or failure leads to obtaining the risk priority number (RPN) [57]. According to the RPN value, the FMEA mode is defined, as well as the types of corrective actions to be implemented [55]. Then, the most critical failures can be determined by arranging the RPNs in descending order [56], where a higher RPN value indicates a more critical risk [58].

3. Materials and Methods

For the design review based on the failure analysis of the AAXXX headset, the following tools are used: Agile PLM® v9.3.6 software, SolidWorks® 2020 v28 design software, Microsoft Excel® 2210 software, and Microsoft Outlook® 2210 software. In turn, the following tools and materials are used for the verification and validity of the environmental requirements: the AAXXX product, environmental camera Labtech RS-TH, laptop computer, Microsoft Excel® 2210 software, and Minitab® 20.4.0 software. Figure 2 shows the method applied to achieve the objectives mentioned above. As can be seen, the applied method is divided into eleven stages. The following is a detailed description of how each stage of the method is carried out.

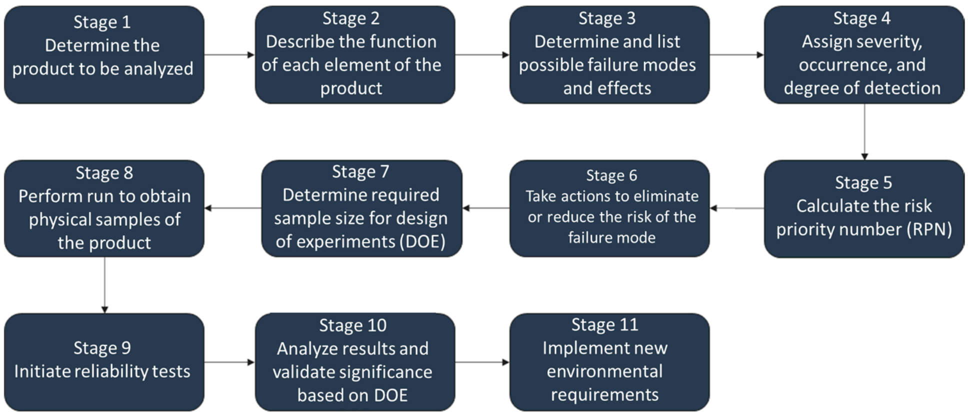

Figure 2. The method applied to perform the design review based on failure analysis and verify environmental requirements.

3.1. Stage 1: Determine the Product to Be Analyzed

At this stage, the product to be analyzed will be determined, depending on the needs of the project the team is working on or the company's needs; so, the criteria to determine the product to be analyzed will depend on the project and the company. In this case, the delivery date required to have the product on the market, the product's position in the market, and the production forecast were considered.

3.2. Stage 2: Describing the Function of Each Product Element

During this stage, and once it is decided which product must be analyzed, three one-hour sessions are scheduled with a multidisciplinary team using the Microsoft Outlook® software tool. The teamwork introducing the product uses the template shown in Figure 3. Subsequently, the functions of each element or mechanism of the product to be analyzed are listed. These functions must be described as the end customer will perceive them. For this purpose, the Agile PLM® software is used to obtain the product's bill of materials (BOM) and the Solidworks® software is used to obtain a rendering of the product to be evaluated.

3.3. Stage 3: Determine and List the Possible Failure Modes and Effects of Failure

Here, the possible failure modes and their effects must be determined and listed using the brainstorming technique, where all the situations in which the product may fail due to end-customer use should be considered. Any situation and proposal for improvement must be considered, considering that there are no bad ideas. This information is documented in a worksheet in Microsoft Excel® software, as shown in Figure 3.

