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# Successful Projects from the Application of Six Sigma Methodology

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## 1. Introduction

This chapter describes briefly the Six Sigma Methodology (SSM) phases and Key factors for the effective implementation as well as the important tools. SSM was first introduced by Motorola in the 1980's to improve product and service quality through the waste and variance reduction (Pyzdek, 2003). The SSM is a systematic way to solve problems with individual projects to attain better profitability. The SSM main objective is to reduce the number of defective parts to as low as 3.4 parts per million. The objective of this chapter is to show that taking into account the key factors and applying the right tools profitable results can be obtained. Three different application cases are used to illustrate the methodology throughout the chapter and were conducted in twin plants in the Juarez area where the authors participated.

The SSM is structured in a five steps or phases in order solve successfully quality problems. These five steps or phases are known as, Define, Measure, Analysis, Improve and Control or DMAIC procedure. This paper describes these steps and illustrates the Key factors and tools that are needed for successful applications. The cases are related to applications that have been published previously (Valles et al., 2009a, 2009b, 2009c) They are design and the Improvement of Binder manufacturing process, Improvement of automotive speakers manufacturing process and the implementation of SSM for the manufacturing of a circuit that is used in inkjet printer cartridges.

The three illustrative applications were successfully implemented by considering the key factors and important tools used throughout the deployment of the SSM. Also, some fundamentals were included such as basic definitions and philosophy, efficient communication, team work, training and management involvement and commitment. Beside the defective part reductions, some other important results were observed in the implementation process, such as culture change, trained employees and better human resources, and better project management skills. In conclusions, there were changes for the better in all the organizations where the SS implementations were conducted.

## 2. DMAIC procedure

The DMAIC procedure will be briefly describe in this section (Pande et al., 2002). The SSM relies on this procedure for the implementation of improvement projects that requires management commitment and team work. It also involves the use of statistical methods, quality improvement techniques and the scientific method as well.

In the Define step, a team defines the problem objectives and goals, identifies the customers of the process and customers requirements. The project charter, work plan, measurement of the customer requirements and process map documentation are needed.

In the Measure step includes the process performance measure selection, measurement system evaluation and analysis and determination of the process performance level and capability. In this step what to measure must be decided by the team. Sometimes, it is difficult to decide, because data collection is even more difficult and time consuming.

The step of Analysis includes the analysis and determination of potential root causes of variation through the use of statistical tools and the basic quality tools such as Pareto charts, Ishikawa Diagrams, etc. The phases of the root cause analysis are used in this step. They are exploring, generating hypotheses about causes and verifying or eliminating causes. The main input of this step is data generated by the measuring the important variables.

The goal of the Improve step is to find and implement solutions that will eliminate the causes of problems, reduce variation in a process or prevent a problem from recurring. The key factor and important tools for the Improve step are identification, evaluation and verification of potential solutions by the use of basic statistical methods, design of experiments, response surface, Taguchi methods, etc. The identification of potential solutions is often generated by brainstorming.

At last, the Control step has the objective to continue measuring the performance of the process periodically and keeping it under control. The process management control and action plans are made by implementing control charts, control plans and mistake-proof devices. It is important to mention that the first three steps are observational studies, that is, there is not intervention in the process. While in the last two steps are designed experiments, where the researchers take active action into the process in order to achieve the established goals.

### 3. Reduction of the nonconforming fraction in manufacturing of a circuit

The specific objectives of this project were grouped in three categories; measurement equipment, failure analysis, and process improvement. Regarding the measurement equipment, the objectives were to evaluate the current measurement system and to assess the repeatability and reproducibility of the electric tester. In relation to the method of failure analysis, the objectives were to: evaluate the standardization of criteria for the technical failures; develop a procedure and sampling plan for defective parts; obtain a reliable estimate of the distribution for failures in the total population; propose an alternate method for the analysis of defective parts; and identify and measure the defects, specially the main electrical defect.

About the analysis of problems and process improvement, the objectives were to; identify the factors or processes that affect the quality feature in question (electrical function of the circuit); identify the levels of the parameters in which the effect of the sources of variation will be minimal; develop proposals for improvement; and to implement and monitor the proposed improvements.

**Definition:** During the years 2006 and 2007 the main product had a low level of performance in electrical test. Historical data shows that on average, 3.12% of the material was defective. The first step was the selection of the Critical Customer Characteristics and the response variable. The critical characteristic, in this case, was the internal electrical defects detected during electrical testing.

**Measurement:** This phase is to certify the validity of the data through the evaluation of the measurement system. The first step is a normality test of the data and an analysis of the process capacity. This began with the measurement of the percentage of electrical failures. The percentage of electrical failures is obtained after a test is performed to the 100% of electric circuits.

Repetition	Measurement	Moving Range	Repetition	Measurement	Moving Range
1	80.1	0	11	80.0	0.2
2	79.9	0.2	12	80.1	0.1
3	80.1	0.2	13	80.1	0
4	79.8	0.3	14	79.9	0.2
5	80.1	0.3	15	79.9	0
6	80.1	0	16	80.0	0.1
7	79.9	0.2	17	79.8	0.2
8	80.2	0.3	18	79.8	0
9	80.1	0.1	19	80.1	0.3
10	79.8	0.3	20	80.0	0.1

Table 1. Measured by Operator (Reference Value of 73.5 Ohms)

In order to evaluate the accuracy of the equipment, a standard piece was used with a reference value of 75.3 Ω, which was measured 20 times by the same operator. According to the results of the data shown in Table 1, it is concluded that a 0.05% accuracy of the calibration of the instrument is acceptable.

The evaluation of the capability of the measurement process in terms of precision was conducted through a study of repeatability and reproducibility (R&R). The evaluation was conducted with 10 pieces of production taken at different hours, with 3 operators and 3 repetitions. The results of the R&R study was performed with Minitab© shown in Table 2. The total variability introduced by the electrical tester is 3.32%, which is considered excellent.

Source	StdDev	Study Var (6 * SD)	%Study Var (%SV)	%Tolerance (SV/Toler)	%Process (SV/Proc)
Total Gauge R&R	4.43E-02	0.265832	48.59	3.32	28.90
Repeatability	3.78E-02	0.232379	42.47	2.90	25.26
Reproducibility	2.15E+00	0.129099	23.60	1.61	14.04
Operator	0.00E+00	0.000000	0.00	0.00	0.00
Operator*Part	2.15E-02	0.129099	23.60	1.61	14.04
Part-To-Part	7.97E-02	0.478191	87.40	5.98	51.99
Total Variation	9.12E-02	0.547114	100.00	6.84	59.48

Table 2. Results of the Repeatability and Reproducibility Study

A study of repeatability and reproducibility for attributes was done with purpose of ensuring the consistency of the criteria used by four different inspection areas. Table 3 shows the result.

Evaluation	Shift A Inspector	Shift B Inspector	Shift C Inspector	Shift D Inspector
% Matched	96.67%	96.67%	93.33%	90.00%
%Appraised Vs. known standard	93.33%	93.33%	86.66%	76.67%

Table 3. Study of Repeatability and Reproducibility for Attributes

**Analysis:** This phase consisted of searching through brainstorming rounds the possible factors that may be affecting the electrical performance of the product. The factors that were considered most important were raised as hypotheses and verified by different statistical tests. The objective was to identify key factors of variation in the process. For the identification of potential causes were prepared Pareto Charts of Defects, in one of them, about 33% of the electrical faults analyzed cannot be identified with the test equipment and 21.58% are attributed to the defect called "Waste of Aluminum Oxide", given that the current equipment does not detect 33% of nonconformities. Samples were sent to an external laboratory, observing that more than 50% of the parts had traces of aluminum oxide so small that they could not be detected with the microscope used in the laboratory of failure analysis. Because this waste may cause several problems, a cause and effect matrix shown in Table 4 was prepared to prioritize areas of focus.

The causes considered important were; the quantity of wash cycles, the thickness of the Procoat layer, Lots circuit, the parameters of grit blast equipment and the operational differences among shifts. With respect to the quantity of wash cycles, to determine if they affect the fraction of electrical defects, an experiment with, one, two and three wash cycles as factor levels with sample sizes of 30 wafers each. Data was tested for normality. The statistical differences among wash cycles are not significant, concluding that Wash Cycle is not an important factor. The results of these tests are not shown. In relation to the thickness of the Procoat finish, it was suspected that the increase of the thickness reduces the percentage of electrical failures. This is to reduce the impact that grains of aluminum oxide has on the semiconductor. An experiment with a single factor was carried out. The factor assessed was the thickness of the layer of Procoat under 4 levels and 30 replications. The 120 runs were conducted completely random. The different thicknesses of Procoat tested were 0, 14, 30, 42 microns. The results of the Anova for this experiment are shown in Figure 1.

The data indicate that there is a difference between the levels, as the p-value is less or equal to 0.0001. Only the level of 0 micron is different from the others and the confidence intervals of the other three levels overlap, then they have the same mean. Figure 2 shows the comparisons of the four levels of procoat in relation to the percentage of electrical failures. The layer of procoat improves electrical performance up to 14 microns (a condition of the current process); however it is not justifiable to increase the thickness of the layer, as it did not represent improvement in the average electric performance or to reduce the variation.

