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EVALUATION OF PULLEY *MANUFACTURING* PROCESS CAPABILITY USING DMAIC APPROACH

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ABSTRACT

The process of taper-turning of pulley groove by adjusting the compound rest of a conventional lathe is consuming much energy and man-hours. The efficiency and trouble free operation of belt or rope drives largely depend on the groove design of the pulley. Elimination of rework and rejection caused by this bottleneck activity (Groove making operation) in the pulley production process requires a Six Sigma approach which was implemented in this study. The use of the define-measure-analyse-improve-control (DMAIC) methodology for the different phases of the project helped eliminate some causes of waste in the process. The result of iteration no. 1 gave a potential capability index (C_P) value equal to 0.65 and performance capability index (C_{PK}) equal to 0.5. The results primarily indicate the first status of the problem on hand before carrying out any improvement work. Iteration no. 2 matches the conciliator phase readings after performing moderate improvements with a marginal increase in C_P to 1.74 and C_{PK} to 1.6. Iteration no. 3 corresponds to the final phase readings taken after introducing the equivalent corrective actions known in the analysis stratum. Moreover, bringing in a noticeable improvement in the process performance with C_P as 2.15 and C_{PK} equal to 1.62. The data points of the control charts are also equally distributed across the mean line indicating that the process means as well as the process variation are stable, and the process is under control. The business impact of implementing the DMAIC methodology at C_p and C_{pk} values > 1.33 consistently indicates that by avoiding 99% component rejection and rework, sixty-one thousand, eight hundred and seventy-five naira (₦61875) can be saved per month. The method offers the benefit of lowering the machining cost using a reduction in machining time, steps, and energy savings.

Keywords: DMAIC, Critical to quality (CTQ), Cause and effects diagram, Physical Mechanism (PM), Analysis of Variance (ANOVA), Process monitoring chart (PMC).

1. INTRODUCTION

The production of metal pulleys is achieved by casting of pulley blanks and the subsequent turning in a lathe machine. The efficiency and trouble free operation of belt or rope drives largely depend on the groove design of the pulley. Elimination of rework and rejection caused by this bottleneck activity (Groove making operation) in the pulley production process reduce the cost of machining pulleys. The cost is reduced by a decrease in machining time, energy consumption and equally an increase in tool life. The groove angle when properly designed and machined places the drive in an optimal position and ensure equal stress put on the drives (belt or rope- tension cord members). The application of DMAIC in the groove making operation increases the process capability levels and creates an awareness of the importance of process monitoring charts in daily production. It also reduces component rejection and rework after sustenance. The groove of any given sheave machined at a specific angle based on diameter and type of belt to be used. The groove is machined because a belt cross section changes as it wraps a radius. The size of the sheave and the radius determine what groove angle is required.

A sheave of 8mm in diameter machined for “B” style belts have a 38^{o} groove angle. In comparison, a 4mm sheave machined for “B” style belts have a 34^{o} groove angle. The standard dimensions of V-grooved pulleys are shown in Table 1.

The DMAIC process was used by Gentil *et al*. (2006) for a production manufacturing process line. The method was used for the manufacture of both professional and kitchen knives. The DAMAIC process was used to improve the process capability of poly jet printing for plastic components. Also, it was used to chart the procedure for attaining the Cpk value attainment>1.33, i.e., 4 sigma level. The value was considered as an industrial benchmark (Sahay, 2011). The failure modes and effects analysis (FMEA) and the cause and effect matrix were used to solve flywheel casting process **(Kumaravadivel and Natarajan, 2013).** Lin *et al*. (2013) elaborated on the accurate yield assessment of the processes of multiple features of the turbine blade manufacturing process.They applied the cause and effect matrix and failure modes and effects analysis (FMEA) to solve flywheel casting process problems. Mariajayaprakash *et al*. (2013) applied the CTQ characteristics of the shock absorber manufacturing process and enhanced the process by minimising the defects using Taguchi approach.