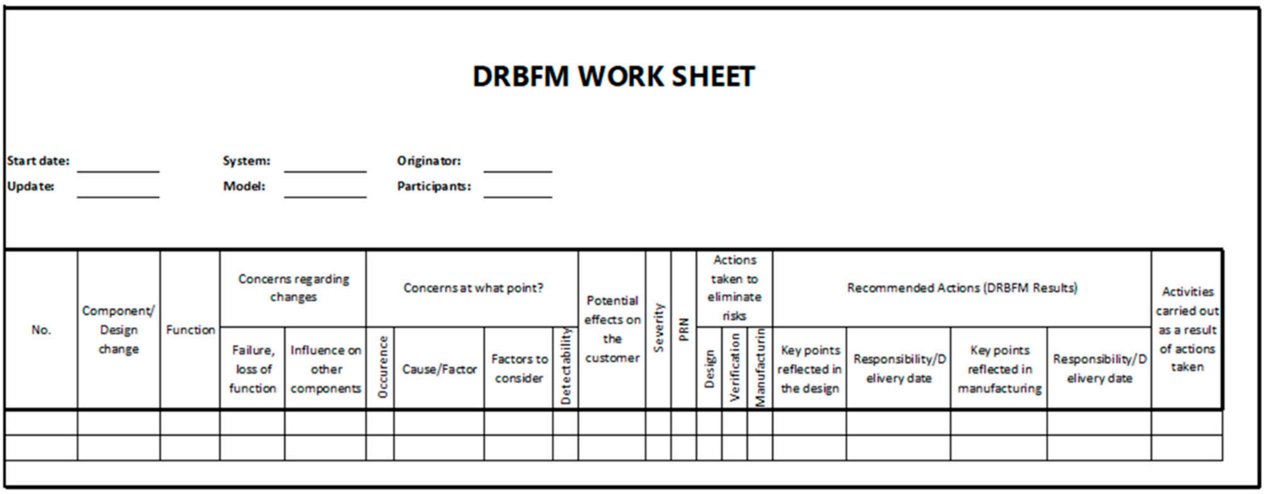

Figure 3. Excel template to perform design review based on the failure mode. Adapted from [59].

3.4. Stage 4: Assign Severity, Occurrence and Degree of Detection

Once the failure modes and effects have been determined, the team must determine the severity of each failure. Each failure's impact on the end customer and the company must be considered. Normally, the impact is usually monetary and a number from 1 to 10 is assigned, depending on the severity determined, as shown in Table 4 [60].

Table 4. Rating of severity.

Rating	Description	Definition
10	Dangerously high	Failure could injure a customer or employee.
9	Extremely high	Failure would cause non-compliance with federal regulations.
8	Very High	Failure renders the unit inoperable or unfit for use.
7	High	Failure causes a high level of customer dissatisfaction.
6	Moderate	Failure results in a subsystem or partial malfunction of the product.
5	Low	Failure creates enough performance loss to cause the customer to complain.
4	Very low	Failure can be overcome with modifications to the customer's process or product, but there is a minor performance loss.
3	Minor	Failure would create a minor nuisance to the customer, but the customer can overcome it without performance loss.
2	Very minor	Failure may not be readily apparent to the customer but would have minor effects on the customer's process or product.
1	None	Failure would not be noticeable to the customer and would not affect the customer's process or performance.

On the other hand, the occurrence determines the assessment of failure during the product's lifetime in the market on a scale from 1 to 10 [60], as shown in Table 5. The degree of detection refers to whether the failure can be detected within the company, either at some inspection point within the production line or in some verification test performed in internal laboratories. It is also rated with a number from 1 to 10, as shown in Table 6, depending on how the failure will be detected by one of the systems mentioned above [60].

Table 5. Rating of occurrence.

Rating	Description	Definition
10	Very High: Failure is almost inevitable	More than 1 occurrence per day or a probability of more than 3 occurrences out of 10 events
9	High: Failures occur almost as often as not	1 occurrence every three to four days or a probability of 3 occurrences in 10 events
8	High: Repeated failures	1 occurrence per week or a probability of 5 occurrences in 100 events
7	High: Failures occur often	1 occurrence every month or 1 occurrence in 100 events
6	Moderately high: Frequent failures	1 occurrence every three months or 3 occurrences in 1000 events
5	Moderate: Occasional failures	1 occurrence every six months to one year or 5 occurrences in 10,000 events
4	Moderately low: Infrequent failures	1 occurrence per year or 6 occurrences per 100,000 events
3	Low: Relatively few failures	1 occurrence every one to three years or <6 occurrences in 100,000 events.
2	Low: Failures are few and far between	1 occurrence every three to five years
1	Remote: failures are unlikely	1 occurrence in greater than five years

Table 6. Detection rating.

Rating	Percentage of Detectability	Description	Definition
10	<60%	Absolute Uncertainty	The product is not inspected or the defect caused by failure is not detectable.
9	60%	Very Remote	The product is sampled, inspected, and released based on Acceptable Quality Level (AQL) sampling plans.
8	65%	Remote	The product is accepted based on no defects found in a sample.
7	70%	Very Low	The product is 100% manually inspected during the manufacturing process.
6	75%	Low	The product is 100% manually inspected using a go/no-go or mistake-proving gages.
5	80%	Moderate	Statistical process control (SPC) is used and the product is finalized offline.
4	85%	Moderately High	SPC is used and there is an immediate reaction to out-of-control conditions.
3	90%	High	An effective SPC program is in place with process capabilities (Cpk) greater than 1.33.
2	95%	Very High	All products are automatically 100% inspected.
1	99.99%	Almost Certain	The defect is obvious or there is a 100% automatic product inspection with regular calibration and maintenance of the equipment.

3.5. Stage 5: Calculate the Priority Risk Number

At this stage, the three factors of severity, occurrence, and detectability are multiplied to calculate the so-called priority risk number (PRN), as shown in Equation (1) [61]:

$$\text{PRN} = \text{Severity} \times \text{Occurrence} \times \text{Detectability} \quad (1)$$

Once the PRN has been calculated, the faults are prioritized based on this number, prioritizing the faults with the highest PRN.