Concerning the Lots of raw material for the Circuit, in order to prove that the condition of the raw material is not a factor that is influencing the electrical performance, it was necessary to verify the following hypotheses:  $H_0$ : There is no difference in the fraction of defective units between different batches vs.  $H_1$ : There is a difference in the fraction of defective units between different batches. Because the four lots of raw material that were selected randomly contain different amounts of wafers, the experiment was an unbalanced completely random design. Each batch contains between 20 and 24 wafers. In a shift 200

circuits can be assembled. Each circuit is mounted in a cartridge for inkjet printers that are electrically tested on an individual basis. The ANOVA results are summarized in Figure 2, indicating that there is no difference in the percentage of electrical failures of wafers per batch. The P-Value of 0. 864 is a high probability that the lots have equal means. Therefore, the null hypothesis is not rejected. Then it is concluded that the lots of wafers show no difference in electric behavior and the assumption that some batches possess a lower electrical performance is discarded.

Cause and Effect Matrix							
Rating of Importance to Costumers		5.91	2.3	1	0.78		
Y's		1	2	3	4	5	
X's		Residual AIO	Scratch	Tester Error	Pad Contamination	Requirement	Total
Process Step	Process Input						
1	Grit Blast	9	9	0	3		75.96
2	Nozzle Attached	6	6	0	6		53.76
3	Lexfilm	0	9	0	9		27.45
4	Electrical Test	0	0	9	0		9.36
5	Dicing	0	3	0	0		6.81
6	Tab Bond	0	0	0	0		0
Total		89	61	9	14		

Table 4. Cause-Effect Matrix

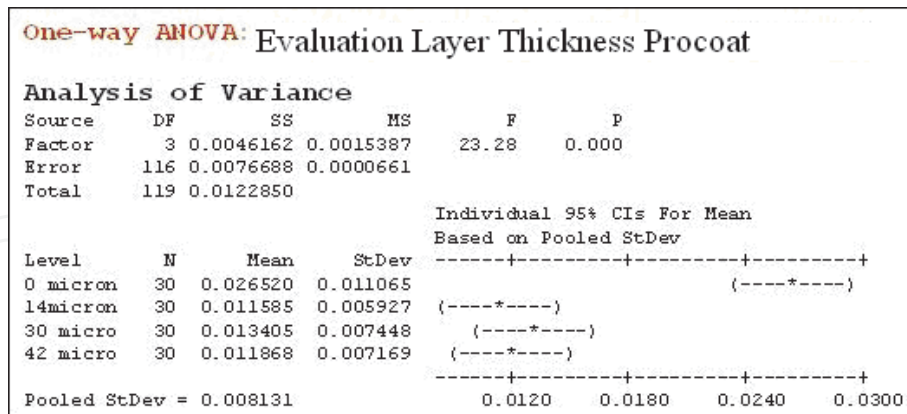


Fig. 1. Results of the ANOVA for the Procoat Layer Thickness

Additionally, the test of equal variances (for the four lots) concluded that there is no hard evidence to suggest that the variability in the percentage of electrical failures depends on the lot or semiconductor wafers. Figure 3 shows the results of Bartlett test, where the p-value of 0.926 ( $P > 0.05$ ). Data was tested for normality before the test the hypothesis of equality of the averages of the batches with an ANOVA. There was no evidence to say that the data was not normally distributed.



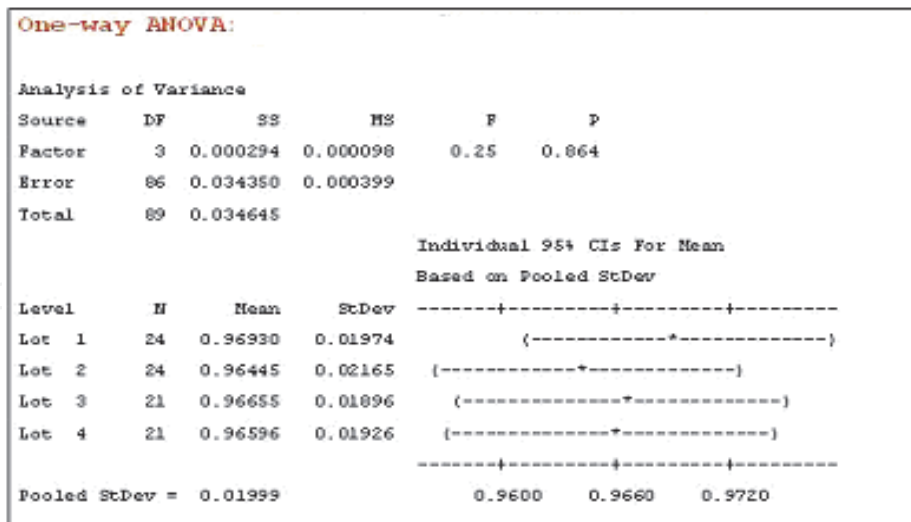


Fig. 2. ANOVA for Different Lots of Wafers

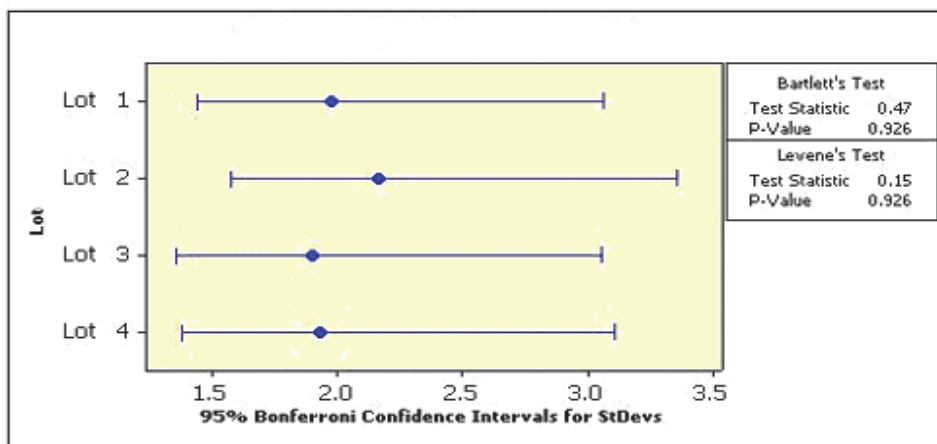


Fig. 3. Variance Test for Lots of Wafers

Factor	Levels		
Pressure (psi)	95	100	110
Tooling Height (inches)	0.060	0.070	0.080
Cycle Time (milliseconds)	6000	7000	8000
Machine	1	2	3

Table 5. Factors Evaluated in Equipment Grit Blast

The analysis for the data from Table 6 was run with a main effect full model. This model is saturated; therefore the two main effects with the smallest Sum of Squares were left out from the model. This is that Machine and Cycle time do not affect the electrical Performance. The analysis for the reduced model is presented in Figure 4. It can be observed that the Pressure and the Tooling Height are significant with p-values of 0.001, and 0.020, respectively.

Pressure (psi)	Tooling Height (in)	Cycle Time (milliseconds)	Machine	% Acceptable
95	0.060	6000	1	0.9951
95	0.070	7000	2	0.9838
95	0.080	8000	3	0.9908
100	0.060	7000	3	0.9852
100	0.070	8000	1	0.9713
100	0.080	6000	2	0.986
110	0.060	8000	2	0.9639
110	0.070	6000	3	0.9585
110	0.080	7000	1	0.9658

Table 6. Results of Runs in Grit Blast

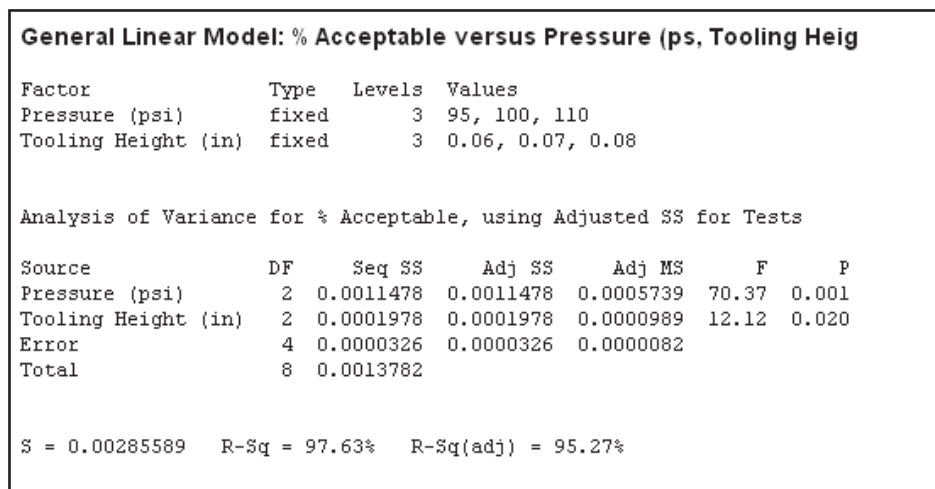


Fig. 4. ANOVA for the Reduced Model for the Grit Blast Parameters

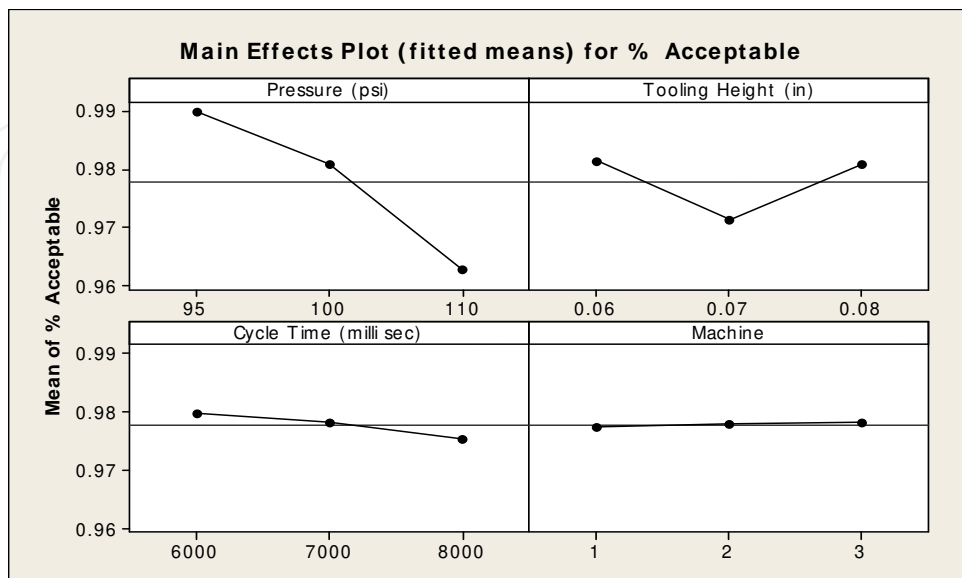


Fig. 5. Chart in Benchmarks Main Effects of Grit Blast



The Figure 5 shows the main effects plot for all four factors, which confirm that only Pressure, Tooling Height and Cycle Time are affecting the quality characteristic. Figure 6 shows that normality and constant variance are satisfied.