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Table 1: Dimensions of standard V-grooved pulleys

Groove cross section symbol	Datum diameter of the pulley (d)	Groove angle (a)	Minimum top width of groove (g)	Minimum groove depth below datum diameter (h)	Centre to Centre of grooves (see note 2) (e)	Edge of pulley to first groove centre (see note 3) (f)	Minimum distance from outside diameter to datum diameter (b)	Groove datum width (W)
	mm	degrees	mm	Mm	mm	mm	mm	mm
Z SPZ	UP TO 80mm	34 *0.5	9.7	9.0	12.0 ± 0.3	8.0 ± 1.0	2.0	8.5
	OVER 80mm	38 *0.5	9.9					
13A SPA	UP TO 118mm	34 *0.5	12.7	11.0	15.0 ± 0.3	$10.0^{+2.0}_{-1.0}$	2.75	11.0
	OVER 118mm	38 *0.5	12.9					
178 SPB	UP TO 190mm	34 *0.5	16.1	14.0	19.0 ± 0.4	$12.5^{+2.0}_{-1.0}$	3.5	14.0
	OVER 190mm	38 *0.5	16.4					
22C SPC	UP TO 315mm	34 *0.5	21.9	19.0	25.5 ± 0.5	$17.0^{+2.0}_{-1.0}$	4.8	19.0
	OVER 315mm	38 *0.5	22.3					
32D	UP TO 475mm	36 *0.5	32.3	19.9	37.0 ± 0.6	$240^{+3.0}_{-1.0}$	8.1	27.0
	OVER 475mm	38 *0.5	32.6					

Source: Engineers Edge, 2017

Schilling (1994), has thrown light on the superiority of process control over the traditional sampling techniques. Locke (1994) stressed the importance of process charts, cause and effect relationship and monitoring charts. Lin (2004), had emphasised on process capability indices for normal distribution. These methods aforementioned compete favourably with the DAMIC approach and can be adopted to solve most complex engineering systems. Tong *et al.* (2004), focused on define–measure– analyse–improve–control (DMAIC) approach and its application for printed circuit board quality improvement.

Project Charter

The project charter (detailed description of the objectives of this study) for the process capability improvement of the groove cutting operation of the pulley production process shown in Table 2. The project charter outlines the objectives, deliverables and success metrics of this improvement project and also the business impact regarding monetary benefits.

Process mapping

The process flowchart for the production of the pulley consists of the following operation sequence as shown in figure 1. The manufacturing sequence of the pulley comprises a total of 10 operations. The operations A to F constitute the casting and roughing operations. The operation G to J constitute the finishing line operation involving mainly the groove angle cutting operation, rounding up of the rim and cutting the keyway. However, Operation “G” in the manufacturing process is of utmost concern and constitutes the bottleneck activity in the pulley manufacturing process.

Table 2: The project charter for the pulley production process

Objectives	(i).	To evaluate groove angle cutting operation of the pulley.
	(ii).	To relieve the groove angle operation from any obstacle and thus preventing staggered inventory.
Deliverables and Success Metrics	(i).	To accomplish the process potential capability index and performance process capability index, i.e., C_p and C_{pk} values for the groove angle process of the V-belt is >1.33, which is more than 4 sigma levels
	(ii).	The C_p and C_{pk} values to be always achieved > 1.33 for over a regular period of 3 weeks.
Business Impact	(i).	Increase the process capability levels and responsiveness of the need for process monitoring charts in production.
	(ii).	decrease the component rejection and rework after supplies.

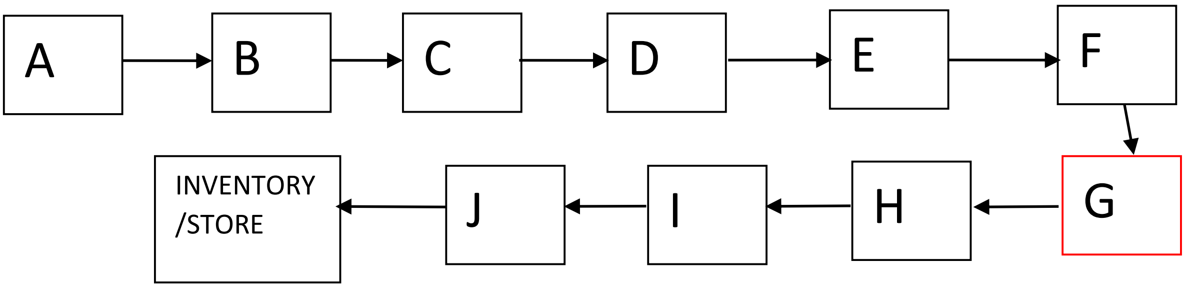


Figure 1: Process flowchart for production of groove pulley

Table 3 depicts the description of the machining operation of pulley manufacture along with their associated CTQ (critical-to-quality) characteristics. CTQ, (critical to quality) characteristics as implied in this work refers to the manufacturing processes or stages which affect the quality of the pulley.