3.6. Stage 6: Determine Actions to Eliminate or Reduce the Risk of the Failure Mode

Once the failure modes with the highest PRN have been analyzed, the team must determine what actions will help them reduce or eliminate the existing risk of a given failure mode, considering what the action entails. In some cases, the action may change a drawing or requirement; others may require a larger change, such as a redesign or material change. The team must also consider the consequences of cost or an impact on the product's delivery date.

3.7. Stage 7: Determine the Number of Samples for the Design of Experiments and Analysis of Variance

During this stage, the design of experiments (DOE) method is initiated. Using the Minitab® statistical tool, the number of product samples needed to perform an ANOVA and verify the requirements of the environmental tests is determined. In the Minitab tool, the calculation is performed using a 95% confidence interval (CI), which indicates the range in which the sample data are found. Additionally, another parameter to be used is a standard deviation equal to 3, based on the Six Sigma methodology [62]. Finally, the power, which is the probability that the null hypothesis can be correctly rejected, should be considered. In this project, we will seek to use a power of 20%, 50%, and 80% [63].

3.8. Stage 8: Perform a Pilot Run to Obtain Physical Samples of the Product

In this stage, the requirement is fulfilled to build the samples determined in Stage 7. The team working on the project generates a requisition to build a product (pilot run) for the manufacturing department. This requisition indicates the product to be built, its bill of materials (BOM), and the quantities of the finished product. Within the required quantities, the sample size to be used for the reliability tests and the verification of the environmental tests are estimated using Minitab®. The manufacturing engineer provides the time per part targets and the expected and acceptable scrap. The engineering team and the design quality engineer determine what criteria to evaluate from a design standpoint, both at the component and the finished product levels. This provides teamwork with the target to reach if the run was successful and the product can be used for verification testing. If the objectives are not met, the team must analyze the information obtained and determine what actions are needed to improve the product design to schedule another pilot run and have a high degree of confidence that the objectives will be met.

3.9. Stage 9: Initiate Reliability Tests

Once the samples have been estimated and constructed, they are delivered to the quality laboratory to start reliability tests. A requisition must be generated for these tests, indicating the quantities of samples to which environmental and cycling tests are performed and to which only cycling tests are performed.

The control factors are defined as follows:

- A = reference group (sample measured before entering environmental testing and cycling).
- B = post-environmental stress test group.
- C = post-environmental stress and mechanical stress test group.
- D = post-mechanical stress test group.

Group D is not subjected to the environmental test to determine if the environmental tests have a significant effect on the microphone torque of the product. Before starting the environmental tests, the strength of the tested component will be measured, as shown in the diagram in Figure 1. This variable will help to determine if the environmental tests have any significant effect (out of specification) on the product.

3.10. Stage 10: Analyze the Results and Validate the Significance of the Environmental Test Based on the ANOVA

Once the tests are concluded, the data obtained are extracted, following the ANOVA methodology and the Minitab® tool. Only one factor will be considered, which, in this case, will be the environmental test; a one-factor ANOVA will be used. The data to be used are obtained by measuring the rotational force of the headset microphone, that is, the dynamic torque of the microphone with a motorized torque meter Mark-10. Ten data are measured over a range of 170°; from these, the average torque will be used to verify if the component is within specification. The data obtained from these measurements will be entered into the Minitab tool, where the ANOVA will be performed and the variance will be used to analyze the dispersion with a confidence level of 0.05. The confidence interval indicates the range in which the sample data are.

In ANOVA, the p-value helps determine the difference between the sample means and thus can determine if the environmental testing has a significant effect on the microphone torque of the product. Since a 95% confidence interval (CI) is used, p-values less than 0.05 indicate sufficient statistical evidence to conclude that environmental testing significantly affects the product microphone torque [64].

3.11. Stage 11: Implement New Environmental Requirements

In this stage, the information obtained from Stage 10 is considered and an engineering change (ECO) is generated using Agile PLM® software, where the new environmental requirements and their implementation are indicated.

4. Results

This section reports the findings obtained by applying the methodology described above. For a better understanding, the results are shown for each of the stages.

4.1. Results of Stage 1

The product to be analyzed was AAXXX. For this product, the date of introduction to the market was a critical factor due to the situation created by the pandemic, which increased the number of people working from home by 15%, according to a survey conducted by the company. A comparison with other products in a similar range showed the need to place AAXXX in a competitive position.

4.2. Results of Stage 2

At the end of the sessions, the team determined 15 functions to be analyzed during the design review based on failure modes (DRBFM), as shown in Table 7. As can be seen, the team divided the components or the design change into two sections: the headband and the headset, as shown in Figure 4. For the headset nine functions were determined, while for the earphone, which is composed of a module with the speaker on the right side and a module on the left side, six functions were determined.

Table 7. Functions of the product elements.