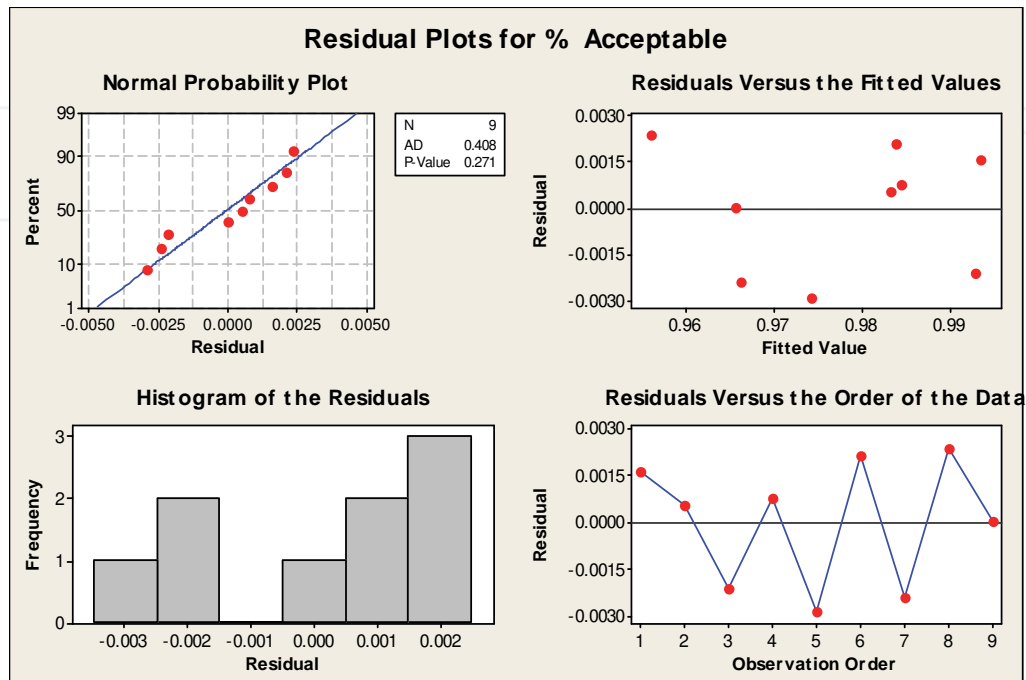


Fig. 6. Residual Plots for the Acceptable Fraction.

Finally, with the intention of determining whether there is a difference in performance of four shifts, a test analysis of variance and equality of means was performed. The Table 7 shows that there is a difference between at least one of the shifts, since the p-value is less or equal to 0.0001. The above analysis indicates that all four shifts are not working with the same average efficiency. For some reason shift A presents a better performance in electrical test. Also it can be observed that shift D has the lowest performance. With the intention of confirm this behaviour; a test of equal variances was conducted. It was observed that the shift A shows less variation than the rest of the shifts, see Figure 7. This helps to analyze best practices and standardized shift A in the other three shifts.

Once it was identified the factors that significantly affect the response variable being analyzed, the next step was to identify possible solutions, implement them and verify that the improvement is similar to the expected by the experimental designs. According to the results obtained, corrective measures were applied for the improvement of the significant variables.

With regard to the inefficient identification of flaws in the failure analysis, and given that 33% of electrical faults analyzed in the laboratory could not be identified with the test equipment that was used. Then, a micromanipulator was purchased. It allows the test of circuits from its initial stage. Furthermore, it is planned the purchase of another equipment different than the currently used in the laboratory of the matrix plant at Lexington. This equipment decomposes the different layers of semiconductor and determines the other particles that are mixed in them. These two equipments will allow the determination of the

particles mixed in the semiconductor and clarify if they are actually causing the electrical fault, the type of particle and the amount of energy needed to disintegrate.

One-way ANOVA: Shifts A, B, C y D					
Source	DF	SS	MS	F	P
Factor	3	13.672	4.557	9.23	0.000
Error	124	61.221	0.494		
Total	127	74.894			
S = 0.7027 R-Sq = 18.26% R-Sq(adj) = 16.28%					
Individual 95% CIs For Mean Based on Pooled StDev					
Level	N	Mean	StDev	+-----+-----+-----+-----	
A	32	3.0283	0.4350	(---*---)	
B	32	3.6078	0.6289	(---*---)	
C	32	3.5256	0.8261	(---*---)	
D	32	3.9418	0.8412	(---*---)	
				+-----+-----+-----+-----	
				2.80 3.20 3.60 4.00	
Pooled StDev = 0.7027					

Table 7. ANOVA Difference between Shifts

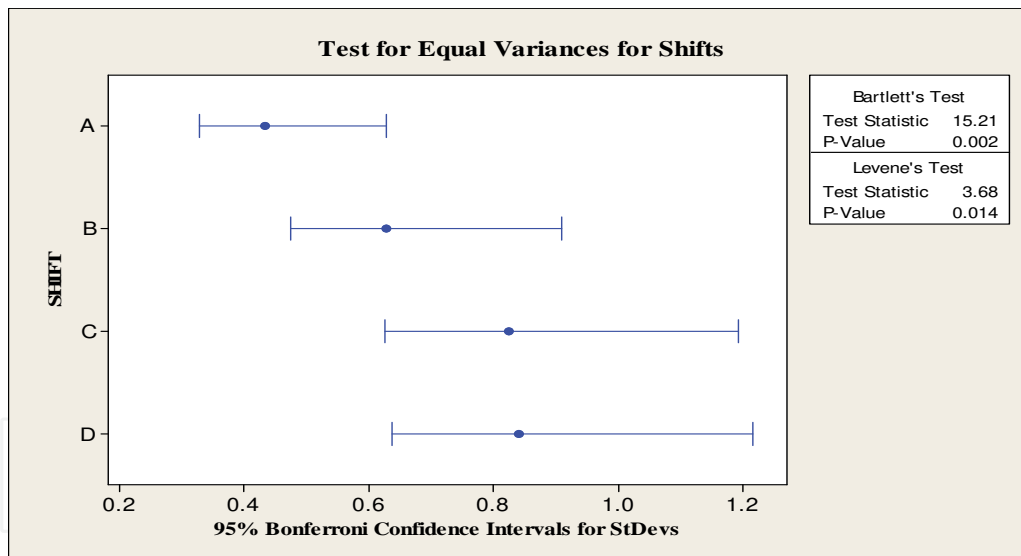


Fig. 7. Equality of Variance Test for the Shifts

About the percentage of defective electrical switches with different thicknesses of Procoat (0, 14, 30 and 42 microns). The use of Procoat will continue because the layer has a positive effect on the electrical performance of the circuit. However, because the results also showed that increasing the thickness of the layer from 14 to 42 microns, does not reduce the level of electrical defects. The thickness will be maintained at 14 microns.

For the drilling pressure in the equipment, lower levels are better and for the improvement of the electrical performance without affecting other quality characteristics, such as the dimensions of width and length of the track. It was determined that the best level for the

pressure would be 95 psi. With respect to the height of the drill, since it significantly affects the electrical performance and this is better when the tool is kept at 0.60 or 0.80 inches on the semiconductor. For purposes of standardization, the tool will remain fixed at a height of 0.60 inches.

In relation to the cycle time, it showed to be a source of conflict between two quality characteristics (size of the track and percentage of electrical failures). Although it is a factor with a relatively low contribution to the variation of the variable analyzed. Several experiments were run with the parameters that would meet the other characteristic of quality. Figure 5 shows the main effect. For the variable electrical performance, a factor behavior of the type smaller is better was introduced. While for the other variable output capacity of the process, a higher is better behavior was selected and for that reason, it was determined that this factor would be in a range from 7,000 to 8,000 milliseconds.

Finally, with respect to the difference between the four-shift operations and electrical performance, results indicate that the "A" shift had better electrical performance, with the intention of standardization and reduction of the differences, a list of best practices was developed and a training program for all shifts was implemented. In this stage is recommended an assessment of the benefits of the project (Impact Assessment of Improvement). Once implemented the proposed solutions, a random sample size 200 was taken from one week work inventory product and for all shifts. This sample was compared to a sample size 200 processed in previous weeks. Noticeable advantages were found in the average level of defects, as well as the dispersion of the data. Additionally, the results of the tested hypotheses to determine if the proposed changes reduced the percentage defective. Electrical test indicate that if there is a difference between the two populations.

