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Six Sigma Improvement Project for Automotive Speakers in an Assembly Process

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This Six Sigma application examined an automotive speaker production process in a multinational corporation twin plant. The process was a semiautomatic assembly operation. A six index assembler chemically bonded a coil to a diaphragm. The problem is described in the first part of the paper, which pinpoints the separation between those two parts. This is a critical process characteristic that was not properly controlled. Operations were malfunctioning. High scrap and rework rates, and high levels of in process inventory as well as inspection stations all contributed to the problem. Variables were measured to determine the problem with accuracy. The fixture and tool capabilities were estimated in the analysis as well. The authors found that the large variation could be attributed to the product and operator procedure. Variation in the product was determined to be explained by unsuitable fixtures and tools. This resulted in having the fixtures and tools re-dimensioned and re-designed. Measurements were then taken to determine whether the improved process design would make significant contributions. A control process and operating procedures were established to insure that the initial process conditions would not be repeated.

Significance: The literature on Six Sigma is extensive, although most of the reports focus on its application. Also, there are differences and coincidences, which is why gathering empirical evidence is extremely important, especially for building a body of Six Sigma knowledge having greater explanatory depth.

Keywords: Six Sigma, Gauge R&R studies, quality improvement

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1. INTRODUCTION

A Six Sigma study that was applied in a company which produces car speakers for world-class automakers is presented. The company received many frequent customer complaints in relation to the subassembly of the pair coil-diaphragm shown in Figure 1. 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. 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.

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2. METHODOLOGY

The Six Sigma methodology was used to control and increase efficiency in the process. According to Escalante (2004), this process consists of five phases: Definition, Measurement, Analysis, Improvement and Control. In each phase, several tools and methods were used: Gauge R&R studies, Process capability Index C_{pk}, Cause and Effect Diagrams, Regression Analysis and the Anderson-Darling normality test. A project multi-task team was integrated for the deployment of Six Sigma, as recommended in the literature.

3. SIX SIGMA PROJECT

For deployment of the Six Sigma 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.

3.1 Phase 1: Definition of the Problem

In the first phase, the multifunctional 6σ team made a precise description of the problem. This involved collecting the subassemblies with problems such as drawings, specifications, and failure modes analyses. Figure 1 shows the speaker parts and the coil-diaphragm subassembly.

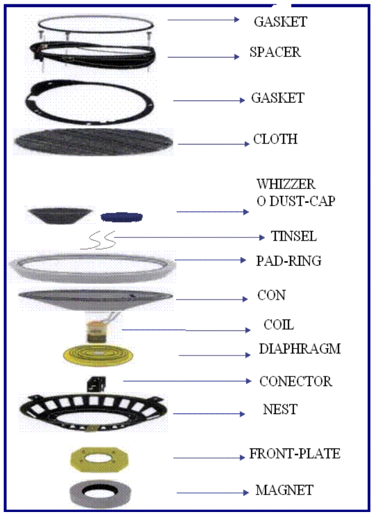


Figure 1. Speaker Explosion Drawing

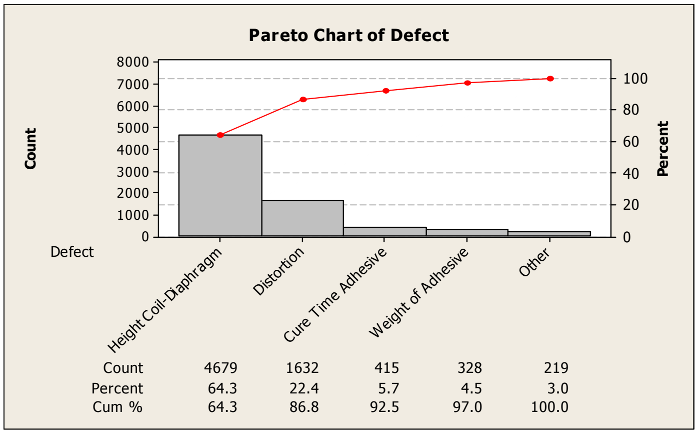


Figure 2. Pareto Diagram for Types of Defects

Then, the critical characteristics were established and documented based on their frequency of occurrence. Figure 2 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 with 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 cumulate a total of 86.8%. By examining Figure 2, 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. Also the cause and effect Matrix was developed and is shown in Table 1. 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.