Component/Change Design	Function
Headband	Lateral extension Antenna holder Headband indicator Headband arm force Headband pivot Synthetic leather on the headband arm Headband cushioning foam Headband cable Headband cushioning foam
Headset	Ear cushion Right speaker back cover Mesh microphone gasket Adhesive for flexible connector Secondary mesh microphone gasket Faceplate fabric

Figure 4. Headband and headset section reference.

4.3. Results of Stage 3

At this stage, 21 potential failure modes were detected, which harmed the customer; additionally, 11 potential effects were caused by the failure modes. The most frequently occurring effect was the poor quality perceived by the customer and, although it is a subjective effect, this is important, as it affects the company's brand. The effect that impacts regulatory certifications is important since failure to comply with these certifications will affect where the product can be sold. Table 8 shows the total failure modes and their potential effects on the customer of the AAXXX product.

Table 8. Possible failure modes and effects of the AAXXX product.

Potential Failure Mode (s)	Potential Effects on the Customer
High clamping force	Customer discomfort when using the headphones
Low clamping force	Customer discomfort when using the headphones
The indicator touches the user's sagittal crest	Customer discomfort when using the headphones
Antenna magnets detach from the fastener	The user may be unable to dock the headset correctly to charge it
Dielectric failure	Poor user experience in terms of security
The indicator is not aligned with the headband	Quality as perceived by the customer
Electromagnetic immunity performance	Regulatory certifications cannot be met
Low headband arm strength	The user may not be able to adjust the headband
High headband arm strength	The user may not be able to adjust the headband
Low headband pivot force	The user may not be able to adjust the headset
High headband pivot force	The user may not be able to adjust the headset
Aesthetic details on the synthetic leather on the arm of the headband	Poor quality as perceived by the customer
Cushioning foam for off-spec headband	Customer discomfort when using the headphones
Electrical continuity	The headset does not work
Acoustic performance	Poor quality as perceived by the customer
Long-term use	Poor quality as perceived by the customer
Damaged component on printed circuit board (PCB)	Limited headset functionality
Microphone isolation	Deteriorated microphone performance
Mesh seal out of position after use	Deteriorated microphone performance
Fabric detached from the substrate	Poor quality as perceived by the customer
The substrate detached from the faceplate	Poor quality as perceived by the customer

4.4. Results of Stages 4 and 5

Concluding the sessions, the team determined the possible causes of the failure modes and assigned the severity, occurrence, detection, and priority risk number (PRN) calculated for each of the potential effects. The results of this stage are shown below in Table 9. As can be seen, the microphone isolation, the high clamping force, the low clamping force, and the dielectric failure turned out to be the failure modes that present the higher PRN. Among these four modes, 50% of the total accumulated PRN is generated. Therefore, these failure modes are more likely to be observed by the end customer of the product.

Table 9. Severity, occurrence, and degree of detection of potential customer effects of product AAXXX.

Potential Failure Mode (s)	Potential Effects on the Customer	Sev.	Cause/Factor	Ocurr.	Current Controls	Det.	PRN
Antenna magnets detach from the holder	The user may be unable to dock the headset correctly to charge it.	5	The antenna holder is out of specification	3	Verification tests	4	60
Microphone isolation	Deteriorated active noise cancelation performance	5	Adhesive not properly activated	4	Production line calibration tests	3	60
Microphone isolation	Deteriorated microphone performance	5	Positioning of the joint during assembly	5	Production line calibration tests	2	50
High clamping force	Customer discomfort when using the headphones	4	Height of ear pads	4	Verification tests	3	48
Low clamping force	Customer discomfort when using the headphones	4	Height of ear pads	4	Verification tests	3	48
Low headband arm force	The user may not be able to adjust the headband	4	Cushioning foam for the headband arm	4	Verification tests	3	48
High headband arm force	The user may not be able to adjust the headband	4	Cushioning foam for the headband arm	4	Verification tests	3	48
Low headband pivot force	The user may not be able to adjust the headset	4	O-ring out of specification	4	Verification tests	3	48
Fuerza de pivote de diadema alta	The user may not be able to adjust the headset	4	O-ring out of specification	4	Verification tests	3	48
High clamping force	Customer discomfort when using the headphones	3	Headband cushioning foam	5	Verification tests	3	45
Low clamping force	Customer discomfort when using the headphones	3	Headband cushioning foam	5	Verification tests	3	45
Headband cushioning foam out of specification	Customer discomfort when using the headphones	3	Headband cushioning foam	5	Verification tests	3	45
Microphone isolation	Deteriorated active noise cancelation performance	5	The adhesive does not withstand environmental stress	4	Verification tests	2	40
Microphone isolation	Deteriorated microphone performance	5	The gasket does not create the correct seal	4	Tolerance analysis	2	40
High clamping force	Customer discomfort when using the headphones	3	Gaps in the lever arm	4	Verification tests	3	36
Low clamping force	Customer discomfort when using the headphones	3	Gaps in the lever arm	4	Verification tests	3	36
The indicator touches the user's sagittal crest	Customer discomfort when using the headphones	3	Silicone molding envelope	4	Industrial design tests	3	36
Acoustic performance	Quality as perceived by the customer	4	Height of ear pads	4	Verification tests	2	32
Dielectric failure	Poor user experience concerning safety	10	Printed electrical circuit	3	Verification tests	1	30
Dielectric failure	Poor user experience concerning safety	10	Wiring routing	3	Verification tests	1	30
Dielectric failure	Poor user experience concerning safety	10	Cable length	3	Verification tests	1	30