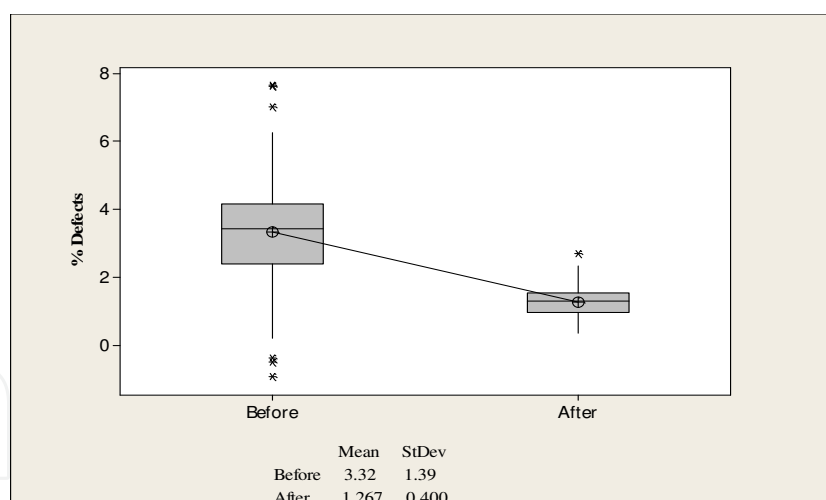


Fig. 8. Box Plots for the Nonconforming Fractions of Before and After

In Figure 8, Box diagrams are shown for the percentage of defects in the two populations. It is noted that the percentages of defects tend to be lower while maintaining the parameters of the equipment within the tolerances previously established as the mean before implementation is 3.20%, against 1.32% after implementation. The test for equality of variances shows that in addition to a mean difference there is a reduction in the variation of the data as shown in see Figure 9. Figure 10 shows a comparison of the distribution of defects before and after implementation. It can be seen that the defect called "Aluminum oxide residue" was considerably reduced by over 50%.

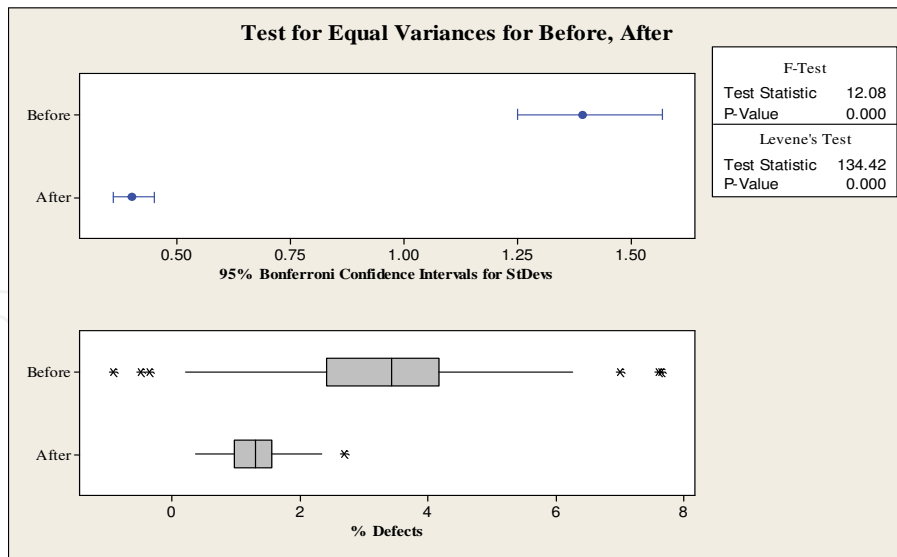


Fig. 9. Test of Equality of Variances for the Nonconforming Fractions of Before and After

**Control:** In order to achieve stable maintain the process, identified the controls to maintain the pressure, height of the tool and cycle time within the limits set on the computer Grit Blast and test electrical equipment. Identification of Controls for KPIV's: Because these three parameters had been covered by the machine operator to offset some equipment failures such as leaks or increasing the cycle time. It was necessary to place devices that will facilitate the process control in preventing any possible change in the parameters.

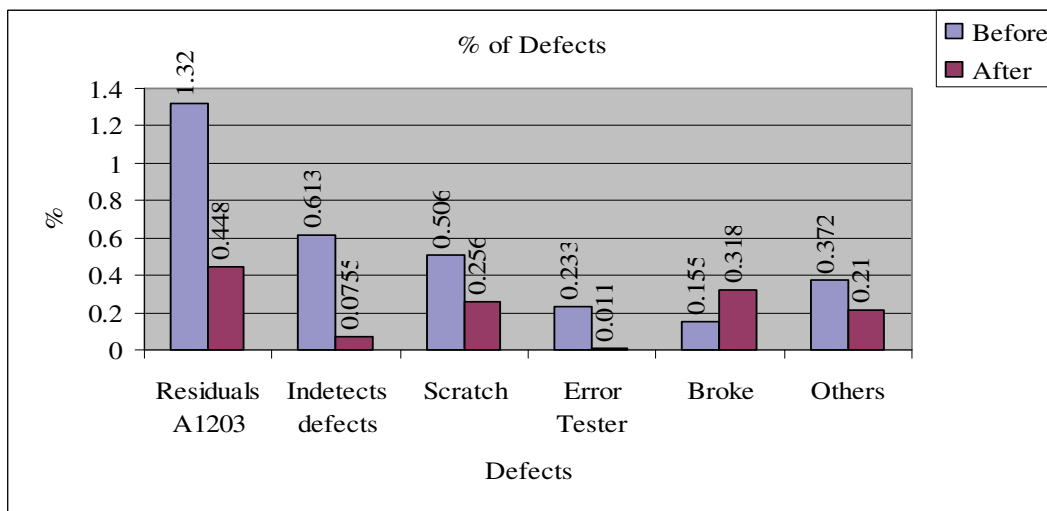


Fig. 10. Distribution of Defects Before and After

Additionally, to help keep the machine operating within the parameters established without difficulty, it was essential to modify the plan of preventative maintenance of equipment. Due to the current control mechanisms are easily accessible to the operator; it was determined to improve those controls to ensure the stability of the equipment and process. All of this coupled with an improvement in preventative maintenance of the equipment. Based on the information generated with the assessment of the assumptions above, it generated an action plan which resulted in a reduction in the percentage of electrical failures

in general. As well as a reduction in the defect called "Short but residue of aluminum oxide". Table 8 shows a comparison of the nonconforming fraction, PPM's and Sigma levels of before and after implementation.

	% Defects	Sigma Level	PPM's
Base Line	3.20	3.35	31982
Goal	1.60	3.64	16000
Evaluation	1.32	3.72	13194

Table 8. Comparison of Before and After

**Conclusion:** The implementation of this project has been considered to be a success. Since, the critical factor for the process were found and controlled to prevent defects. Therefore the control plan was updated and new operating conditions for the production process. The based line of the project was 3.35 sigma level and the gain 0.37 of sigma. Which represent the elimination of 1.88% of nonconforming units or 18,788 PPMs. Also, the maintenance preventive program was modified to achieve the goal stated at the beginning of the project. It is important to mention that the organization management was very supportive and encouraging with the project team. The Six sigma implementation can be helpful in reducing the nonconforming units or improving the organization quality and personal development.

#### 4. Capability improvement for a speaker assembly process

A Six Sigma study that was applied in a company which produces car speakers is presented. The company received many frequent customer complaints in relation to the subassembly of the pair coil-diaphragm shown in Figure 11. This subassembly is critical to the speaker quality because the height of the pair coil-diaphragm must be controlled to assure adequate functioning of the product. Production and quality personnel considered the height was not being properly controlled. This variable constitutes a high potential risk of producing inadequate speakers with friction on the bottom of the plate and/or distortion in the sound. Workers also felt there had been a lack of quality control in the design and manufacture of the tooling used in the production of this subassembly. The Production Department as well as top management decided to solve the problems given the cost of rework overtime pay and scrap which added up to \$38,811 U.S. dollars in the last twelve months. Improvement of the coil-diaphragm subassembly process is presented here, explaining how the height between such components is a critical factor for customers. This indicates a lack of quality control.

**Define:** For deployment of the Project, a cross functional project team was integrated with Quality, Maintenance, Engineering, and Production personnel. The person in charge of the project trained the team. In the first phase, the multifunctional 6 $\sigma$  team made a precise description of the problem. This involved collecting the subassemblies with problems such as drawings, specifications, and failure modes analyses. Figure 11 shows the speaker parts and the coil-diaphragm subassembly. The subassembly was made in an indexer machine of six stations. The purpose of this project was to reduce quality defects; specifically, to produce adequate subassemblies of the coil-diaphragm. Besides, the output pieces must be delivered within the specifications established by the customer. The objective was to reduce process variation with the Six Sigma methodology and thus attain a  $C_{pk} \geq 1.67$  to control the tooling.



Fig. 11. Speaker Explosion Drawing

Then, the critical characteristics were established and documented based on their frequency of occurrence. Figure 12 shows the five critical defects found during a nine month period. It can be seen that height of the coil-diaphragm out of specifications is the most critical characteristics of the speaker, since it contributes 64.3% of the total of the nonconforming units. The second highest contributing defect is the distortion with 22.4%. These two types of nonconforming speakers accumulate a total of 86.8%. By examining Figure 10, the Pareto chart, it was determined that the critical characteristic is the height coil-diaphragm. The project began with the purpose of implementing an initial control system for the pair coil-diaphragm. Then, the Process Mapping was made and indicated that only 33.2% of the activities add value to parts.

