Improving the statistical process control chart by applying a DNOM chart for multiprocessor products

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Abstract. Statistical control charts generally study only one property. The purpose of this research was thus to generate a control chart for a full set of properties for the product of the multiprocessors executing the operation of a lathe machine. In short-term production, there is often insufficient data in each product run to achieve an ideal estimate of operation parameters, which can result in reduced performance and inefficient control charts. A case study research methodology was applied in the Al- Noaman factory. Minitab-17 Software was used to calculate and plot control charts and to analyse the process capability index. The results of process capability (Cp) for three processes (drilling, face, and external length) were equal to 0.828, with the third process giving an external diameter equal to 0.248. Another index (Cpk) for shifting indicators, gave results for the lower specification limits for drilling and external diameter processes, while the other processes, face and external length, shifted towards the upper specification limit. The Cpm indicators showed the same behavior for Cp, and the Cpkm indicator gave results that suggested the same behavior as the Cpk.

Keywords: statistical process control (SPC), control charts, short run production, Process Capability Indices.

1. Introduction

Statistical Quality Control is a powerful set of useful problem-solving tools that allow stabilisation of a process and improve capacity by reducing variance [1]. This method provides the statistical techniques needed to ensure and improve the quality of products. One of the most widely used statistical tools is the application of control charts, as introduced by Shewhart in 1924. However, no two products are completely alike, as the processes that produce these products have many opportunities for variance [2], and while the control scheme is an effective tool for analysing the differences in repetitive processes, in a general process, two different types of differences can be distinguished. Chance or (common) variations are the "noise" of production systems, and lead to uncontrollable variations. The other type are customizable (or special) variations that can be properly identified and controlled [3]. In this paper, batch production will be defined as per the American Society for Production Control and Inventory (APIS) "as a form of manufacturing that passes through technical departments in a lot or batches and for each lot the directive may be different". This is characterised by manufacturing a limited number of products that are produced at regular intervals and stored until sold [4].

2. Control chart principles

Several schemes are widely used in industry as graphical techniques for monitoring process outputs; in these, statistics are calculated from the measured values of a given process versus its time characteristics to determine whether the process is still in statistical control. A control chart always has a centre line for the average value of the quality characteristic measurement, with two other horizontal lines. The top line is called the upper limit of the control, and the lower line is the minimum control (LCL). The upper and lower control limits are set at ± 3 standard deviation, as in Figure 1. When control limits are set, if all points charted fall between them, the process is in control. In this case, no action is required. If a point falls outside one of the control limits, it signals that the process is out of control. Variable control diagrams are designed to control product properties that can be measured in a continuous range [5].

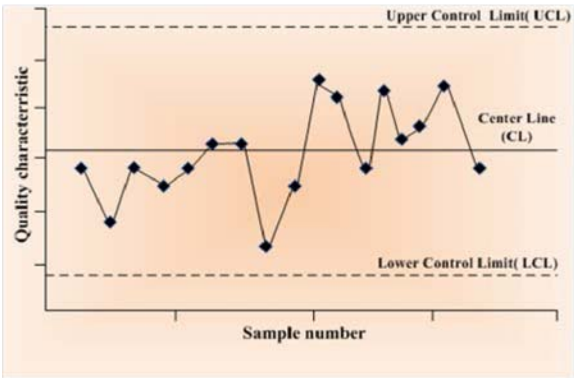

Figure 1. Quality control chart structure [1]

The construction of X bar and range schemes are the most common control schemes used to measure continuous data. They are the basic tools used to display the range of differences inherent in static operations or to identify special reasons that have changed the operating characteristics of a process, allowing elimination of these special reasons [6].
The subgroup average is calculated by applying the following equation [7]:

$$\bar{X}_i = \sum_{j=1}^{n} X_{ij}/n \quad (1)$$

The grand average of subgroups is then found by applying the following equation [7]:

$$\bar{\bar{x}} = \sum_{i=1}^{k} \bar{x}_i / k \quad (2)$$

Thus, $\bar{\bar{x}}$ is used as the centre line on the control chart. To create control limits, an estimate of the range of samples must be found [7]:

$$R_i = Max\,(x_{i1}, \ldots, x_{in}) - Min\,(x_{i1}, \ldots, x_{in}) \quad (3)$$

The average range can be calculated as [7]

$$\bar{R} = \frac{R_1+R_2+\cdots+R_k}{k} \quad (4)$$

To calculate the trail control limit for the $\bar{x}$ chart, the following equations are applied [1]:

$$UCL_{\bar{X}} = \bar{\bar{X}} + A_2\bar{R} \quad (5)$$

$$Center\ line = \bar{\bar{X}} \quad (6)$$

$$LCL_{\bar{X}} = \bar{\bar{X}} - A_2\bar{R} \quad (7)$$

where
$UCL_{\bar{X}}$ = upper control limits for $\bar{X}$ charts,
$LCL_{\bar{X}}$ = lower control limits for $\bar{X}$ charts, and
A_2 = Factor from table (1) for subgroup size (n).