Measurement Stratum

The measurement stratum involved data collection of the critical-to-quality characteristics and performed for 30 consecutive machined pulleys. The data used in the study were obtained from the Engineering Research department of the National Root Crops Research Institute Umudike, Abia State Nigeria. Data collection were performed in 3 iterations spanning a period of 3 weeks, i.e., about 60 components (machined groove pulleys).

Analysis stratum

The analysis stratum comprises of performing the calculation for the C_p and C_{pk} values across each iteration. In this stratum, the cause analysis was conducted with the help of various quality control tools like the cause and effect diagram, physical mechanism analysis followed by a one-way ANOVA (Analysis of Variance) method of investigation to test the differences between the three iterations of the data sets.

Equations 1 to 4 were used to determine the C_p, C_{pk}, C_{pku}, and C_{pkl}.

$$C_p = \frac{USL-LSL}{6\sigma} \quad (1)$$

$$C_{pku} = \frac{USL-MEAN}{3\sigma} \quad (2)$$

$$C_{pkl} = \frac{MEAN-LSL}{3\sigma} \quad (3)$$

$$C_{pk} = \min.\,(C_{pku}, C_{pkl}) \quad (4)$$

Where C_p = Potential Capability Index
C_{pk} = Performance Capability Index
C_{pku} = Upper performance capability Index
C_{pkl} = lower performance capability index.
USL = upper Stratification level (maximum value in each iteration)
LSL = lower Stratification level (minimum value in each iteration)
σ = standard deviation.

Table 2 shows the dimensional readings of the groove angle of the V-belt pulley. The angle was determined using a groove angle set spanned over three iterations. The values of the potential capability index (Cp) and performance capability index (Cp k) are shown in Table 3.

Iteration no. 1 primarily indicates the first status of the problem on hand before carrying out any improvement work. The continuous sets of measurements of the CTQ characteristic taken, and were seen that the C_P and C_{PK} values are below the target value of 1.33, with C_P value equal to 0.65 and C_{PK} equal to 0.5.

Table 2: Dimensional readings of Groove angle spanned over three iterations

S.No	ITERATION 1	ITERATION 2	ITERATION 3
1	33.60	34.50	34.00
2	33.70	34.00	34.20
3	33.50	34.50	34.10

4	34.10	34.20	34.00
5	33.60	34.20	34.10
6	33.90	34.30	34.10
7	33.90	34.10	34.10
8	33.50	34.50	34.00
9	33.90	34.30	34.20
10	33.80	34.10	34.00
11	33.60	34.30	34.10
12	33.90	34.20	34.20
13	34.20	34.20	34.00
14	33.80	33.90	34.00
15	33.70	34.30	34.20
16	34.10	34.40	34.10
17	33.70	34.20	34.10
18	34.20	33.90	34.10
19	33.50	34.50	34.20
20	34.20	34.30	34.20
21	33.80	34.00	34.20
22	34.00	34.00	34.10
23	33.60	34.30	34.20
24	33.50	34.20	34.10
25	34.20	34.20	34.20
26	33.90	34.50	34.20
27	33.90	34.20	34.20
28	33.90	33.90	34.10
29	33.90	34.00	34.20
30	33.50	34.20	34.20

Iteration no. 2 corresponds to the intermediary phase readings after performing moderate improvements. They include the setting up a standard procedure for tool-insert setting on the lathe, cleaning the lubrication system and replacing the worn out cutting tool insert edge. In Iteration 2, a slight cyclic pattern is obtained. The reason is that there is a constant progressive wear out of the boring bar insert on the continued cutting operation. After every ten components machined, the boring bar insert must be compensated for the wear by elevating the insert by about five micrometres over the diametric dimension. In this iteration, there were marginal increases in C_P to 1.74 and C_{PK} to 1.6.

Finally, Iteration no. 3 corresponds to the final phase readings as shown in Table 3. It was taken after introducing the corresponding corrective actions known in the analysis stratum and bringing in a noticeable improvement in the process performance with C_P as 2.15 and C_{PK} = 1.62.