Table 1. Cause and Effect Matrix for the Height of Coil-Diaphragm

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

3.2 Phase 2: Measurement

Gauge R&R and process capability index C_{pk} 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 in the measurements were found:

- Errors due to the measuring instrument
- Errors due to the operator of the instrument
- Errors due to the inspection method

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. The steps followed to analyze the measurement system are given below:

- Calculation (by each appraiser) of the measurements rank and of all the pieces
- Calculation of the mean range (by one appraiser), and of the average of all the measurements (by the three appraisers)
- Registration of the mean range average and the range of averages
- Calculation of the amplitude of variation of the equipment (VE), multiplying 5.15 times the standard deviation of the equipment error. The factor 5.15 that multiplies the standard deviation is a span of 99% of the area under the

curve of a normal distribution. If the factor 6 is used, then the amplitude will span 99.73% of the probability of a normal distribution.

- Calculation of the amplitude of variation of the operator, Reproducibility (VO = Variation of the operator)
- Calculation of the combined variation (Repeatability and reproducibility) or error of measurement (EM): P/T = 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 2 shows the Minitab© output.

Table 2. Calculations of R&R with Minitab©.

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			

The next step was to estimate the Process capability index Cpk. Table 3 shows the observations that were made as to the heights of the coil-diaphragm.

Table 3. Heights of Coil-Diaphragm before the Six Sigma Project.

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

The result of the index C_{pk} 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 3 shows the output of the Minitab© C_{pk} 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 nonstandard parts.

Verification of the data normality is important in estimating the C_{pk}. For the normality test, therefore, the hypotheses considered were:

H_0: The data were taken from a normal population.
H_1: The data were not taken from a normal population.

There are several tests to verify normality, some of which are Goodness of fit χ^2, Kolmogorov-Smirnov, Ryan-Joiner similar to Shapiro-Wilks, and Anderson-Darling. Verification of the hypotheses was done in Minitab with the Anderson-Darling statistic. Stephens (1974) found the AD 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.

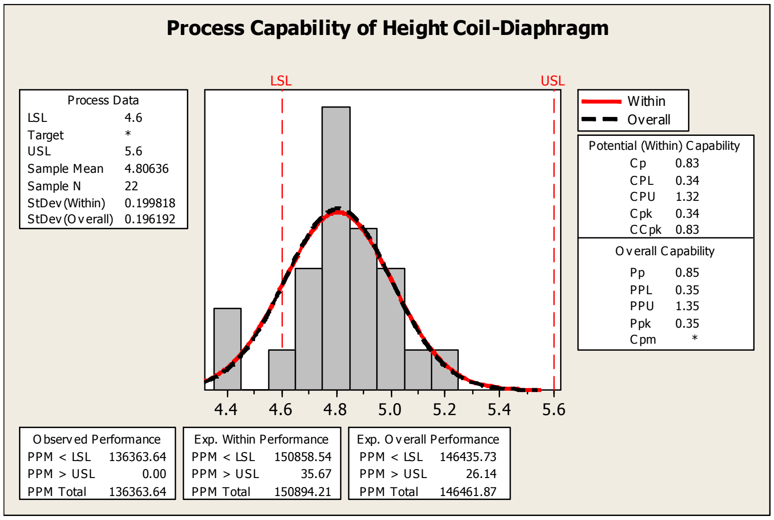


Figure 3. Estimation of the C_{pk} Index for a Sample of Coil-Diaphragm Subassemblies