Table 1. Coefficients for control charts for variables [1].

X-bar Chart Constants			For Sigma estimated	R Chart Constants		S Chart Constants	
Sample Size = m	A_2	A_3	d_2	D_3	D_4	B_3	B_4
2	1.88	2.659	1.128	0	3.267	0	3.267
3	1.023	1.954	1.693	0	2.575	0	2.568
4	0.729	1.628	2.059	0	2.282	0	2.266
5	0.577	1.427	2.326	0	2.115	0	2.089
6	0.483	1.287	2.534	0	2.004	0.03	1.97
7	0.419	1.182	2.704	0.076	1.924	0.118	1.882
8	0.373	1.099	2.847	0.136	0.864	0.185	1.815
9	0.337	1.032	2.97	0.184	1.816	0.239	1.761
10	0.308	0.975	3.078	0.223	1.777	0.284	1716
11	0.285	0.927	3.173	0.256	1.744	0.321	1.679
12	0.266	0.886	3.258	0.283	1.717	0.354	1.646
13	0.249	0.85	3.336	0.307	1.693	0.382	1.618
14	0.235	0.817	3.407	0.328	1.672	0.406	1.594
15	0.223	0.789	3.472	0.347	1.653	0.428	1.572
16	0.212	0.763	3.532	0.363	1.637	0.448	1.552
17	0.203	0.739	3.588	0.3778	1.622	0.466	1.534
18	0.194	0.718	3.64	0.391	1.608	0.482	1.518
19	0.187	0.698	3.689	0.403	1.597	0.497	1.503
20	0.18	0.68	3.735	0.415	1.585	0.51	1.49

21	0.173	0.663	3.778	0.425	1.575	0.523	1.477
22	0.167	0.647	3.819	0.434	1.566	0.534	1.466
23	0.162	0.633	3.858	0.443	1.557	0.545	1.455
24	0.157	0.619	3.895	0.451	1.548	0.555	1.445
25	0.153	0.606	3.931	0.459	1.541	0.565	1.435

The trail control limit for the $\bar{R}$ chart is calculated by applying the equations [1]

$$UCL_{\bar{R}} = D_4\bar{R} \tag{8}$$

$$lCL_{\bar{R}} = D_3\bar{R} \tag{9}$$

where
$UCL_{\bar{R}}$ = Upper Control Limit for $\bar{R}$ chart,
$LCL_{\bar{R}}$ = Lower control limit for $\bar{R}$ chart, and
D_4,D_3 = Factors from table (1) for subgroup size (n).

3. Short run control chart

Much mass production is generally large-scale and building a control chart is thus not difficult. However, modern manufacturing trends are to produce a lot of small size batches or to use short-term production for flexible manufacturing using the labour shop system; this requires some adjustments to traditional control charts. Cullene and Both presented a control scheme called the deviation from the nominal method (DNOM), which can be expressed as in the following equation [8]:

$$X_i = M_i - T_A \tag{10}$$

where
M_i= measurement of sample and
T_A= target value for sample.

4. Process capability analysis

In the field of quality control, process capability is used to compare the output of a process with the specification limits of the product produced. The process capability index (PCI) is widely used to measure the inherent variability of a process and thus reflect its performance [9]. Several common PCIs, including Cp, Cpk, Cpu, Cpl, Cpm, and Cpmk, are widely used in practice. In the Cp index, the overall change in the process is relative to the tolerability of the specifications, and it therefore reflects only the consistency of product quality characteristics. Cp can be expressed mathematically as [10]

$$Cp = \frac{USL-LSL}{6\sigma} \tag{11}$$

where
USL=Upper Specification Limit,
LSL=lower Specification Limit, and
σ= Standard Deviation obtained from $\bar{R}/d_2$, where d_2 = the factor from table (1) for subgroup size (n).