Table 3: Calculations of C_p and C_{pk}

	ITERATION 1	ITERATION 2	ITERATION 3
USL	34.5	34.5	34.5
LSL	33.5	33.5	33.5
SIGMA	0.258	0.096	0.077
CP	0.65	1.74	2.15
CPKU	0.8	1.6	1.62
CPKL	0.5	1.88	2.68
CPK	0.5	1.6	1.62

The Cause and effect diagram

The process monitoring analysis and the cause and effect diagram were used to identify the reasons for the poor performance of machining operations. Through the identification of these causes, subsequently corrective actions were taken to improve the process capability. The figure 2 shows the cause and effect diagram.

The variables considered in the process include,

(i) Cutting tool: Cutting tool insert indexing, insert changing for single point cutting tool; cutting tool holder location and clamping aspects; calibration of cutting tool setting in the tool-pre-setting area.

(ii) Workpiece, Work location, work holding, work clamping, work supporting, the power required for driving the work and related machinery, coolant circulation continuity for flushing out the chips generated in the cutting process, heat dissipation by the coolant.

(iii) Measurement aspect: The measurement system comprises of the go and no-go gauges on the shop floor, calibration of gauges in-process sensing instrument sensitivity and repeatability. The process is monitoring charts for the three iterations given below. Each chart comprises the number of observations (i.e., the number of pulleys) in the X-axis and values of the groove angles in each iteration in the Y-axis. The red dotted lines represent the Upper stratification limit (USL) and lower stratification limit (LSL) of each iteration. It can be observed from the process monitoring charts that iterations 2 and 3 are within the boundaries of iteration 3 values closer to the control limit whereas the values of iteration 1 tend to fall below the lower stratification limit.

Among the various enlisted causes from the cause and effect diagram and process monitoring analysis. The cause which showed the highest poor performance of the CTQ characteristics was identified using the ANOVA method. The following steps obtained the analysis of variance.

(i) Formulation of the hypothesis to be tested

(ii) Test for the assumption of the normality of the data used.

(iii) Test for the homogeneity of variance among the sets of the data used.