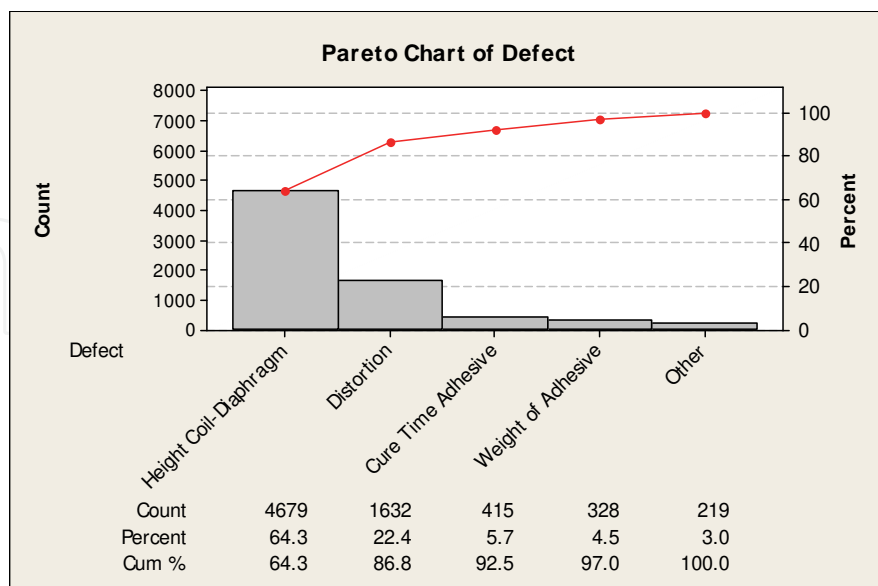


Fig. 12. Pareto Diagram for Types of Defects

Also the cause and effect Matrix was developed and is shown in Table 9. It indicates that tooling is the main factor that explains the dispersion in the distance that separates coil and



diaphragm. At this point, there was sufficient evidence that points out the main problem was that the tooling caused variation of the height of the coil diaphragm.

**Measurement:** Gauge R&R and process capability index Cpk studies were made to evaluate the capability of the measuring system and the production process. Simultaneously, samples of the response variables were taken and measured. Several causes of error found in the measurements were: the measuring instrument, the operator of the instrument and the inspection method.

Step Number	Level of Effect 1.- NO EFFECT 4.- MODERATE EFFECT 9.- STRONG EFFECT	Present	Functionality	Appearance	Adhesion	Total
	Factor in Process					
1	Tooling	9	9	9	9	342
2	Diaphragm dimension	9	9	4	9	302
3	Weight of adhesive	9	9	4	9	302
4	Weight of accelerator	9	9	4	9	302
5	Diameter of coil	9	9	9	4	292
6	Cure time	9	9	4	4	252
7	Injection devise	9	9	4	4	252
8	Air pressure	9	9	4	4	252
9	Wrong material	9	9	4	4	252
10	Broken material	9	4	4	4	202
11	Personal training	9	9	1	1	198
12	Manual adjustment	1	4	4	4	122
13	Production Standard	1	9	1	1	118
14	Air	1	1	1	1	38

Table 9. Cause and Effect Matrix for the Height of Coil-Diaphragm

To correct and eliminate errors in the measurement system, the supervisor issued a directive procedure stating that the equipment had to be calibrated to make it suitable for use and for making measurements. Appraisers were trained in the correct use and readings of the measurement equipment. The first topic covered was measurement of the dimension from

the coil to the diaphragm, observing the specifications. The next task was evaluation of the measurement system, which was done through an R&R study as indicated in (AIAG, 2002). The study was performed with three appraisers, a size-ten sample and three readings by appraiser. An optical comparative measuring device was used. In data analysis, the measurement error is calculated and expressed as a percentage with respect to the amplitude of total variation and tolerance. Calculation of the combined variation (Repeatability and reproducibility) or error of measurement (EM):  $P/T = \text{Precision/Tolerance}$ , where 10% or less = Excellent Process, 11% to 20% = Acceptable, 21% to 30% = Marginally Acceptable. More than 30% = Unacceptable Measurement Process and must be corrected.

Since the result of the Total Gage R&R variation study was 9.47%, the process was considered acceptable. The measuring system was deemed suitable for this measurement. Likewise, the measuring device and the appraiser ability were considered adequate given that the results for repeatability and reproducibility variation were 8.9% and 3.25%, respectively. Table 10 shows the Minitab© output.

The next step was to estimate the Process capability index Cpk. Table 11 shows the observations that were made as to the heights of the coil-diaphragm. The result of the index Cpk study was 0.35. Since the recommended value must be greater than 1, 1.33 is acceptable and 1.67 or greater is ideal. The process then was not acceptable. Figure 13 shows the output of the Minitab© Cpk study. One can see there was a shift to the LSL and a large dispersion. Clearly, the process was not adequate because of the variation in heights and the shift to the LSL. A 22.72% of the production is expected to be nonconforming parts.

Source	StdDev(SD)	Study Var (5.15*SD)	%Study Var(%SV)
Total Gage R&R	0.022129	0.11397	9.47
Repeatability	0.020787	0.10705	8.90
Reproducibility	0.007589	0.03908	3.25
C2	0.007589	0.03908	3.25
Part-To-Part	0.232557	1.19767	99.55
Total Variation	0.233608	1.20308	100.00
Number of Distinct Categories = 15			

Table 10. Calculations of R&R with Minitab©

Height/ Measurement	Sample/Hour										
	1	2	3	4	5	6	7	8	9	10	11
1	4.72	4.88	5.15	4.75	4.42	4.76	5.14	5	4.88	4.66	4.75
2	4.67	4.9	5	4.4	4.81	4.81	4.78	4.8	5	4.58	4.88

Table 11. Heights of Coil-Diaphragm before the Six Sigma Project

Verification of the data normality is important in estimating the Cpk, which was done in Minitab with the Anderson-Darling (AD) statistic. Stephens (1974) found the AD test to be one of the best Empirical distribution function statistics for detecting most departures from normality, and can be use for n greater or equal to 5. Figure 14 shows the Anderson-Darling test with a p-value of 0.51. Since the p-value was greater than 0.05 ( $\alpha=0.05$ ), the null hypothesis was not rejected. Therefore, the data did not provide enough evidence to say that the process variable was not normally distributed. As a result, the capability study was valid since the response variable was normally distributed.

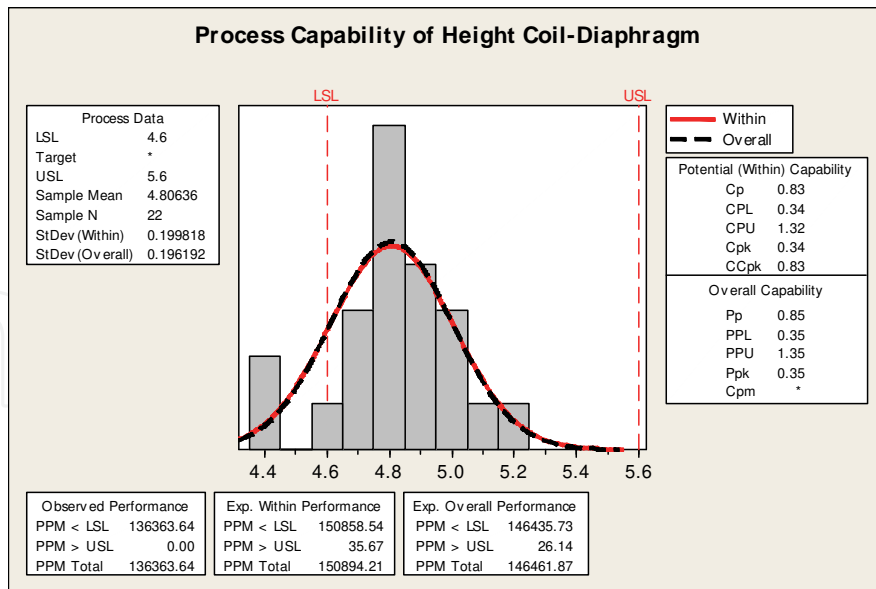


Fig. 13. Estimation of the Cpk Index for a Sample of Coil-Diaphragm Subassemblies

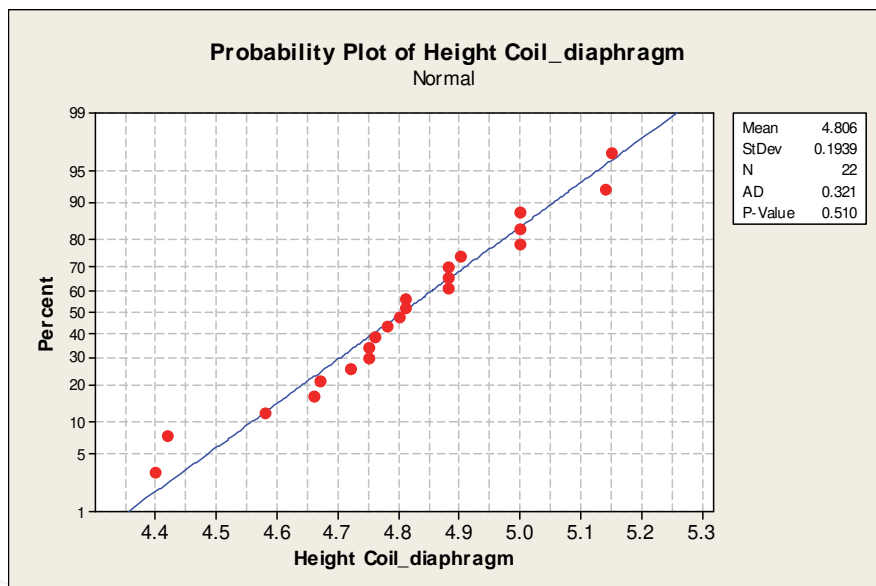


Fig. 14. Normality Test of the Coil-Diaphragm Heights

**Analysis:** The main purpose of this phase was to identify and evaluate the causes of variation. With the Cause and Effect Matrix, the possible causes were identified. Afterward, the Six Sigma Team selected those which, according to the team’s consensus, criteria and experience, constituted the most important factors. With the aim of determining the main root-causes that affected the response variable, a diagram of cause and effect (Ishikawa diagram) was prepared in a brainstorm session where the factors that influenced the height between the coil and the diaphragm were selected. The causes were statistically analyzed, and the tooling was found to have had a moderate effect in the critical dimensions. The tooling effect had the largest component of variation. Several causes were found: first, the tools did not fulfill the requirements, and their design and manufacture were left to the supplier; also, the plant had no participation in designing the tools; second, the weight of

the adhesives and the accelerator were not properly controlled. Since the tools were not adequate given that some variation was discovered in the amounts delivered, this had an impact on the height.