The common indicator compares the distance between the average operation and the maximum specification with a half-distribution view (Cpu), as shown in the relevant equation below. Similarly, Cpl compares the distance between the average operation and the minimum specification with half the distribution width, as seen in the equation. Cpk takes into consideration the fact that the process mean can be defined as follows [11]:

$$\text{Cpu} = \frac{USL-\mu}{6\sigma} \tag{12}$$

$$\text{Cpl} = \frac{\mu-LSL}{6\sigma} \tag{13}$$

$$\text{Cpk} = \frac{\min(USL-\mu\ ,LSL-\mu)}{3\sigma} \tag{14}$$

where:
μ = process mean.
Both Cp and Cpk indices do not take into account departures operations, or the means of the target value, which Chan et al. (1988) [12] suggested as a new development. The CPM indices, which include the departure process in their meta tags to reflect the degree of targeting of the process, can be expressed mathematically as per the equation below [13]:

$$Cpm = \frac{USL-LSL}{6\sqrt{\sigma^2+(\mu-T)^2}} \tag{15}$$

For a power index that is more sensitive to the departure from the mean process than the target value, Pearn, Kotz, and Johnson (1992) introduced Cpmk [14], which combines the merits of the three basic indices (Cp, Cpk, and Cpm). Cpmk is defined as in the equation below [15]:

$$Cpmk = \frac{min\ (USL-\mu,\mu-LSL)}{3\sqrt{\sigma^2+(\mu-T)^2}} \tag{16}$$

5. Practical applications

Such indices can help to cover the needs of the market and to meet the specifications of competing products in the global market. Figure 2 shows a gas cylinder neck, a part produced on a lathe machine. Four processes are required for this product.

Figure 2. Gas cylinder neck sample

The dimensions and tolerances of the manufactured material for gas cylinder neck steel 37-2 are shown in figure (3-a). The four stages of manufacture for this part are as follows:

Stage 1: Cutting Process
The first stage of the technical path is to cut the raw material using a reciprocating saw, as seen in figure (3-b), to a length of 28 mm.

Stage 2: Drilling Process
After the cutting stage, the raw material is loaded into and setup on the manual lathe machine.
During this stage, it is drilled to diameter $22.5^{\pm 0.5}$ mm, with tolerances as shown in figure (3-c).

Stage 3: Face Turning Process
Work piece length is reduced from 28 mm to 26^{+0}_{-1}mm by face turning, as shown in figure (3-d).

Stage 4: External Turning Process
At this stage, two overlapping operations are applied to the work piece to achieve dimensions of diameter $45^{+0}_{-0.3}$mm, and length 16^{+0}_{-1}mm: figure (3-e) show the dimensions for these processes.