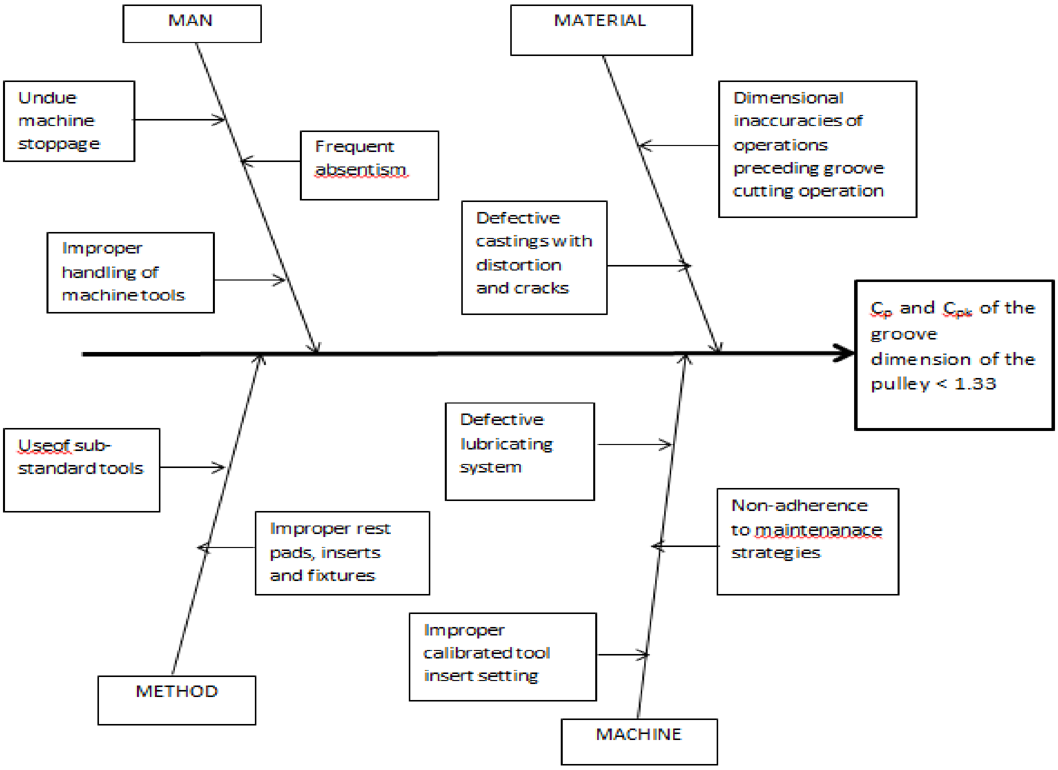


Figure 2: The cause and effect diagram

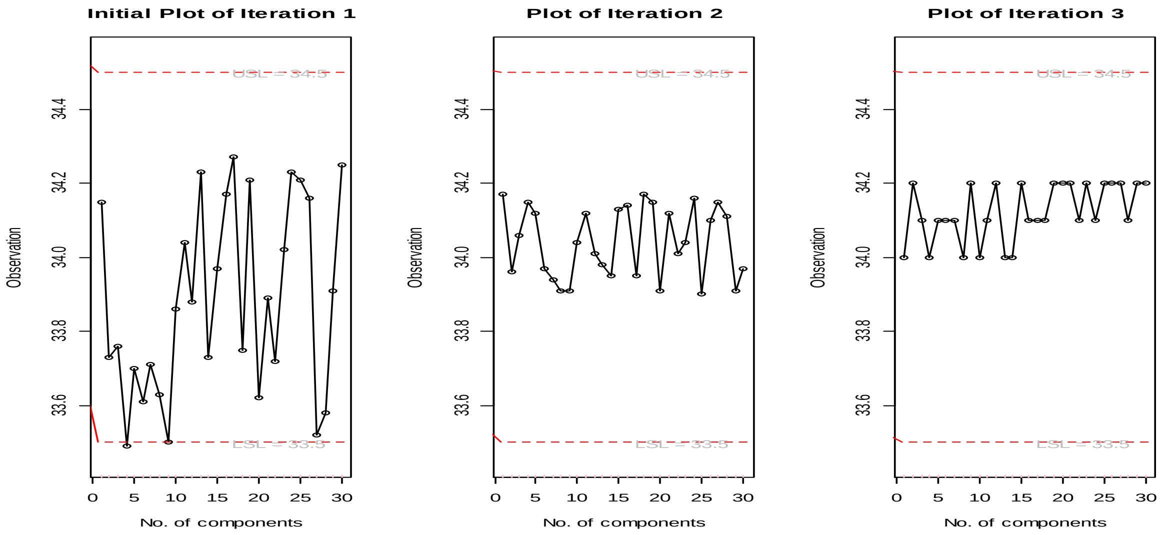


Figure 3: The Process monitoring charts (PMC)

A post hoc analysis will be needed if $F_{statistic}$ is greater than $F_{critical}$. The data plot for normality and histogram bar chart are shown in Figures 4 and 5 respectively. The null hypothesis (H0) and the alternate hypothesis (H1) can be formulated in the present context as

$H0: \mu_i = \mu$ all $i = 1, 2, 3$;

Where, $H1: \mu_i \neq \mu$ for some $i = 1, 2, 3$;

Where μ_i is the population mean for level i, and μ is the overall grand mean of all levels. Table 2, shows that there are 3 levels (i.e., 3 iterations) with each level consisting of 30 measurement readings of groove angle of the pulley.

