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Design Approach for Quality Improvement and Cost Reduction: A Case Study of Cable Manufacturing

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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Case Study

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ABSTRACT

In this study, an extrusion process was studied in a cable manufacturing company located in Southeastern Nigeria. The critical-to-quality (CTQ) characteristic considered in the study was the cable diameter and the design effort was to reduce the possibilities of having cables with inconsistent dimensions. Taguchi Orthogonal Array Design L16 (4^2) was used to achieve the optimum parameter settings after statistically investigating the assumed correlations between the process parameters in relation to cable dimension. Thereafter, an appropriate engineering tolerance interval for the improved process was designed to tighten the existing tolerance of the process from T±0.185 to T±0.032, thus reducing the engineering tolerance by 82.7% from the initial tolerance limit. After the process improvement, the Taguchi loss function approach was used to estimate cost attributed to deviations. The loss function estimation result has shown that the cost attributed to cable diameter deviations from the nominal value reduced from the initial value of ₦7.34/coil to a reduced cost of ₦2.08/coil. The sigma level increased from 0.6 to 5.2 at the project termination stage and the estimated annual loss decreased by 72% from the baseline value.

Keywords: Cable manufacturing; engineering tolerance; loss function; sigma level; Taguchi design.

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1. INTRODUCTION

It is generally accepted that the high number of CTQ characteristics attached to cable manufacturing makes the possibility of having defective products almost inevitable. Few of these quality considerations range from insulation thickness, conductor diameter, insulation smoothness, high voltage failure, poor conductor resistance, uniform/consistent dimension etc. The organization under investigation has been plagued with a high percentage of cables extruded with inconsistent dimensions, and this production anomaly of having inconsistent dimensioned cables requires a design attention to cut the possibilities of having over-dimensioned and under-dimensioned products. Over-dimensioned cable (ODC) is an indication that the process is using more Polyvinyl chloride (PVC) material that is required for production, which negatively affects the company's returns on investment (ROI). Apart from the direct financial impact, in practice, over-dimensioned cables often pose serious challenges to workers due to the difficulty of passing these cables through defined electric sockets and gangways. Low dimensioned cables are on the other hand attributed to insulation thickness failures, and when used in practice often leads to electrocutions as a result of energy leakages.

The organization's approach to solving this problem has been un-systematic. It has always been a thing of trial and error among the operators manning the production shifts. This production anomaly often time seize to occur mostly when the operators have gotten themselves acquainted with the control settings, but with time this identified production odd resurface again and mainly as a result of job rotation, retrenchment and retirement. The previous approach deployed by the organization in solving this problem does not consider translating production losses in financial terms for cables with dimension off from the nominal value. Design of experiment (DOE) using Taguchi concept would be followed to systematically arrive at optimal control settings that would be documented for daily productions activities and thus circumvent the cost of not knowing.

In other words, recent review reports from literature examination in the sphere of Taguchi method of experimental designs has shown that the approach has been widely implemented in a whole lot of improvement studies such as; in the machining/drilling operations [1,2,3,4,5] in service sector [6], in the design of injection moulds and thin-wall plastics [7,8] (Oktem & Erzurumlu., 2009); in wastewater treatment and Aluminium recycling processes [9,10], in welding processes [11,12] in neural computing [13], in aquatic studies [14]. Venil et al. [15] applied Taguchi experimental design to optimize the conditions for protease production by *Bacillus subtilis* HB04. Akbarzadeh., Kouravand & Imani [16] designed a robust Bimetallic Micro Thermal Sensor using Taguchi method. Triggering of chemical oxidation processes and Biodiesel production was achieved using Taguchi design [17,18]. Laccase production from Marasmielluspalmivorus LA1 was optimized using Taguchi design approach [19]. The approach has also been applied in environmental building designs [20]. Lastly, in the healthcare industry, Luo et al. [21] reportedly used Taguchi design-based optimization of sandwich immunoassay microarrays to optimally detect breast cancer biomarkers.

From the above-cited literature, it can be deduced that the Taguchi approach is generally used in finding the optimal processes parameters in a whole number of organizations. In this study, the Taguchi design and loss function approach were used primarily to set up the optimal control parameters for the cable extrusion and in relating quality losses in financial terms.

2. RESEARCH METHODOLOGY

Taguchi method was used in this study to create a fractional design of the experiment considering time, cost, and mathematical simplicity over a full factorial design. The experimental design, considered two optimization stages in sequential order, the parameter design and the tolerance design. Taguchi designed experiment often use a 2-step optimization process, and the two-step optimization order as observed in the study are as follow:

1. **Step 1:** Use the Signal to Noise ratio to identify those control factors that reduce variability.
2. **Step 2:** Identify the control settings that bring the mean to the nominal value.