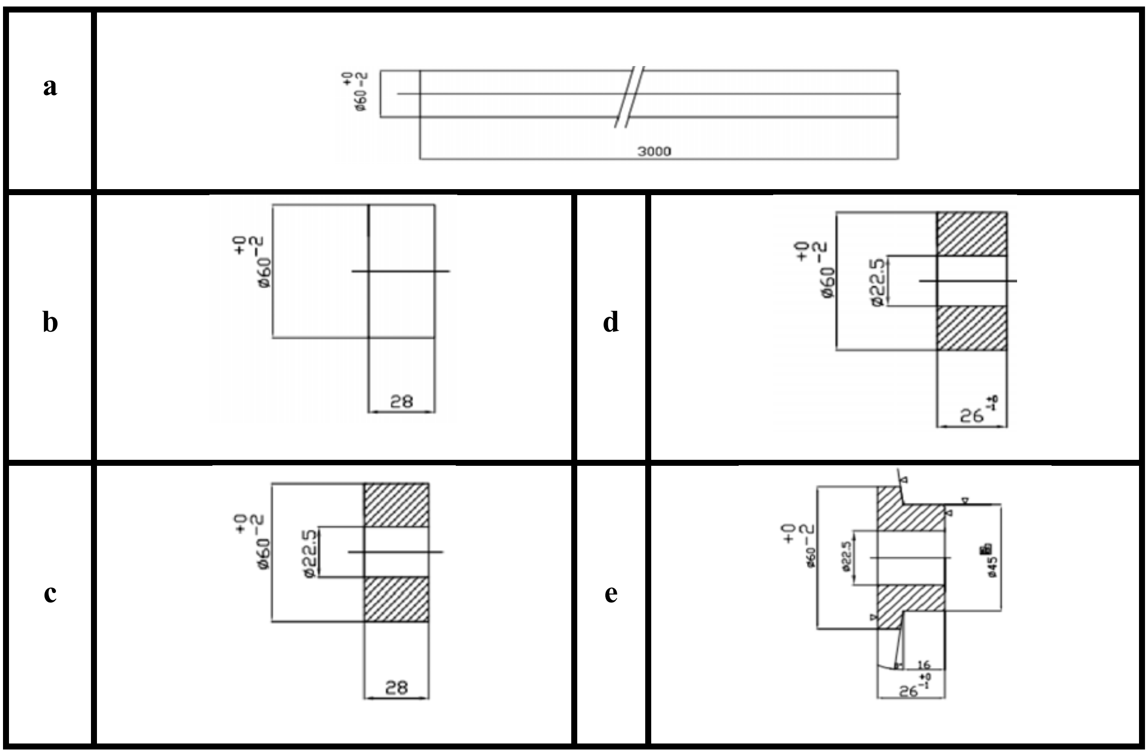

Figure 3. Technological path of manufacturing a gas cylinder neck [16]

Data were collected for the four properties shown in table 2, After the completion of the production of a piece, the measurements of the properties to be controlled were calibrated using verniers prior to the start of aggregation to ensure accuracy (0.01 mm) and scale range (50 to 27 mm); these were then measured and a fixed factor for a single production feed taken at intervals between the samples to determine the extent of change in the process due to the effect of the machine. The differences between processes are introduced by switching the equipment, feed rate, and direction. Figure 5 shows the process in a controlled state after deleting samples 10 and 13 in the (Xbar-R) chart shown in figure 4. Table 3 displays the statistical calculations constructed using Minitab-17 software after treatment in short run form using Microsoft Excel 2013. Table 4 shows the summary calculations for data used in the final step. After all characteristic reached a controlled state, equations 11, 12, 13, 14, 15, and 16 were applied to find the PCI, as shown in table 5.

Table 2. Data collection

N.P.	S.N.	Readings (mm)				
		X_1	X_2	X_3	X_4	X_5
	1	22.05	22.45	22.27	22.43	22.39
	2	22.52	22.39	22.3	22.31	22.06
	3	22.14	22.08	22.48	22.09	22.43
1	4	22.28	22.52	22.36	22.47	22.07
	5	22.1	22.02	22.45	22.19	22.15
	6	22.51	22.57	22.17	22.07	22.5
	7	22.44	22.42	22.9	22.45	22.31
	8	25.9	25.1	25.98	26	25.55
	9	25.96	25.99	25.84	25.61	25.6
	10	25.55	25.88	25.27	25.52	25.41
2	11	25.4	25.79	25.18	25.90	25.64
	12	25.9	25.88	25.52	25.76	25.86
	13	25.61	25.13	25.87	25.94	25.03
	14	44.97	45.01	44.95	44.72	44.96
	15	44.93	44.95	45.01	45.09	44.77
	16	45.18	45.12	44.85	45.03	45.02
3	17	44.98	44.74	44.84	44.93	44.97
	18	45.04	44.89	45.01	44.81	44.93
	19	44.96	45.01	44.72	44.95	44.89
	20	15.88	15.49	15.29	15.7	15.84
	21	16	15.9	15.8	15.71	15.98
4	22	15.75	15.69	15.68	15.95	15.98
	23	15.9	15.54	15.55	15.88	16
	24	15.76	16	15.63	15.65	16.02
	25	15.82	16.05	15.22	15.48	16.01