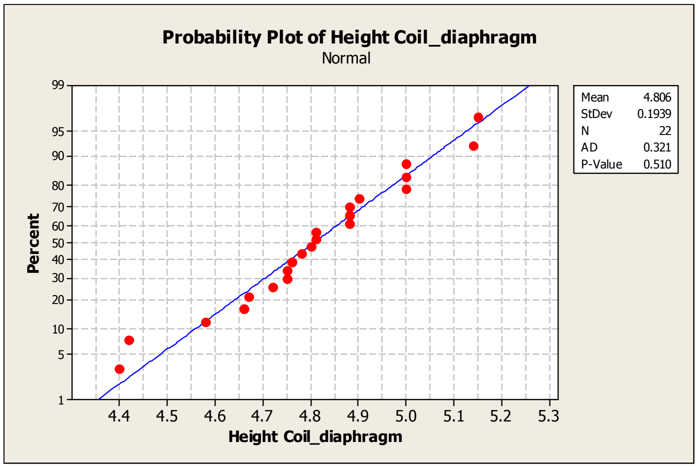


Figure 4. Normality Test of the Coil-Diaphragm Heights

Figure 4 shows the Anderson-Darling test with a p-value of 0.51. Since the p-value was greater than 0.05 (α=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.

3.3 Phase 3: 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 following hypotheses:

H_0: The dimensions of the tooling do not affect the height between the coil and the diaphragm.

H_1: The dimensions of the tooling affect the height between the coil and the diaphragm.

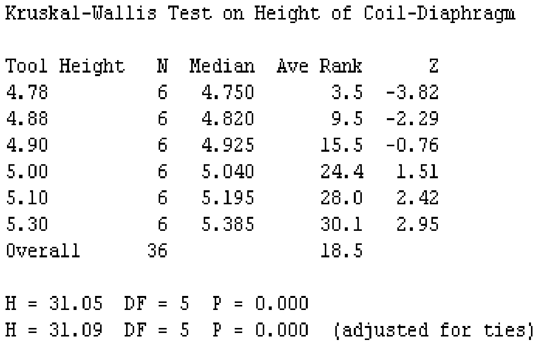
The First two test procedures used to verify the above hypothesis were the regression analysis and the one-way ANOVA. The results of both procedures were discarded because the basic assumptions about normality and homocedasticity were not met. Then the Kruskal-Wallis test was carried out to verify the hypothesis. The response variable was the Height of the Coil-Diaphragm and the factor was the Tooling height. Table 4 illustrates the results

Table 4. Results of Tooling Height vs. Coil-Diaphragm Height

	Tooling Height	Coil-Diaphragm Height (in mm)						
Levels		1	2	3	4	5	6	Mean
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

Figure 5 show the results Kruskal Wallis analysis with a p-value<0.0. 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.

Kruskal-Wallis Test: Height of Coli-Diaphragn versus Tool Height



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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)
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Figure 5. 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 ± 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 C_{pk} 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 C_{pk} 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 $C_{pk} = 1.67$. 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 6. 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.

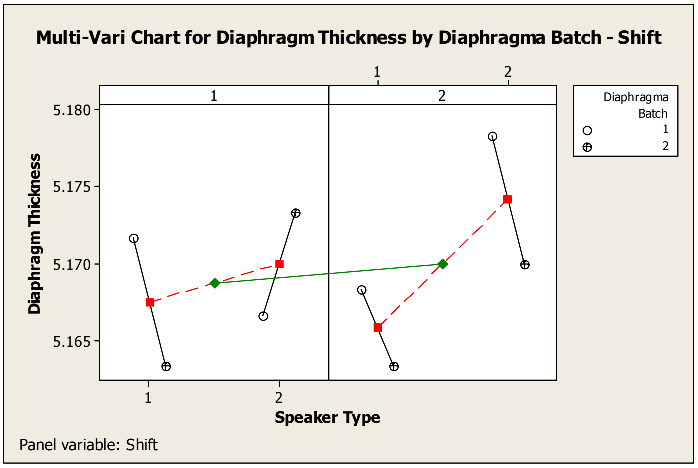

Figure 6. Multi-Vari chart for Diaphragm Height by Diaphragm Batch, Speaker Type and Shift.

3.4 Phase 4: 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, controlling the dimensions carefully according to work instructions. No importance had been previously given to the tools design, drawings and production. 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. Such a tooling appraisal, as can be seen in Figure 7, was not carried out as part of a system in the past. Figure 8 shows the tooling now used in 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.