Table 9. *Cont.*

Potential Failure Mode (s)	Potential Effects on the Customer	Sev.	Cause/Factor	Ocurr.	Current Controls	Det.	PRN
The indicator is not aligned with the headband	Quality as perceived by the customer	2	Gaps created between plastic parts	5	Industrial design tests	3	30
Electromagnetic immunity performance	It is not possible to comply with regulatory certifications	10	Printed electrical circuit	3	Pre-regulatory tests	1	30
Microphone isolation	Deteriorated microphone performance	5	Low gasket compression	3	Tolerance analysis	2	30
Microphone isolation	Deteriorated active noise cancelation performance	5	Finishing of plastic surfaces	3	Verification tests	2	30
Microphone isolation	Deteriorated active noise cancelation performance	5	Routing of flexible connectors	3	Verification tests	2	30
Aesthetic details on the synthetic leather on the arm of the headband	Quality as perceived by the customer	2	Synthetic leather processing	4	Incoming inspection	3	24
Long-term use	Quality as perceived by the customer	3	Height of ear pads	4	Verification tests	2	24
Damaged component on printed circuit board (PCB)	Limited headset functionality	6	Interference of the back cover with the printed circuit board	4	Tolerance analysis	1	24
Tissue detached from the substrate	Quality as perceived by the customer	3	Adhesive contact surface	4	Verification tests	2	24
The substrate detached from the faceplate	Quality as perceived by the customer	3	Adhesive contact surface	4	Verification tests	2	24
Mesh gasket out of position after use	Deteriorated microphone performance	5	Positioning of the joint during assembly	4	Production line calibration tests	1	20
Aesthetic details on the synthetic leather on the arm of the headband	Quality as perceived by the customer	2	Headband geometry	3	Incoming inspection	3	18
Electrical continuity	The handset does not work	6	Cable crimping	3	Production line user tests	1	18
Tissue detached from the substrate	Quality as perceived by the customer	3	Tissue tension causes detachment	3	Verification tests	2	18
Tissue detached from the substrate	Quality as perceived by the customer	3	Incorrectly applied adhesive	3	Verification tests	2	18

Serv—Severity; Occur—Occurrence; Det—Degree of detection (Det.) of potential customer effects of product AAXXX.

4.5. Results of Stage 6

As can be seen in Figure 5, the failure modes with the highest cumulative PRN were microphone isolation, high and low clamping force, and dielectric failure. Although electromagnetic immunity performance was not among the failure modes indicated by the Pareto principle [65], we chose to address it since it is a regulatory requirement. Based on these results, it was decided to perform the actions indicated in Table 10 for the failure modes mentioned above.

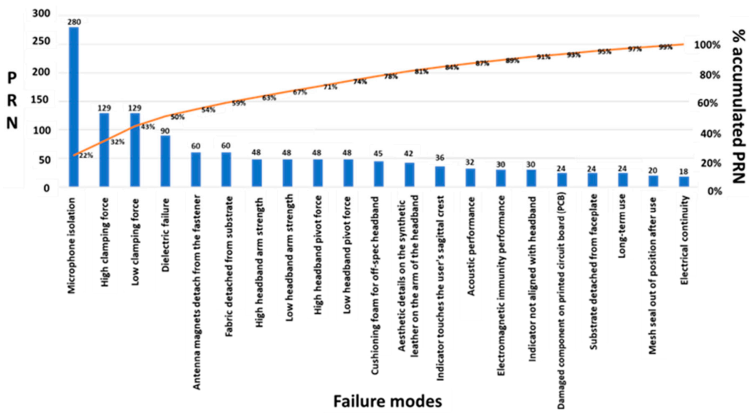

Figure 5. Pareto diagram for failure modes.

Table 10. Actions performed and recalculation of the PRN to mitigate the risks of potential failure modes in product AAXXX.