Table 3. Calculations for short run

S.N.	X_1	X_2	X_3	X_4	X_5	$\bar{X}$	R
1	-0.45	-0.05	-0.23	-0.07	-0.11	-0.18200	0.400
2	0.02	-0.11	-0.20	-0.19	-0.44	-0.18400	0.460
3	-0.36	-0.42	-0.02	-0.41	-0.07	-0.25600	0.400
4	-0.22	0.02	-0.14	-0.03	-0.43	-0.16000	0.450
5	-0.40	-0.48	-0.05	-0.31	-0.35	-0.31800	0.430
6	0.01	0.07	-0.33	-0.43	0.00	-0.13600	0.500
7	-0.06	-0.08	0.40	-0.05	-0.19	0.00400	0.590
8	-0.1	-0.9	-0.02	0	-0.45	-0.294	0.900
9	-0.04	-0.01	-0.16	-0.39	-0.4	-0.200	0.390
10	-0.45	-0.12	-0.73	-0.84	-0.59	-0.546	0.720
11	-0.6	-0.21	-0.82	-0.1	-0.36	-0.418	0.720
12	-0.1	-0.87	-0.48	-0.24	-0.14	-0.216	0.380
13	-0.39	-0.35	-0.13	-0.06	-0.97	-0.484	0.910
14	-0.03	0.01	-0.05	-0.28	-0.04	-0.07800	0.290
15	-0.07	-0.05	0.01	0.09	-0.23	-0.05000	0.320
16	0.18	0.12	-0.15	0.03	0.02	0.04000	0.330
17	-0.02	-0.26	-0.16	-0.07	-0.03	-0.10800	0.240
18	0.04	-0.11	0.01	-0.19	-0.07	-0.06400	0.230
19	-0.04	0.01	-0.28	-0.05	-0.11	-0.09400	0.290
21	-0.16	-0.30	-0.71	-0.51	-0.12	-0.36000	0.590
22	-0.02	-0.29	-0.20	-0.10	0.00	-0.12200	0.290
23	-0.02	-0.05	-0.32	-0.31	-0.25	-0.19000	0.300
24	0.00	-0.12	-0.45	-0.46	-0.10	-0.22600	0.460
25	0.02	-0.35	-0.37	0.00	-0.24	-0.18800	0.390

Table 4. Summary calculations for short run

S.N.	X_1	X_2	X_3	X_4	X_5	$\bar{X}$	R
1	-0.45	-0.05	-0.23	-0.07	-0.11	-0.18200	0.400
2	0.02	-0.11	-0.20	-0.19	-0.44	-0.18400	0.460
3	-0.36	-0.42	-0.02	-0.41	-0.07	-0.25600	0.400
4	-0.22	0.02	-0.14	-0.03	-0.43	-0.16000	0.450
5	-0.40	-0.48	-0.05	-0.31	-0.35	-0.31800	0.430
6	0.01	0.07	-0.33	-0.43	0.00	-0.13600	0.500
7	-0.06	-0.08	0.40	-0.05	-0.19	0.00400	0.590
8	-0.10	-0.90	-0.02	0.00	-0.45	-0.2940	0.900
9	-0.04	-0.01	-0.16	-0.39	-0.40	-0.200	0.390
10	-0.60	-0.21	-0.82	-0.10	-0.36	-0.4180	0.720

11	-0.10	-0.12	-0.48	-0.24	-0.14	-0.216	0.380
12	-0.03	0.01	-0.05	-0.28	-0.04	-0.0780	0.290
13	-0.07	-0.05	0.01	0.09	-0.23	-0.0500	0.320
14	0.18	0.12	-0.15	0.03	0.02	0.04000	0.330
15	-0.02	-0.26	-0.16	-0.07	-0.03	-0.1080	0.240
16	0.04	-0.11	0.01	-0.19	-0.07	-0.0640	0.230
17	-0.04	0.01	-0.28	-0.05	-0.11	-0.094	0.290
18	-0.16	-0.30	-0.71	-0.51	-0.12	-0.36000	0.590
19	-0.02	-0.29	-0.20	-0.10	0.00	-0.12200	0.290
20	-0.02	-0.05	-0.32	-0.31	-0.25	-0.19000	0.300
21	0.00	-0.12	-0.45	-0.46	-0.10	-0.22600	0.460
22	0.02	-0.35	-0.37	0	-0.24	-0.18800	0.390
23	0.01	-0.52	-0.78	0.05	-0.18	-0.28400	0.830
						$\bar{\bar{X}}$	$\bar{R}$
						-0.20168	0.468
					$\hat{\sigma}_{Xbar-R}$	0.201204	