The tooling was analyzed to check whether the dimensions had affected the height between the coil and the diaphragm. The regression analysis was made to verify the hypothesis that the dimensions of the tooling do not affect the height between the coil and the diaphragm. The First two test procedures used to verify the above hypothesis were the regression analysis and the one-way ANOVA. The results of both procedures were discarded because the basic assumptions about normality and homogeneity in the variances were not satisfied. Then the Kruskal-Wallis test was carried out to verify the hypothesis. The response variable was the Height of the Coil-Diaphragm and the factor was the Tooling height. Table 12 illustrates the results

Figure 15 shows the results of Kruskal Wallis analysis with a p-value less than 0.001. Then the decision is to reject the null hypothesis. Consequently, it is concluded that the data provide sufficient evidence to say that the height of the tooling affects the height of subassembly coil- diaphragm.

Levels	Tooling Height	Coil-Diaphragm Height (in mm)						Mean
		1	2	3	4	5	6	
1	4.78	4.70	4.75	4.70	4.75	4.78	4.76	4.74
2	4.88	4.81	4.83	4.85	4.87	4.81	4.81	4.83
3	4.90	4.88	4.91	4.95	4.94	4.92	4.93	4.92
4	5.00	5.10	5.20	4.98	4.98	5.31	4.97	5.09
5	5.10	5.12	5.14	5.23	5.20	5.19	5.31	5.19
6	5.30	5.40	5.55	5.38	4.97	4.99	5.39	5.28

Table 12. Results of Tooling Height vs. Coil-Diaphragm Height

Kruskal-Wallis Test: Height of Coil-Diaphragm versus Tool Height				
Kruskal-Wallis Test on Height of Coil-Diaphragm				
Tool Height	N	Median	Ave Rank	Z
4.78	6	4.750	3.5	-3.82
4.88	6	4.820	9.5	-2.29
4.90	6	4.925	15.5	-0.76
5.00	6	5.040	24.4	1.51
5.10	6	5.195	28.0	2.42
5.30	6	5.385	30.1	2.95
Overall	36		18.5	
H = 31.05 DF = 5 P = 0.000				
H = 31.09 DF = 5 P = 0.000 (adjusted for ties)				

Fig. 15. Result of Kruskal Wallis Test

In addition, the thickness of the diaphragm was analyzed. A short term sample of pieces of diaphragms were randomly selected from an incoming lot, and measured to check the capability of the material used in the manufacturing. This analysis was conducted because

when the thickness of the diaphragm could be out of specification and the height coil-diaphragm could be influenced. The diaphragm specifications must have a thickness between  $0.28 \pm 0.03$  mm for a certain part number. The material used in the subassembly is capable because the measurements were within specifications and had a Cpk of 1.48. Which is acceptable because was greater than 1.33. Also, the weight of adhesive was analyzed, thus, another short term sample of 36 deliveries were weighted. The weight of the glue must be within 0.08 and 0.12 grams. The operation of delivering the adhesives in the subassembly is capable because the Cpk was equal to 3.87, which greater than 1.67 and acceptable. The weights of the adhesive appear to be normal. Regarding the accelerator weight, 36 measurements were made on this operation, whose specifications are from 0.0009 to 0.0013 grams. Also, the data about weights of the accelerator indicates a Cpk of 1.67. Therefore, this process was complying with the specifications of the customer.

Finally, the Multi-Vari analysis allowed the determination of possible causes involved in the height variation. To do the Multi-Vari chart, a long term random sample of size 48 was selected, stratifying by diaphragm batch, speaker type and shift. The main causes of variation seem to be the batch raw material (diaphragm and coil) used, and the second work shift in which the operators had not been properly trained. See Figure 16. Two different lots of coil and the two shifts were included in the statistical analysis to verify whether raw material and shifts were affecting the quality characteristic. The results of multivariate analysis indicated that these factors did not influence significantly the subassembly height.

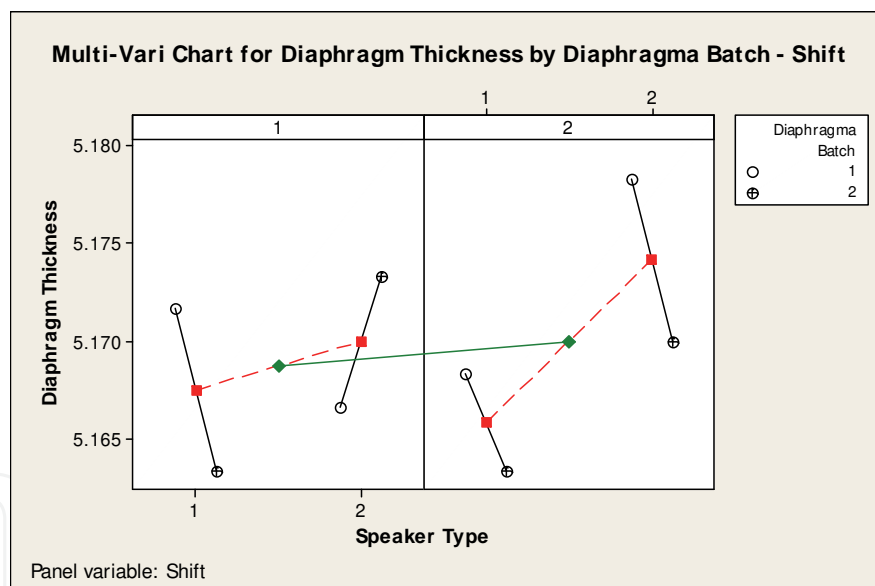


Fig. 16. Multi-Vari chart for Height by Batch, Speaker Type and Shift.

**Improvement:** In the previous phase, one of the causes of variation on the Height of Coil-Diaphragm was found to be the Tooling height. The tooling height decreases due to the usage and wearing out. The phase began with new drawings of the tooling subassembly coil and diaphragm, and the verification and classification of drawings and tooling, respectively. The required high-store tools (maximum and minimum) supplemented this as well. Tooling drawings were developed for the production of the subassemblies coil-diaphragm, the coil-diaphragm subassemblies, controlling the dimensions carefully according to work instructions. No importance had been previously given to the tools design, drawings and production.

After all the improvements were carried out, a sample of thirty-six pieces was drawn to validate the tooling correction actions by estimating the Cpk. The normality test was performed and the conclusion was that the data is not normally distributed. Then, Box-Cox transformation was applied to the reading to estimate the process capability. Figure 17 shows the substantial improvement made in the control of the heights variation. The study gave a Cpk of 2.69; which is greater than 1.67. This is recommended for the release of equipment and tooling.

**Control:** This investigation in addition to the support of management and the team all strengthened the engineering section and led to very good results. A supervisor currently performs quality measurements of the tooling for control. Such a tooling appraisal was not carried out as part of a system in the past, but now it is part of the manufacturing process. This change allowed an improvement through the control of drawings and tooling as well as by measuring the tooling before use in the manufacture of samples and their release.

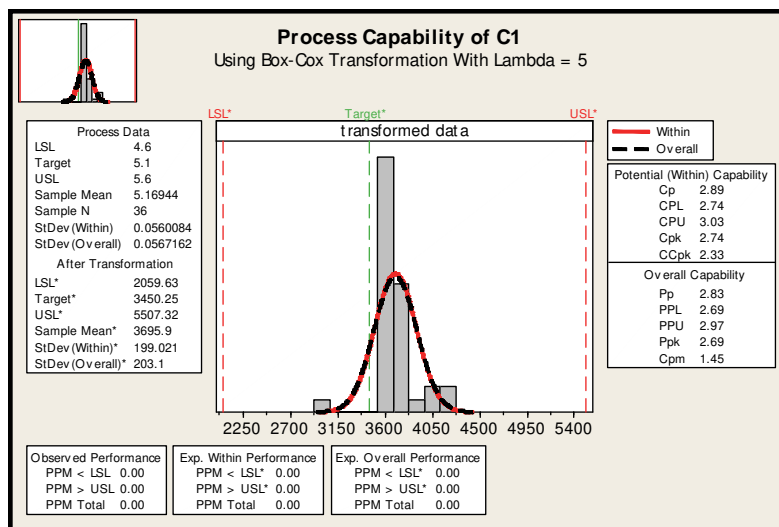


Fig. 17. Estimation of Cpk for Height Coil-Diaphragm with Control in the Tooling

A management work instruction was mandatory to control the production of manufacturing tooling for subassemblies. The requirement was fulfilled through the high-quality system ISO / TS 16949 under the name of "Design Tools". Furthermore, management began to standardize work for all devices used in the company. The work instruction "Inspection of Critical Tooling for the Assembly of Horns" was issued and applies to all the tooling mentioned in the instruction. Design of the tooling was documented in required format that contains the evidence for the revision of the tooling. Confirmatory tests were conducted to validate the findings in this project, and follow-up runs to be monitored with a control chart were established.