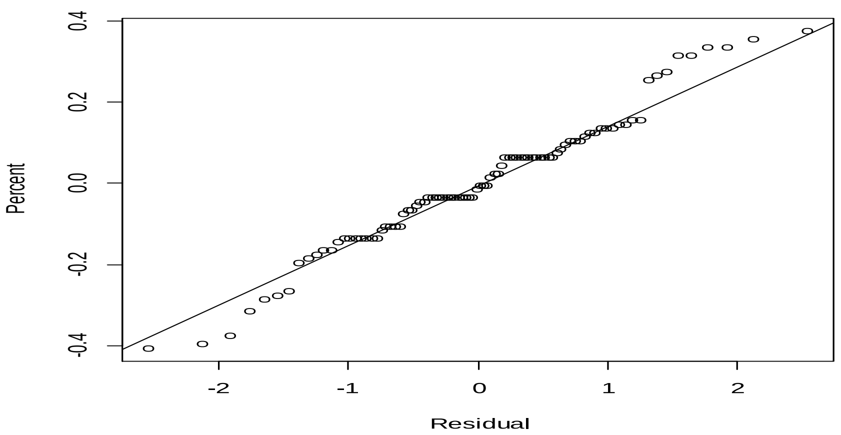


Figure 4: Normality plot of residuals for groove dimensional observations

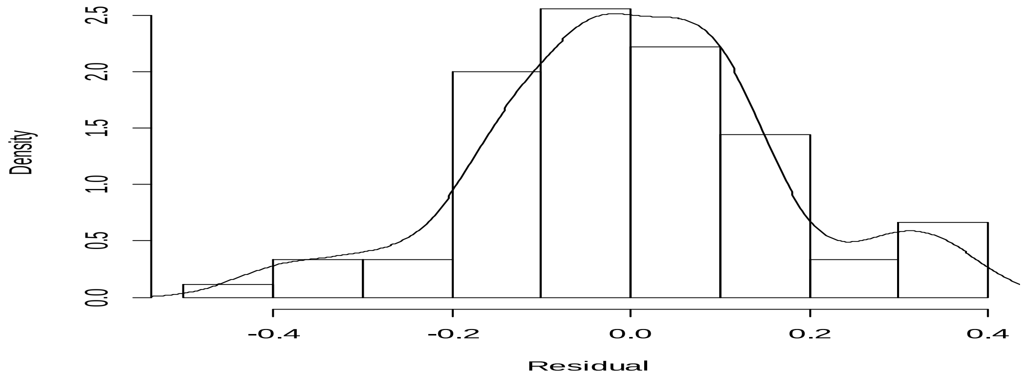


Figure 5: Residual histogram for pulley groove dimensional observations

One way ANOVA was used in the study to find the departure from normality. Also, to check the homogeneity of variance among the sets of data used. The normal probability plot in figure 4 is linear with equispaced values.It was further supported by the near bell-shaped curvature of the histogram. The P value is <0.005, and it is less than α value of 0.05. It shows that a linear relationship exists with normality retained. The results showed no significant data points. The sample size of 30 is sufficient to detect differences among means. The reason is that all the sample sizes are greater than 33 (which is the overall lower stratification limit), normality is not an issue (i.e. the residuals of the groove operation in each iteration usually distributed as evidenced by the dumb bell shape of the histogram).

The ANOVA Table is presented in Table 4.

Table 4: The ANOVA table

ANOVA					
ITERATION					
	Sum of Squares	Df	Mean Square	F	Sig.
Between Groups	.891	2	.446	16.408	.000
Within Groups	2.363	87	.027		
Total	3.255	89			

Here it is seen that $F_{STATISTIC}= 16.408$ (5)

The α value of 0.05 corresponding to 95 % confidence levels was used. If α is defined to be equal to 0.05, then the critical value for rejection region is $F_{CRITICAL\ (\alpha,\ K-1,\ N-K)}$. Thus, is obtained to be 3.09.

$F_{CRITICAL} = 3.09$ (6)

Hence, it is seen that

$F_{STATISTIC} > F_{CRITICAL}$ (7)

Therefore, the decision is to reject the null hypothesis. If the decision from the ANOVA is to reject the null hypothesis, then it shows that at least one of the means (μ_i) is different from the remaining other means. To find where the difference lies, a post hoc ANOVA test is needed. If "C1" denotes "Iteration 1", "C2" denotes "Iteration2" and "C3" denotes "Iteration 3", then using Tukey method as shown in Table 5.