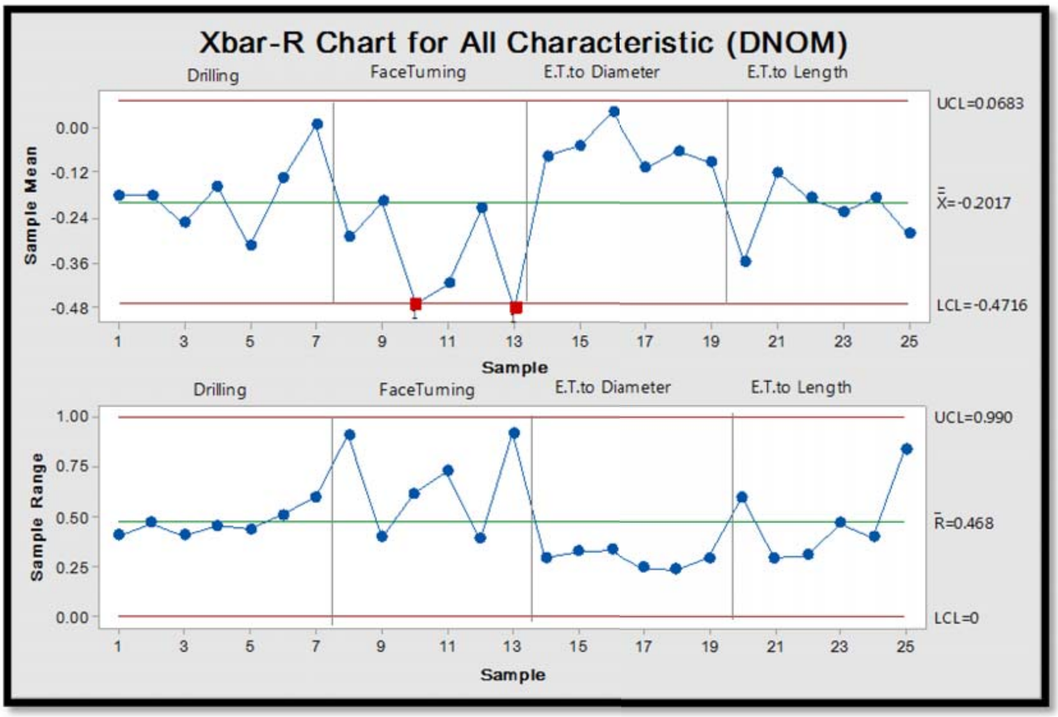

Figure 4. Xbar-R_{SR} for all characteristics

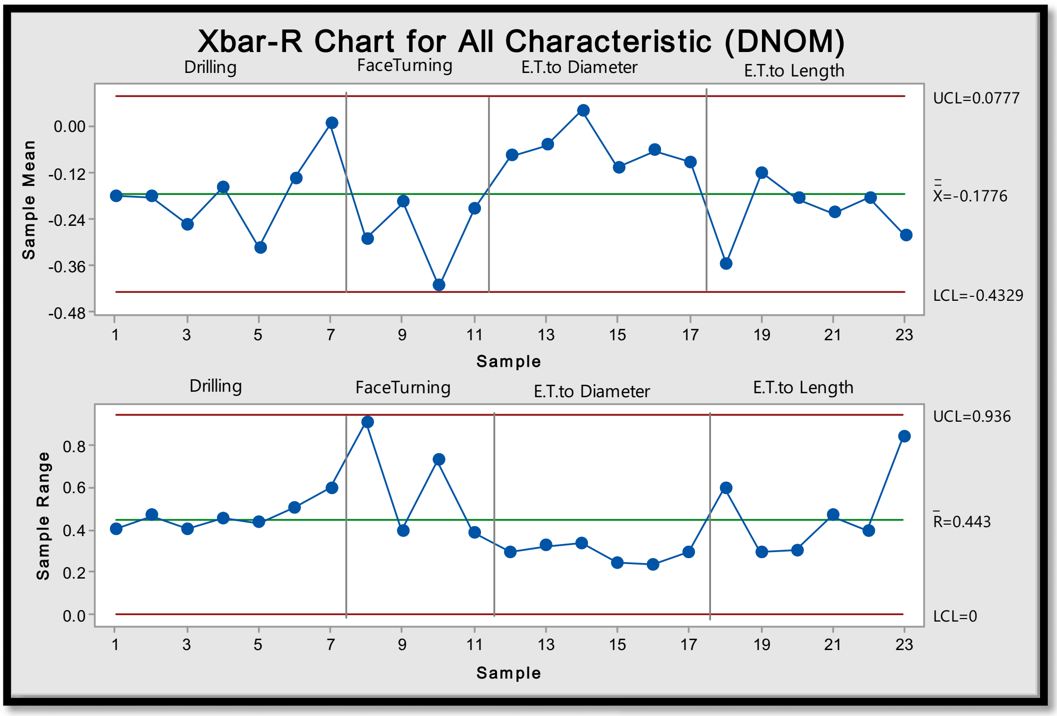

Figure 5. X bar-R_{SR} approved for all characteristics

6. Results and Discussion

After all characteristics reached the control state, equations (11), (12), (13), (14), (15), and (16) were applied to find the relevant values of Cp, Cpu, Cpl, Cpk, and Cpm.