**Conclusion:** At the beginning of this project, the production process was found to be inadequate because of the large variation: Cpk's within 0.35, as can be seen in Figure 13. Implementing the Six Sigma methodology has resulted in significant benefits, such as no more re-tooling or rework, no more scrap, and valuable time saving, which illustrates part of the positive impact attained, the process gave a Cpk of 2.69, as shown in Figure 17.

Furthermore, this project solved the problem of clearance between the coil and the diaphragm through the successful implementation of Six Sigma. The estimated savings per year with the subassembly is \$31,048 U.S. dollars. The conclusion of this initial project has helped establish the objective to go forward with another Six Sigma implantation, in this case to reduce distortion in the sound of the horn.



## 5. Improvement of binder manufacturing process

In process of folders, a family of framed presentation folders is manufactured. The design has a bag for placing business cards. The first thing that took place in this project was to define the customer requirements:

1. Critical to Quality: Folders without damage and without Flash.
2. Critical for Fill Rate: Orders delivered on time to the distribution centers and orders delivered on time to customers.
3. Critical for Cost: Less waste of materials and scrap.

**Define:** The problem is that the flash resulting in the sealing operation of business cards, damages the subsequent folders rivet operation, reducing the quality and increasing the levels of scrap. Figure 18 shows the sample of the location and the business card bag. The Figure 19 shows the distribution of plant where the problem appears.



Fig. 18. Folder and Business Card Holder

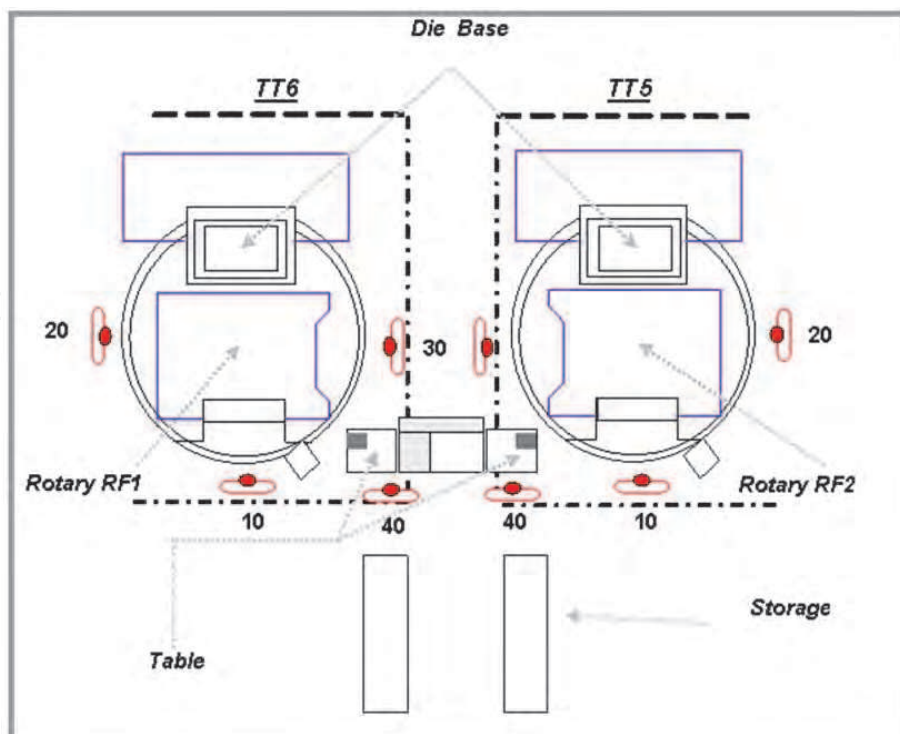


Fig. 19. Layout of the machines Rotary Table 5 & 6

**Measure:** The record sheet is a simple, graphical method for collection of the occurrences of events. Each mark represents an occurrence and the operator can quickly tabulate the count of the occurrences. Table 14 shows the record sheet for the defects of the binder.

Defect	Count														Subtotal
	x	x	x	x	x	x	x	x	x	x	x	x	x	x	
Feeder	x	x	x	x	x	x	x	x	x	x	x	x	x	x	14
Maintenance	x	x													2
Vinyl Problem	x														1
RF Problem	x														1
Load and unload problem	x	x	x	x	x	x	x	x							8
Total															26

Table 13. Record Sheet for the location of problem appearance

The Pareto Chart helps focus the most important causes; Figure 20 shows the main flaws in the area of folders and the damage, The most common defect is the damage in the BC holder, that is the major contributor with 60% of the problems of the BC.

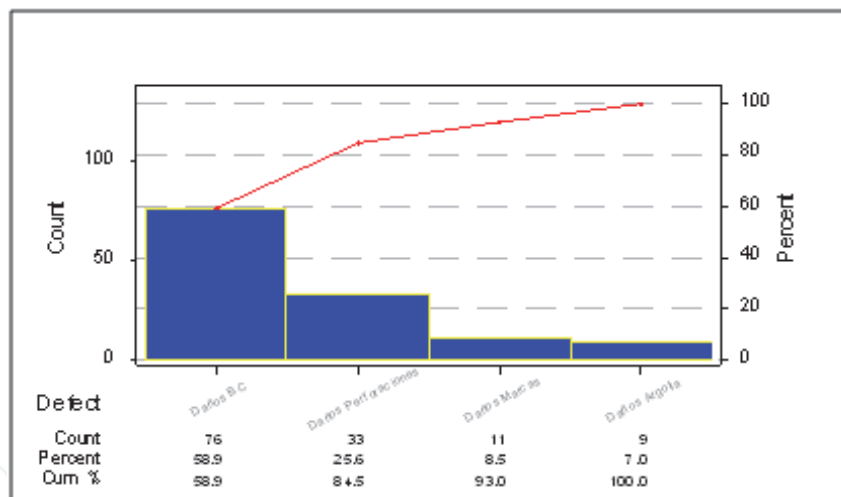


Fig. 20. Pareto Chart for the Type of Damage

**Analysis:** To illustrate where the damage occurs see Figure 21, that shows an overview of the “Hang” machine, as the station is loaded with subassemblies that will rivet the ring (the operator decides what amount to place), station load and the movement of the conveyor. Rotary Table 4 (R4) machine is similar to the rotaries 5 & 6, except that here the BC is sealed to the bag. The R4 makes a good seal with the appropriate parameters, but it has the disadvantage of producing an average 20 pieces of scrap per shift. This is where our problem lies, because if the surplus is not cut or partially cut. This can damage other subsequent subassemblies in the riveting process. A Cause and Effect diagram shows the supposed relationship between a problem and their potential causes. Figure 22 shows the possible causes of variation in the cutting of vinyl for BC, the machine where it is cut like a giant guillotine, caused flash after the sealing operation around the vinyl bag.



Fig. 21. Hang Machine where the Loading and Unloading problem Occurs

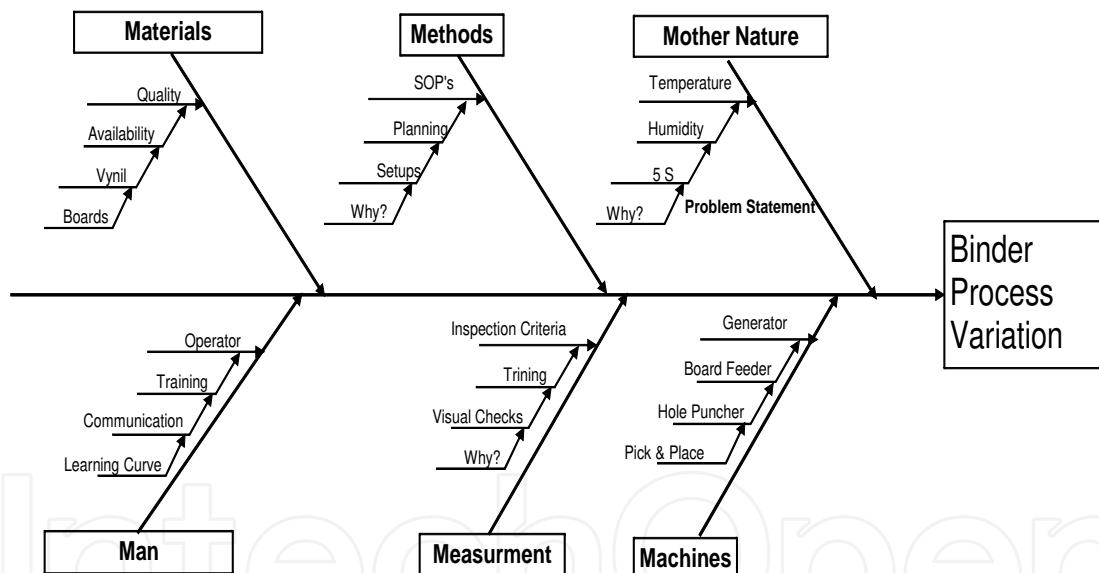


Fig. 22. Cause and Effect Diagram for the Assembly Binder Process

**Improvement:** A possible solution was changing the design of the BC, shown in Figure 23. This modification was to replace the vinyl bag with 4 cuts at 45 degrees (this design is used in another model of folders). This option would reduce the cost by not using clear vinyl for BC, by eliminating the cutting and sealing operations; by doing so, additionally, completely eliminates the damage caused by the flash of BC.