2.1 Parameter Design Stage

The parameter design stage involves improving the uniformity in cable dimensions by finding the optimal parameter settings that will reduce the effect of available noise factors. In this study, cable dimension is the quality characteristics under investigation, thus a nominal-is-best characteristic was chosen. The nominal is the best Signal-to-noise ratio (SN_N) assumes that the given target is best and is appropriate when there is nominal value with both upper and lower tolerance limits. The goal of this experiment is to reduce variability around a specified nominal value. The following guidelines were followed in the experimental design:

1. Recognition and statement of the problem
2. Choice of factors and levels
3. Selection of the response variable
4. Choice of experimental design
5. Performing the experiment

Equations 1-3 are used to compute the SN_N using Minitab-17 statistical software.

$$S/N_N = 10\log\left(\frac{\overline{x^2}}{s^2}\right) \tag{1}$$

$$\text{Mean response } (\bar{x}) = \frac{1}{n}\sum_{i=1}^{n} xi \tag{2}$$

$$\text{Standard deviation (s)} = \sqrt{\sum_{i=1}^{n}\frac{(xi-\bar{x})^2}{n-1}} \tag{3}$$

Where; k is a constant, $\bar{x}$ and s^2 are the mean and variance of the measurements of quality characteristics respectively, and n is the nominal value of the process.

2.2 Tolerance Design Stage

The tolerance stage is for determining the acceptable range of variability around the nominal value determined in the parameter stage. Equation (4) and (5) were used to compute the tolerance after the process improvement.

$$\bar{X} \pm Ks \tag{4}$$

$$S = \sqrt{\frac{\sum(x-\bar{x})^2}{N-1}} \tag{5}$$

where K is a constant and is determined so that the interval will cover a proportion P of the population with confidence ϒ, s = sample standard deviation, x = each value in the sample, $\bar{x}$= the mean of the values and N = the sample size.

The loss function approach was used in this study to determine the economic impact of tightening the engineering tolerance. Equation (6) was used to compute the quality loss function due to deviations from the nominal value.

$$L(y) = k\,(y-T)^2 \tag{6}$$

$$k = \frac{A}{\Delta^2} \text{ (At specification)} \tag{7}$$

Let y be the measured value of the characteristics, and that the adjustment of the process is not needed when y=T. A = cost incurred producing cables off the specified nominal value, Δ = tolerance limit.

However, if y≠T, then an amount of adjustment needed equal to y-T. The quantity (y-T) is usually estimated based on available data, and the usual estimate of mean square deviation (MSD) is denoted as follows:

$$MSD = \frac{1}{n}\left[(y_1-T)^2 + (y_2-T)^2 + \ldots + (y_n-T)^2\right] \tag{8}$$

Where n is the number of measurements available, and y_i is the value of the ith measurements, k= cost coefficient, L(y) = loss associated with producing a part at "y" value, T = nominal value, MSD = (y-T).

3. ANALYSIS OF RESULTS

Common knowledge of the extrusion process has linked the existence of a correlation between Capstan and Extruder speed to variations in the cable dimension. ANOVA test was first conducted to statistically investigate the assumed correlation between these two cable extruding parameters; Capstan speed and Extruder speed.

The test output in Table 1 indicates there is a correlation between the Capstan speed and Extruder speed. The p-value of 1.08E-18 is an indication there is a significant difference between the rows (extruder speed), a p-value of 2.61E-12 is an indication of a significant difference between the different columns (Capstan speed), while the interaction of Capstan speed & Extruder speed is not significant by the level of 0.202625.

Table 1. Two-way ANOVA experiment with replicate for the cable diameter

ANOVA						
Source of variation	**SS**	***df***	**MS**	**F**	**P-value**	**F *crit***
Sample	0.485774	3	0.161925	60.67432	1.08E-18	2.748191
Columns	0.242544	3	0.080848	30.2943	2.61E-12	2.748191
Interaction	0.03871	9	0.003763	1.4102	0.202625	2.029792
Within	0.1708	64	0.002669			
Total	0.932989	79				

In the present study, the interaction between the two extruding parameters is neglected. Using the degree of freedom (df) rule to determine the number of experimental runs; overall mean = 1, Capstan speed = (4-1), Extruder speed = (4-1), and the total df = ∑ 1+3+3 = 7. The total df is seven; we choose a Taguchi Orthogonal Array Design L16 (4^2) for the study, meaning that the experiment was designed to undergo 16 runs at four levels of the two experimental parameters.