Potential Failure Mode (s)	Potential Effects on the Customer	Previous PRN	Actions Performed	New Sev.	New Ocurr.	New Det.	New PRN
Microphone isolation	Deteriorated active noise cancelation performance	60	Conduct engineering tests with prototypes before requesting samples from the supplier	5	2	2	20
Microphone isolation	Deteriorated microphone performance	50	Design and implementation of assembly template	5	2	2	20
High clamping force	Customer discomfort when using the headphones	48	Develop inspection methods for the supplier. Request compliance report prior to shipment of materials	4	2	3	24
Low clamping force	Customer discomfort when using the headphones	48	Develop inspection methods for the supplier. Request compliance report prior to shipment of materials	4	2	3	24
High clamping force	Customer discomfort when using the headphones	45	Develop inspection methods for the supplier. Request compliance report prior to shipment of materials	3	2	3	18
Low clamping force	Customer discomfort when using the headphones	45	Develop inspection methods for the supplier. Request compliance report prior to shipment of materials	3	2	3	18
Microphone isolation	Deteriorated active noise cancelation performance	40	Conduct engineering tests with prototypes before requesting samples from the supplier	5	3	2	30
Microphone isolation	Deteriorated microphone performance	40	Perform seal fit simulation in Solidworks	5	3	2	30
High clamping force	Customer discomfort when using the headphones	36	Perform force simulation in Solidworks with the 3D of the product.	3	3	3	27
Low clamping force	Customer discomfort when using the headphones	36	Perform force simulation in Solidworks with the 3D of the product.	3	3	3	27
Dielectric failure	Poor user experience concerning safety	30	Review with the electrical test engineering team prior to printed circuit board approval	10	2	1	20
Dielectric failure	Poor user experience concerning safety	30	Review with the electrical test engineering team prior to printed circuit board approval	10	2	1	20
Dielectric failure	Poor user experience concerning safety	30	Conduct engineering tests with prototypes before requesting samples from the supplier	10	2	1	20
Electromagnetic immunity performance	It is not possible to comply with regulatory certifications	30	Review with the electrical test engineering team and regulatory certifications prior to printed circuit board approval	10	2	1	20
Microphone isolation	Deteriorated microphone performance	30	Develop inspection methods for the supplier. Request compliance report prior to shipment of materials	5	2	2	20
Microphone isolation	Deteriorated active noise cancelation performance	30	Approval of reference sample to have aesthetic approval criteria in the incoming inspection area	5	2	2	20
Microphone isolation	Deteriorated active noise cancelation performance	30	Review with the electrical test engineering team prior to printed circuit board approval	5	2	2	20

Table 10 shows a reduction in the PRN, which indicates that the actions performed were effective. These actions will also support similar future projects that the company can use as a basis for product development. Table 11 compares previous projects with the mechanical failures of developing a new product and, as can be seen, this type of failure was reduced in the AAXXX project. The DRBFM performed in this development focused on the mechanical aspects of the product.

Table 11. Comparison of the failures found in the last four projects and the AAXXX product.

Type of Failure	Project USB A	Project USB B	Project USB C	Project USB D	AAXXX	Total
Acoustic	15	8	4	14	2	43
Electric	5	7	16	20	8	56
Mechanical	45	60	67	72	38	282
Manufacturing	4	10	8	10	6	38
Packaging	2	7	3	3	1	16
Testing	1	4	12	4	4	25
User	3	2	15	8	5	33
Total	75	98	125	131	64	493

4.6. Results of Stages 7 and 8

During the pilot run, a yield of 97% was obtained, which is considered acceptable by company standards. At the end of the run, 150 units were constructed, from which samples were extracted to start the ANOVA and reliability tests. Table 12 shows the results obtained for determining the sample size using the Minitab® software.

Table 12. The sample size for ANOVA.

Sample Size	Power	Standard Deviation	Confidence Interval (CI)
13	0.20	3	95%
42	0.50	3	95%
70	0.80	3	95%

The sample size selected was 40 units due to financial resource restrictions on the company's part.

4.7. Results of Stage 9

Table 13 shows the baseline data obtained prior to reliability testing. These data correspond to group A. The measurement is provided in ounces per inch (oz-in).

Table 13. Microphone torque measurement on Mark-10.

Sample	Torque (oz-in)	n	Torque (oz-in)	n	Torque (oz-in)	n	Torque (oz-in)
1	5.08	11	5.20	21	6.17	31	5.67
2	5.10	12	4.14	22	6.25	32	4.07
3	4.35	13	5.97	23	4.91	33	5.90
4	4.56	14	4.21	24	5.82	34	5.18
5	5.23	15	5.37	25	4.09	35	5.01
6	4.52	16	4.16	26	4.31	36	3.61
7	5.02	17	6.05	27	4.42	37	4.89
8	6.11	18	5.86	28	4.75	38	4.63
9	5.46	19	6.22	29	5.83	39	4.12
10	5.43	20	5.16	30	4.28	40	4.65

The company has an internal specification of a minimum torque of 4 oz-in and a maximum of 7 oz-in before starting the test. As can be seen in Table 13, the values of the 40 samples are within acceptable limits to proceed to start the reliability test.