Marketing rejected this proposed BC bag, arguing that the folder was submitted and that the update of the catalogs on the Internet had been just published. Therefore it can be able to modify it until next year. This option was rejected, and then team decided to build a die cut (36 holes), with exact measurements of the size of BC bag in order to avoid the variation in the BC gap (see Figure 24 and 25).



Fig. 23. BC Bags Actual and Proposed for Reducing the Scrap



Fig. 24. Press Machine that cuts the BC Bags

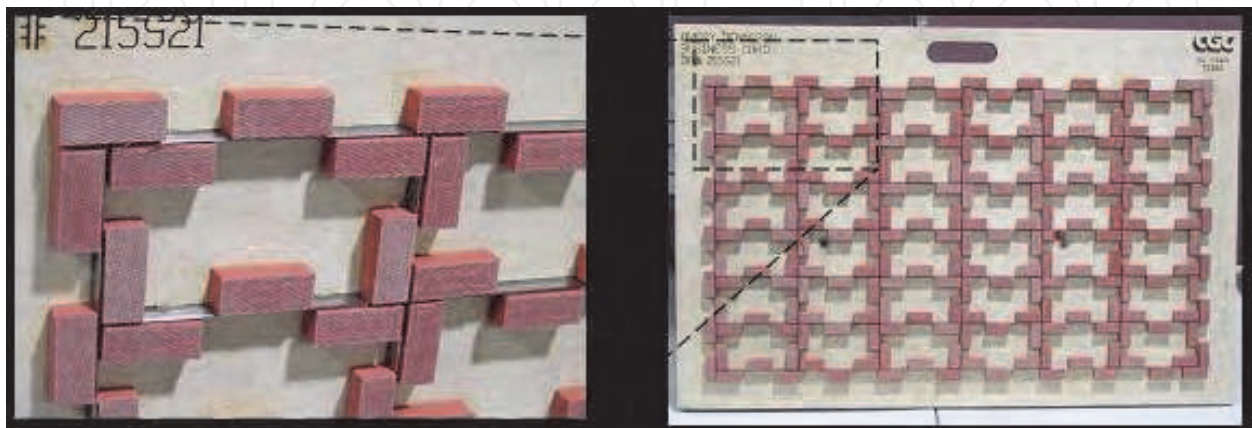


Fig. 25. New Die Design with Smaller Tolerance in the BC Bag Dimensions



Another improvement was to change the dishes where the BC is placed to be sealed with the bag; a frame of Delrin was used with the exact size of BC, to serve as a protector. Consequently, the BC does not move until it passes the sealing operation. The results of the changes made were remarkable. BC cutting was accurate and there was not any flash (see Figure 26).

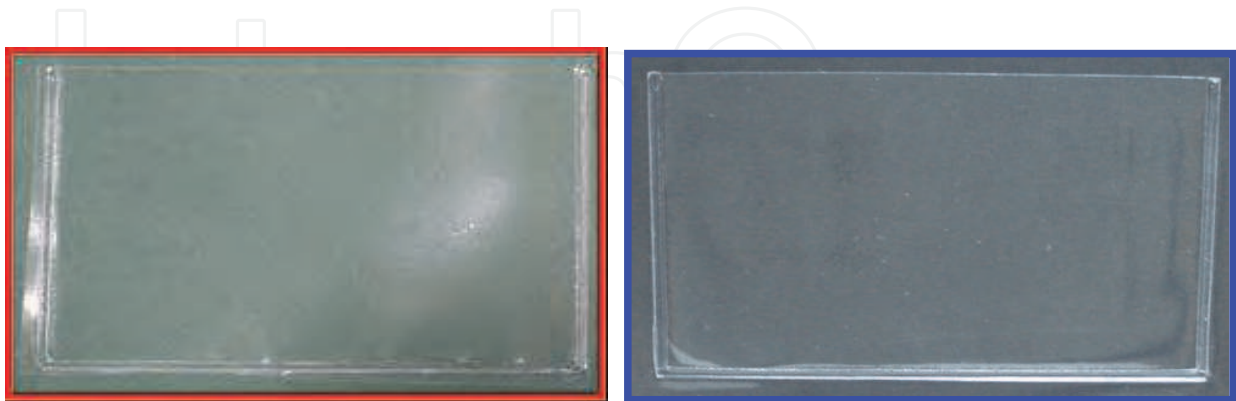


Fig. 26. Product before and after the Improvement

**Control:** The use of the fixture was supervised being mandatory its use, it was used to comply with the exact dimensions and assure that the measure of the BC is correct (see Figure 27). The reduction of defects was from 90 pieces to 3. These 3 defects occurred because the vinyl was misaligned.

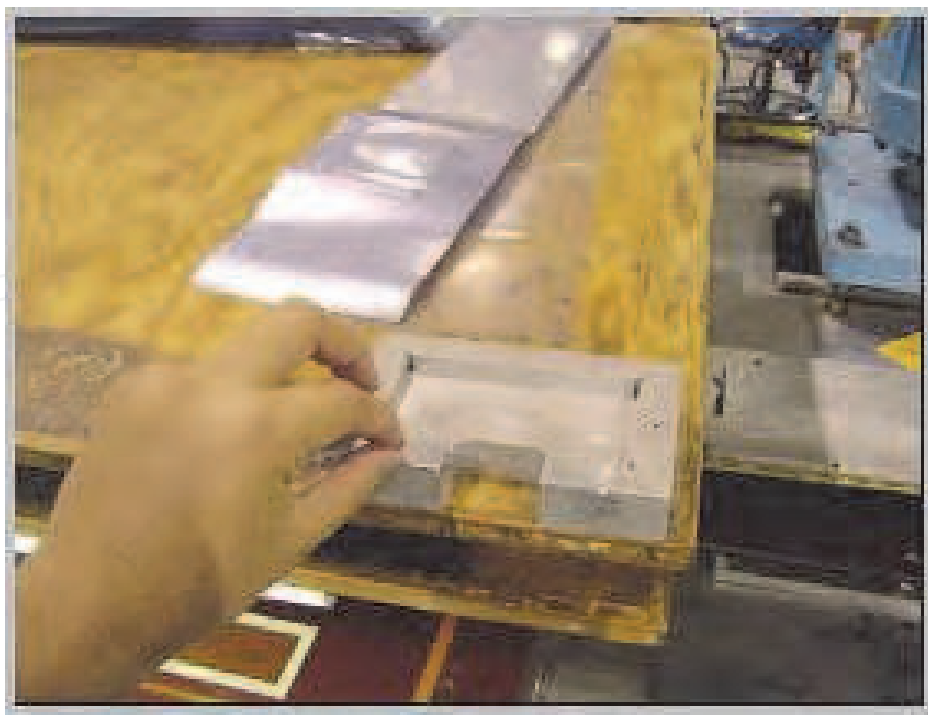


Fig. 27. Fixture to check the correct dimension of BC

## 6. Conclusions

The implementation of these projects has been considered to be a success, since in the project of manufacture of circuits the based line of the project was 3.35 sigma level and the gain 0.37 of sigma. Which represent the elimination of 1.88% of nonconforming units or 18,788 PPM's. The second project speaker manufacturing, the initial Cpk was .35 and after the project implementation the resulting Cpk is 2.69. The binder manufacturing process was improved from 90 to 3 defects in a shift.

The key factors in these implementations were; team work, multidisciplinary of the team, management commitment, team training and knowledge, communication and project management (Antony & Banuelas, 2002; Byrne, 2003; Henderson & Evans, 2000). Also, the maintenance preventive program was modified to achieve the goal stated at the beginning of the project 2. It is important to mention that organizations management was very supportive and encouraging with the project teams. The Six sigma implementation can be helpful in reducing the nonconforming units or improving the organization quality and personal development. The conclusion of these projects has helped establish the objective to go forward with others Six Sigma implementations. This results show that DMAIC methodology is a systematic tool that ensures the success out of a project. In addition to the statistical tools that factual information is easier to understand and to show evidence about the veracity of the results, because many of them are very familiar.

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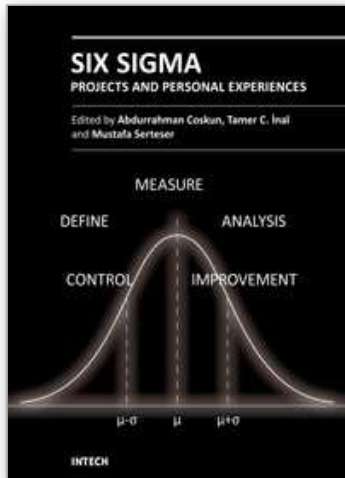


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In the new millennium the increasing expectation of customers and products complexity has forced companies to find new solutions and better alternatives to improve the quality of their products. Lean and Six Sigma methodology provides the best solutions to many problems and can be used as an accelerator in industry, business and even health care sectors. Due to its flexible nature, the Lean and Six Sigma methodology was rapidly adopted by many top and even small companies. This book provides the necessary guidance for selecting, performing and evaluating various procedures of Lean and Six Sigma. In the book you will find personal experiences in the field of Lean and Six Sigma projects in business, industry and health sectors.

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