Figure 7. Measuring Tool against Drawing

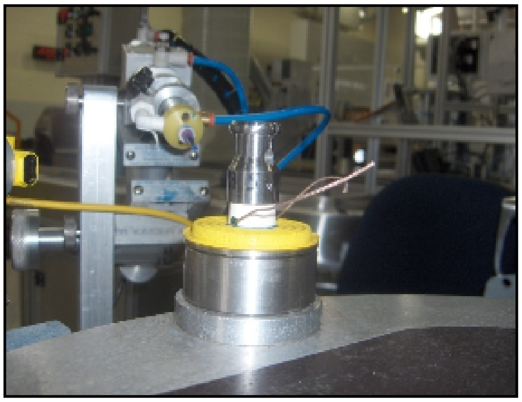

Figure 8. Tooling used in the S/A of Coil-Diaphragm

After all the improvements were carried out, a sample of thirty-six pieces was drawn to validate the tooling and estimate the C_{pk}. 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 9 shows the substantial improvement made in the control of the heights variation. The study gave a C_{pk} of 2.69; which is greater than 1.67. This is recommended for the release of equipment and tooling.

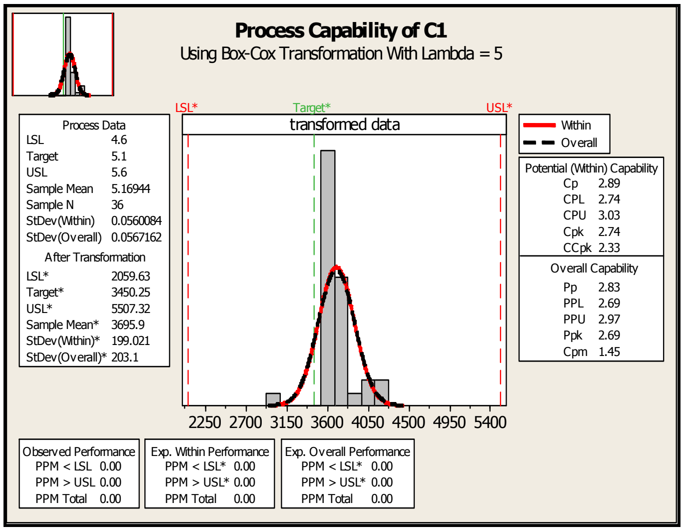

Figure 9. Estimation of Cpk for Height Coil-Diaphragm with Control in the Tooling

3.5 Phase 5: Control

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 with number QUEJZ-W-305750, which applies to all the tooling mentioned in the instruction.

Design of the tooling was documented in format EUEJZ-F303961. Format QUEJZ-F-304079 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.

4. CONCLUSIONS

At the beginning of this project, the production process was found to be inadequate because of the large variation: C_{pk}s within 0.35, as can be seen in Figure 3. 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 C_{pk} of 2.69, as shown in Figure 9. Table 5 shows specific savings made in the project.

Table 5. Cost-Benefit Analysis

Description	Annual Savings
1333 Speakers scrap x 2 dollars	2,666.00
8039 Coil – diaphragm x 0.52 dollars	4,180.00
Line Production Savings	7,442.00
Internal reduction of rework	5,171.00
External reduction of rework	11,558.00
Cost reduction of Supervision and Engineering	7,794.00
Annual Savings	38,811.00
Project Cost	7,763.00
Total Savings = 38,811 – 7763 =	31,084.00
Total Annual Savings	31,048.00

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.

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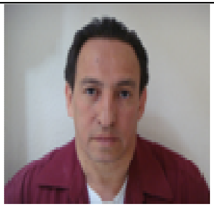

BIOGRAPHICAL SKETCH

Adan Valles is a Professor of the Instituto Tecnologico de Cd. Juarez. He has a Masters and a Dr. Sc. Degrees in Industrial Engineering from the Instituto Tecnologico de Cd. Juarez. He has a Black Belt Certification in Six Sigma. His areas of specialty include lean manufacturing, statistical quality control, experimental optimization, design of experiments and Six Sigma. He has more than twenty years experience in the industry; he worked in Delphi, United Tecnologies Automotive and Lear.

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