Table 14 shows the measurements obtained for groups B and C and Table 15 shows the measurements for group D. The samples for factor D correspond to samples 21 through

40 in Table 13. These samples were extracted randomly once the run was concluded. The numbering provided was performed for unit identification and traceability.

Table 14. Microphone torque measurement on Mark-10 during environmental and reliability tests.

Group B				Group C			
Sample	**Torque (oz-in)**	**Sample**	**Torque (oz-in)**	**Sample**	**Torque (oz-in)**	**Sample**	**Torque (oz-in)**
1	4.84	11	5.44	1	5.36	11	5.44
2	5.29	12	3.96	2	5.06	12	3.96
3	4.51	13	6.05	3	3.48	13	6.05
4	5.87	14	5.78	4	3.23	14	5.78
5	5.38	15	5.72	5	3.19	15	5.72
6	4.96	16	4.03	6	4.91	16	4.03
7	4.89	17	5.86	7	2.20	17	5.86
8	5.45	18	6.10	8	2.45	18	6.10
9	4.58	19	4.58	9	4.13	19	4.58
10	4.91	20	4.91	10	4.82	20	4.91

Table 15. Microphone torque measurement on Mark-10 during microphone cycling tests.

Group D			
Sample	**Torque (oz-in)**	**Sample**	**Torque (oz-in)**
21	4.84	31	5.44
22	5.29	32	3.96
23	4.51	33	6.05
24	5.87	34	5.78
25	5.38	35	5.72
26	4.96	36	4.03
27	4.89	37	5.86
28	5.45	38	6.10
29	4.58	39	4.58
30	4.91	40	4.91

As seen in the data obtained, the values of the samples remained within acceptable limits (from 4 to 7 oz-in) once the environmental and reliability tests were completed.

4.8. Results of Stage 10

Table 16 shows the data obtained from the ANOVA performed. The CI column shows the upper and lower limits obtained for the confidence interval at 95%. As can be seen, the data remained within the specification required by the company after the reliability tests, which is a minimum of 1.9 oz-in and a maximum of 7 oz-in. As can be seen, the p-value was less than 0.05 for all the groups. Therefore, it can be said that the environmental test has significant effects on the torque degradation of the product, i.e., if the test is not performed, there is a possibility of not detecting any torque-related problems and having market complaints.

Table 16. Statistical data for analysis of variance for microphone torque.

Group	Sample Size	Average	Standard Deviation	95% CI	*F-Value*	*p*-Value
A	40	4.969	0.764	(4.724, 5.214)	9.09	0.001
B	20	5.1543	0.639	(4.808, 5.500)	9.09	0.001
C	20	4.0646	1.028	(3.718, 4.411)	9.09	0.001
D	20	5.1543	0.639	(4.808, 5.500)	9.09	0.001

4.9. Results of Stage 11

According to the information obtained in Section 4.7, it was not necessary to implement new environmental requirements for the AAXXX product. However, an engineering change (ECO) was generated and approved to be documented in the technical specification of the product, which is the document containing the parameters and requirements that the product must meet, the activities performed, and is where results obtained by the team during this investigation are recorded. Functional teams will use this information for future projects. Additionally, an ECO was generated and approved to include the DRBFM in the new product development process.

Based on the actions performed in the DRBFM, a comparison was performed of the average delivery time of the last four projects developed in the office category with the time required by the company. The results are shown in Table 17. As can be seen, the turnaround time was 1.8 weeks, which is shorter than the required 2 weeks.

Table 17. Average delivery time after application of DRBFM.

Project	Average Delivery Time Per Run (Weeks)	Difference with the Required Time (weeks)
Project USB A	4.5	+2.5
Project USB B	3.5	+1.5
Project USB C	2.7	+0.7
Project USB D	3.7	+1.7
Project AAXXX	1.8	−0.2

5. Result Discussions

As the number of defects and the average delivery time were reduced in the project of AAXXX compared with those occurring in the four previous projects, the sustainability was increased in several ways as follows:

- Quality—since the number of defects is reduced, the quality is increased.
- Economics—since the reduction in defects decreases the cost of production in the long term.
- Environment—since defects are reduced, inorganic pollutants and waste discharged into the environment are also reduced.
- Efficiency—the sustainability was increased since the delivery time was reduced and agreements with customers for the delivery date were fulfilled.

In the case of the quality dimension, this result is consistent with Braccini and Margherita [66] because they found that reducing the defects rate increases quality and its economical dimension. Similarly, our findings agree with Goyal et al. [20] that declares that a defect in a process/product can negatively impact sustainability in its quality, environment, and economic dimensions; so, the quality process can be determined based on the number of defects produced from a quantitative and qualitative point of view and their severity.