From Fig. 1., following the first optimisation step, the control factor settings that have the greatest S/N ratio value was found at the Capstan speed of 425 rpm and Extruder speed of 900 rpm.

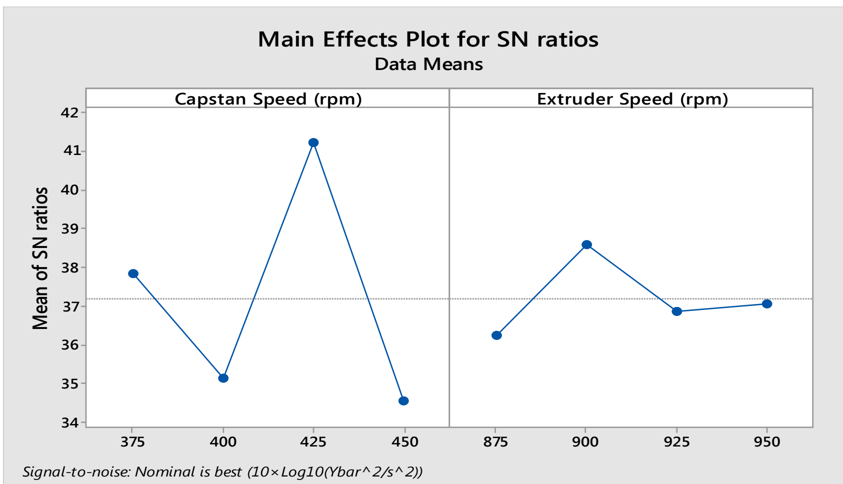

Fig. 1. Main effect Plot for SN ratio

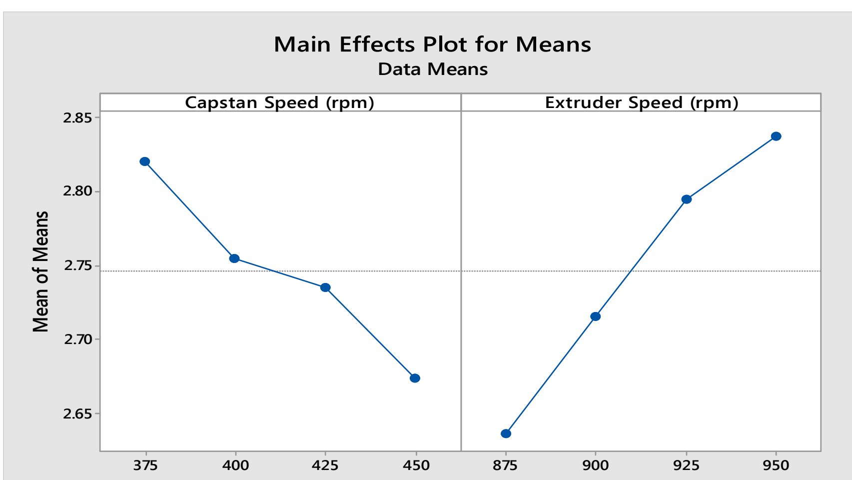

Fig. 2. Main efect plot for means

From Fig. 2., following the second optimisation step, the control settings that bring the mean to the nominal value was also found at a Capstan speed of 425rpm and Extruder speed of 900rpm.

However, it was observed that after the experimental design, that the engineering tolerance of the process was too wide, with the upper and lower specification limits being far apart from each other. To determine the acceptable range of variability in the extrusion process, equations 4 and 5 as described in the research methodology section were used to design for new tolerance intervals to truly capture the capability of the process and subsequent six sigma ratings.

3.1 Tolerance Interval Design

$$S = \sqrt{\frac{0.0014706}{19}} = 0.0087977$$

Tolerance intervals now becomes;2.7114 ± K(0.0087977). Finding K value for two sided limits from table of factors for Tolerance intervals, for n=20, P=0.99 and Y = 0.95, K= 3.615. Then, the Tolerance interval becomes: 2.7114±3.615(0.0087977) = 2.7114±0.032. In the new estimation, from 2.67 to 2.74 will contain 99% of the population with 95% confidence.