a) Drilling Process
1. Cp value = 0.828, which gives an indication that process is not capable, because the process dispersion is outside the range specified.
2. The value of Cpk = 0.494, which indicates that the process mean is not centred; the target is shifted toward the lower specification limit.
3. Cpm = 0.585; this means that Cpm<Cp, which shows that the mean of the process is transferred away from the target value.

b) Face Turning Process
1. The value of Cp = 0.828; thus, it can be concluded that process capability is not adequate because Cp<1.
2. The value of Cpk = 0.344, indicating that the process mean is not centred, being shifted toward the upper specification limit.
3. The Cpm value =0.585, which means Cpm<Cp; this shows that the mean of the process is moved away from the target value.

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c) External Turning to Diameter
1. The value of Cp = 0.248; this indicates poor capability for this process because Cp<1. Any increase in the value of σ results in a decrease in the Cp value of the process due to the increase in the range of measured sample sizes
2. The value of Cpk = 0.126, indicating that the process mean is not centred, being shifted toward the lower specification limit.
3. The Cpm value = 0.175; this means that Cpm<Cp, which shows that the mean of the process is transferred away from the target value.
4. These place limits on the adoption, alongside the presence of six samples on one side of the centre line where they are statistically unregulated, creating the absence of random distribution in the mean and range chart. Observation should be increased for this type of operation and the measurer and measuring instrument should be checked.

d) External Turning to Length
1. The value of Cp = 0.828, which indicates a poor process because Cp<1. An increase in the value of the σ results in a decrease in the Cp value of the process due to the increase in the range of measured sample sizes.
2. The value of Cpk = 0.334, which means the process mean does not equal the target value, being shifted toward the upper specification limit.
3. The value of Cpm = 0.585, which means there is a shift in the process mean away from the target value.

7. Conclusion
This paper reviewed and implemented a short run method to calculate process capability, reaching the following conclusions:
1. The Cp value for all processes was smaller than 1 suggesting the need for greater control.
2. The values of Cpk and Cpm for all processes were smaller than 1, indicating a need to re-install the machine from time to time, so as to reduce dispersion and allow the process mean to be shifted closer to the target value.
3. The Cpk values indicate that failures in the drilling process and external turning can be reworked instead of being sent to scrap.
4. To reach a Cp of 1 in drilling, face turning, and external turning, the processes must decrease the σ to a maximum of 0.034; it should be decreased to at least 0.1512 for external turning of the diameter.
5. Instead of using four charts for the separate processes only one chart was used, with the same control limits. This leads to a reduction in the cost and time for inspection.

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Symbols	**Description**
A_2	Factor for converting the average range to three standard errors for the X-bar chart from
d_2	Factor for converting the average range to an estimate of sigma see in
D_3, D_4	Factors for converting the average range to three sigma limit for the R chart
k	Number of subgroup s used in calculation of control limit
n	Subgroup size , number of observation in a subgroup
R_i	Range of the observation in the *i*th subgroup for the R chart
$\bar{R}$	Average of the *k* subgroup ranges
T	Process target value for process mean
X	Reading Value
$\overline{X_i}$	Average of the *i*th subgroup observations for the x-bar chart
$\bar{\bar{X}}$	Average of the *k* subgroup averages for the x-bar chart
Cp	Process Capability Index , used when USL and LSL are Relevant
Cpk	Process Capability Index , used when USL and LSL are Relevant
Cpl	Process Capability Index , Used When LSL and μ are Relevant
Cpu	Process Capability Index , Used When USL and μ are Relevant
Cpm	Process Capability Index , Used when μ and *T* are Relevant
Cpmk	Process Capability Index , Used When σ , μ and *T* Relevant
σ	Standard Deviation
$\hat{\sigma}$	Estimated common cause standard deviation of the process
6σ	Process spread
μ	Process Mean
σ^2	Process Variance
Xbar-R_{SR}	Chart mean and range in short run method