Regarding the environmental dimension, our findings converge with Erdil et al. [67], who mention that environmental sustainability naturally aligns with improvement activities in good-producing industries such as manufacturing. Moreover, these authors point out that an increase in defects leads to an increase in rework, which causes a higher use of materials and energy. Regarding efficiency, the findings from this research agree with Nahmens and Ikuma [68], who indicate that reducing or eliminating waste (including waiting time) in a manufacturing process helps to increase sustainability. Their report is based on case studies to show the effects of lean strategy (i.e., a strategy based on reducing wastes such as waiting times and defects) on each dimension of sustainability.

5.1. Theoretical Implications

The findings in this research contribute to theoretical knowledge in the following ways:

1. Statistical reliability testing reduces the number of defects, thus increasing the sustainability of manufacturing processes and products in an easy way because managers can obtain information from their own process.
2. Temperature and humidity can affect the quality in the product here investigated and, therefore, the sustainability, which is why managers must control these parameters.
3. Defect reduction significantly impacts the sustainability of manufacturing processes and products in the quality, environmental, and economic dimensions.
4. The reduction in lead times positively impacts the sustainability of processes, specifically in the efficiency dimension.

Figure 6 shows a model for these theoretical implications.

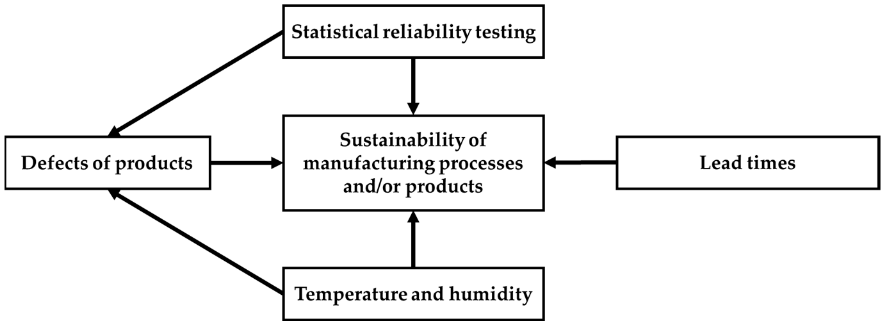

Figure 6. Model of theoretical implications.

5.2. Practical Implications

The results of this study lead to the following practical implications, all of them based on the critical realism approach [69]:

1. Regardless of their economical size, manufacturing companies should pay special attention to the defects in their products, not only in quantity but also in severity, to be sustainable companies.
2. Performing a statistical analysis of a product's defects before its release to the market helps companies to define actions to prevent them once the product is already in the market. ANOVA, DOE, and FMEA are tools that help in this purpose.
3. Likewise, the results of this study imply that, to maintain or increase their sustainability, companies must adopt a lean manufacturing philosophy aimed at eliminating waste (defects and lead times). This implies adopting and applying tools and methodologies such as the Plan-Do-Check-Act cycle, work standardization, kaizen, and poka-yoke for continuous improvement, to mention a few.
4. To increase the sustainability of processes and products, companies must consider variables outside the knowledge and skills of workers, such as temperature and humidity, because they know the production process better.

6. Conclusions

Based on findings from this research, it is concluded that reducing defects and delivery times leads to increased sustainability. Moreover, this conclusion shows that reliability tests are a useful strategy to improve sustainability in product and manufacturing processes. Regarding the FMEA tool, this research provides evidence to conclude that it is a useful tool for improving the sustainability of manufacturing companies, as confirmed by Nguyen et al. [70], because it facilitates the efforts of industrial manufacturers in prioritizing failures that require corrective actions for continuous quality improvement.

A similar conclusion is stated in ANOVA, because Peyer et al. [71] use it to establish a multidimensional sustainability profile for the voluntary simplifier and to examine how strongly voluntary simplifiers are rooted in sustainability. Finally, it is concluded that case studies are acceptable to show the effects of different tools on sustainability, such as ANOVA, DOE, and FMEA. This last conclusion is based on the critical realism approach, as mentioned by Tsang [69] and Easton [72].

7. Limitations, and Future Research

The limitations of this project were the time available and the necessary human resources since some workers were not specifically assigned to the project and only contributed their knowledge when they had time. Another limitation was access to products and process-related information, as only authorized personnel could access it. Finally, a fourth limitation was the sample size. This was due to financial resource constraints on the part of the company.

For future work, it is recommended that the company review other processes (including projects) and products and perform reliability tests to find improvement opportunities in the first instance and to improve sustainability in the second. Additionally, it is recommended to include the social dimension in future reliability tests.

In future research, it is recommended to perform a more general study about the impact of reliability tests, delivery times, and defects on the different dimensions of sustainability. To perform this, developing different hypothetical causal models and collecting data from different manufacturing companies is suggested. Moreover, it is recommended to increase the sample size.

Finally, designing a framework of reference for sustainability development in manufacturing companies is recommended. To perform this, it is suggested to use indicators that allow continuous evaluations and comparisons of recorded performance.

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