3.2 Economic Impact Estimation on the Before and the after Improvement Measurements

The next step aims to express the quality level of the cable diameter in financial terms using the new tolerance intervals. The new tolerance intervals for the process was changed from 2.90 to 2.74 for USL, and 2.53 to 2.67 for LSL, Assuming an estimated warranty cost of ₦30 for any 1.0mm single coil produced that does not meet with the target value, and also considering that customers will complain if the diameter is a bit less, and the organization stands also to lose materials if the prescribed diameter value is above by a bit. Tolerance interval range from T-Δ to T +Δ; Δ = 0.035,
Whereby,

$$T\ (\text{Original}) = \frac{(USL + LSL)}{2} = \frac{(2.90 + 2.53)}{2} = 2.715.$$

Original Δ = (2.90-2.715) = 0.185,

$$T\ (\text{New}) = \frac{(USL + LSL)}{2} = \frac{(2.74 + 2.67)}{2} = 2.705 \pm 0.035.$$

New Δ = (2.74-2.705) = 0.035,

Substituting the cable diameter values before the Improvement in Equation (8)

MSD = MSD = $\frac{1}{n}\sum(yi - T)^2$ = MSD = 1/100[0.838478] = 0.00838478

L (2.715) = [30] [0.00838478]/(0.185)^2 = ₦7.34 per coil

Substituting the cable diameter values after the Improvement in Equation (8)

MSD = $\frac{1}{n}\sum(yi - T)^2$ = MSD = 1/100[0.008508] = 0.00008508

L (2.715) = [30] [0.00008508] / (0.035)^2 = ₦2.08 per coil

Assuming the organization worked for 300 days in a year and the daily production capacity is maintained on the average of 810 coils per day, then the estimated overall annual loss amounts to 2.08 x 300 x 810 = ₦505,440.

The result of the comparative economic impact analysis between the baseline measurements and improved measurements with the tightened tolerance limit depict a remarkable improvement. A whole lot of positive deviations were noticed in the baseline measurements compared to the after improvement measurements, thus an indication that there were more material usage in the production process before the improvement process.

Net yearly improvement due to redesigning the tolerance after the experimental design becomes = [7.34-2.08]*243,000 = ₦1,278,180. The percentage decrease in the annual loss estimation after improvement is computed with the formula:

Decrease in annual loss estimation= Orignal loss estimation-New estimated loss (9)

% Decrease in annual loss estimation =

$$\frac{\text{Decrease in Cost}}{\text{Original Cost}} * 100 \tag{10}$$

Decrease = 1,783,620-505,440 = 1,278,180

$$\%\text{Decrease} = \frac{1,278,180}{1,783,620} * 100 = 72\%$$

Table 3. Quality improvement achieved due to the designed experiment

	Tolerance	MSD	K	Expected quality loss per unit (₦)	Expected annual loss (₦)	Net annual Improvement due to new design (₦)
Original	T±0.185	8.38478E-03	876.55	7.34	1,783,620	*******
Tightened	T± 0.032	8.5088E-05	24489.8	2.08	505,440	1,278,180

Table 3 contains the results of the improvement study as translated in financial terms. With the original tolerance of the process T±0.185, the expected quality loss per unit of coil is ₦7.43, but with the tightened tolerance T ±0.032, the expected quality loss per unit of coil now reduced to ₦2.08.

4. CONCLUSION

The study was conducted in a cable manufacturing industry located in the southeast of Nigeria that specialized in the manufacture of cables of different sizes and colours. The study emphasis was on the extrusion process of 1.0mm single cable. Five notable contributions were made from the study:

1. Taguchi design of experiment is a powerful technique in prediction and selection of input factors that will give a reduced amount of variation on the output response in case of cable extrusion.
2. Capstan speed and Extruder speed has significant effects on cable diameter variations.
3. The optimal parameter setting for the extrusion process was determined from the Taguchi method of experiment.
4. Tightening the engineering tolerance after improvement process is essential in ensuring that the engineering tolerance is not far apart from each other with a large standard deviation.
5. Economic impact assessment of the process after improvement was estimated through loss function approach in order to relate the quality level of the improvement in financial terms.

5. RESEARCH LIMITATION

Due to budgetary and time constraint, the duration of data collection after the experimental design were not well spaced-out to accommodate the likely effects of ageing machine components on the parameter speeds.

1. The machine was solely powered by 50kva energy set during the study, thus the researchers were not able to test/validate the results from the design using alternate (the main) power source.
2. During tolerance interval design, smaller sample were randomly selected from the stable process population and as result of this the designed tolerance interval may not be long enough to cover a large portion of the distribution.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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