Table 5: Grouping information using Turkey method

Multiple Comparisons

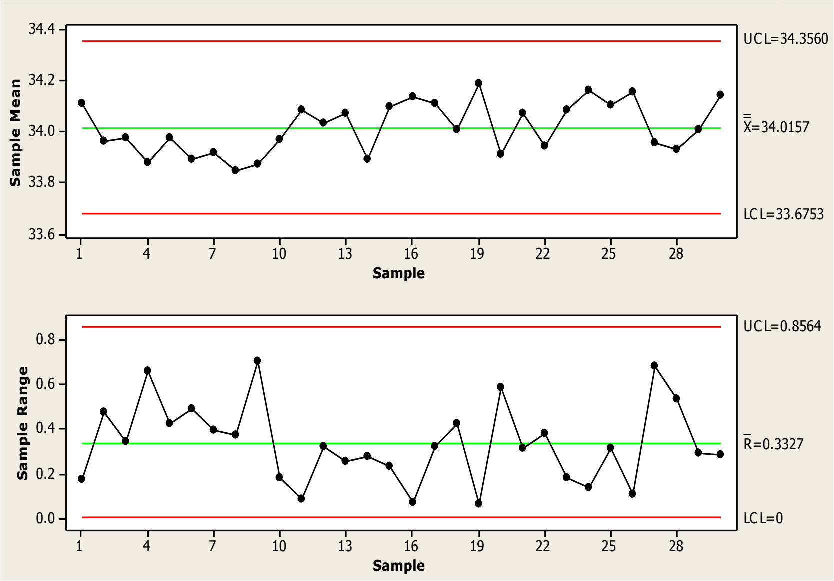
ITERATION
Turkey HSD

(I) FACTOR	(J) FACTOR	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
ITERATION 1	ITERATION 2	-.15700*	.04255	.001	-.2585	-.0555
	ITERATION 3	-.24000*	.04255	.000	-.3415	-.1385
ITERATION 2	ITERATION 1	.15700*	.04255	.001	.0555	.2585
	ITERATION 3	-.08300	.04255	.131	-.1845	.0185
ITERATION 3	ITERATION 1	.24000*	.04255	.000	.1385	.3415
	ITERATION 2	.08300	.04255	.131	-.0185	.1845

***. The mean difference is significant at the 0.05 level.**

The study showed that among all the different causes listed in the cause and effect diagram. The most influencing causes are the worn out cutting tool insert, insert setting v-block to wear out and non-calibration of the vernier callipers, operators' laxity, and tool setting mandrel.

From the control stratum, the X-bar and R control charts are used at the workplace for monitoring the process. Also, it can be used to prevent it from deviating.



The X-Bar and R chart are shown in Fig 6. It is observed that the mean and the range values are within the upper and lower control limits. It also indicates that there are no outliers and no out-of-control subgroups. The data points are equally distributed across the mean line.

Thus, the process mean as well as the process variation are stable and the process controlled.

Figure 6: X-bar and R control charts

Table 6: Business Impact

S. No	Components of the project area	Value
1.	Total number of rejects and rework per day, i.e., two production shifts of 8 hr each	8 pulleys
2.	Time is taken for rework and segregation of components	50mins per day
3.	Production loss due to rejection and rework per month	5/6 * 30 = 24.9hr
4.	Monetary loss of 50mins delays in the machining cell	₦2500
5.	Total monetary loss per month with 25 working days per month	₦2500 * 25 = ₦62500
6.	By avoiding 99% of rejection and rework, the amount saved per month	0.99 * 62500 = ₦61875

CONCLUSION

The efficiency and trouble free operation of belt or rope drives largely depends on the groove design of the pulley. Elimination of rework and rejection caused by this bottleneck activity (Groove making operation) in the pulley production process requires a Six Sigma approach implemented in this study. The use of the DMAIC methodology for the different phases of the project helped eliminate some causes of waste in the process. Iteration no. 1 with C_P value equal to 0.65 and C_{PK} equal to 0.5 primarily indicates the first status of the problem on hand before carrying out any improvement work. Iteration no. 2 matches the intermediary phase readings. Moreover, it is after performing moderate improvements with a marginal increase in C_P to 1.74 and C_{PK} to 1.6. Iteration no. 3 matches the final phase readings. Moreover, it was taken after introducing the corresponding corrective actions observed in the analysis stratum. Moreover, it brought a noticeable improvement in the process performance with C_P as 2.15 and C_{PK} equal to 1.62. The data points of the control charts are also equally distributed across the mean line indicating that the process means as well as the process variation are stable, and the process is under control. The business impact of implementing the DMAIC methodology at C_p and C_{pk} values > 1.33 consistently indicates that by avoiding 99% component rejection and rework, sixty-one thousand, eight hundred and seventy-five naira (₦61875) saved per month.The method offers the advantage of lowering the machining cost via a reduction in machining steps, time, and energy in pulley manufacturing.

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