6.8 Cylinder Liner Boring Case Study – Demonstrating the Process of SPC

The following case study demonstrates the application of $\overline{X}$ and R control charts to the study of a manufacturing operation. As will be seen, the case study uses control charts to identify the presence of faults within a cylinder boring operation. It also demonstrates how the simple graphical techniques that have been presented in this Chapter may be utilized to find the root causes of the faults and eliminate them. The case study illustrates the complete process of SPC to bring a process into a state of statistical control.

The Situation

As part of recent management change, a supplier to an engine manufacturer has initiated a company-wide quality improvement strategy. The company's principal product is a cast iron cylinder liner (or sleeve) that is inserted into the aluminum block produced by the engine manufacturer. Given the reliance of the liner company on this single class of products, it needs to respond quickly to the ever-increasing expectations of the customer. In fact, word has it, that the engine manufacturer soon plans to announce new, more stringent specifications for the liner. Given this background, the company decided to investigate the liner production process. To conduct the investigation, a vertically and horizontally integrated study team was formed, and asked to identify sources of variation that may pose potential quality problems and negatively impact cost/productivity. The first action taken by the team was to construct a flow chart of the cylinder liner production process (Figure 6.24).

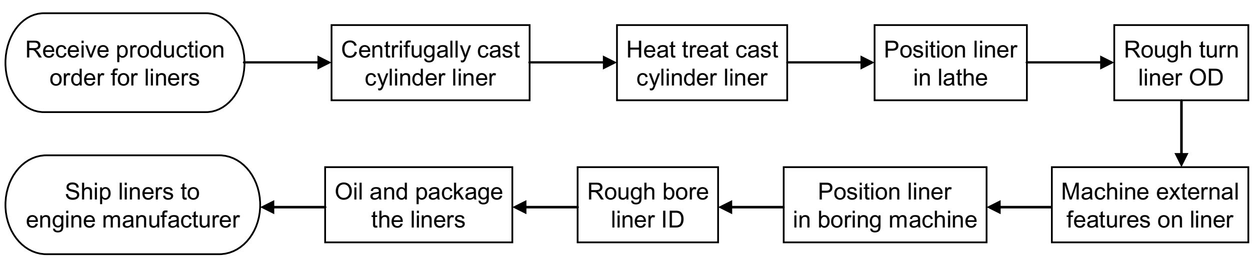


Figure 6.24 Flow Chart of Cylinder Liner Manufacturing Process

In examining Figure 6.24, it is evident that the liners are produced by a centrifugal casting operation, and then heat treated. Machining operations are then performed on the liners, i.e., rough turning of outer diameter (OD), turning of external features to manufacturer specifications, and rough boring of liner inner diameter (ID). Following the completion of the rough boring operation, each liner is inspected, then an oil film is applied to prevent rusting, and finally the liners are packaged and shipped to the engine manufacturer. It may be noted that once the liners are received at engine manufacturer, the liners are inserted as cores in the block casting operation. The engine manufacturer subsequently performs a finish ID boring operation, and a honing operation on the cylinder (liner) wall surface.

The planned new specifications were applied to a subset of the historical liner data to determine which quality characteristics would be affected by the more stringent liner specifications. The data analysis revealed instances where liner quality characteristics would fail to meet the new specifications (a defect or nonconformity). For the specific subset of the liner data examined, the defects were grouped by type; the study team then prepared the Pareto chart shown in Figure 6.25 for the defect data.

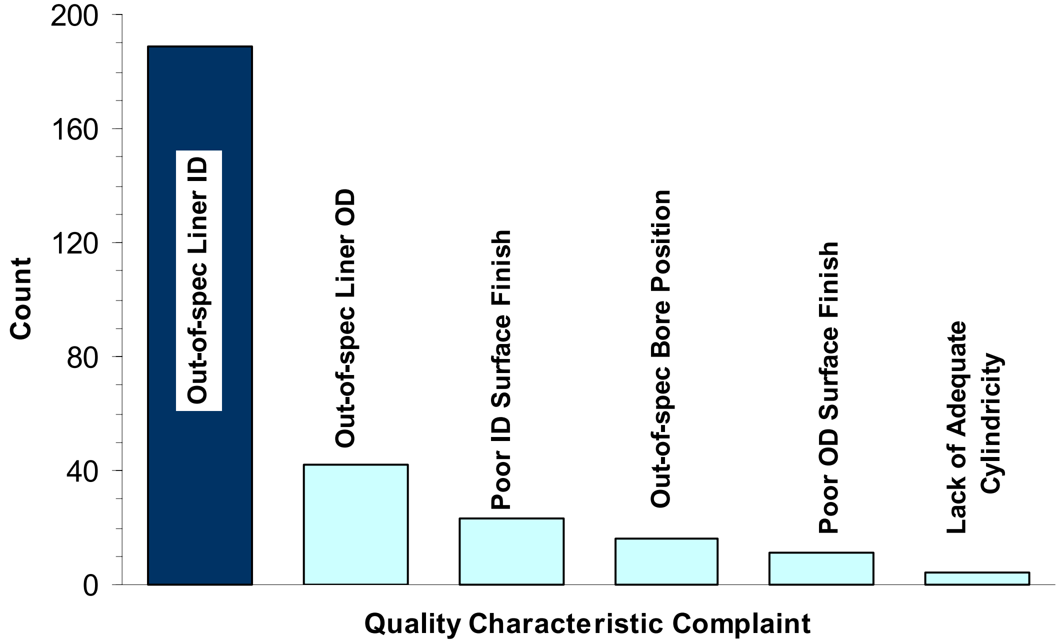


Figure 6.25 Pareto Chart for Cylinder Liner Defects

An examination of Figure 6.25 shows that when the new liner specifications are applied to the historical data, a large number of the liner inner diameter (ID) values fall outside the specifications. The Pareto chart reveals that this "defect" occurs most frequently. This revelation was extremely useful to the quality study team; it provided insight into which quality characteristic would be the most sensitive to the planned change in liner specifications. The focus of the study team then shifted to inventorying those factors that could contribute to an out-of-spec liner ID defect. This inventory was captured via the cause and effect diagram displayed in Figure 6.26. The diagram summarizes the collective knowledge relative to potential root causes of the liner ID quality concern. In this case, the construction of the diagram significantly benefited from the involvement of a diverse set of team members. The vertical nature of the team provided differing viewpoints of the system in terms of detail/perspective, and the horizontal character of the team brought together experts from across the liner manufacturing system.

As the team examined and discussed the cause and effect diagram of Figure 6.26, much of the attention centered on the cylinder liner boring process that produces the rough ID. In the figure, four of the categories were associated with the boring operation: tooling, boring machine, machine operator, and fixturing. It was decided to collect new data to assess the stability of the boring process through the construction of control charts. The data that were collected from the boring process were diameter measurements made to the nearest 1/10,000 of an inch. Samples of size n=5 were taken to obtain some data to initiate $\overline{X}$ and R control charts.

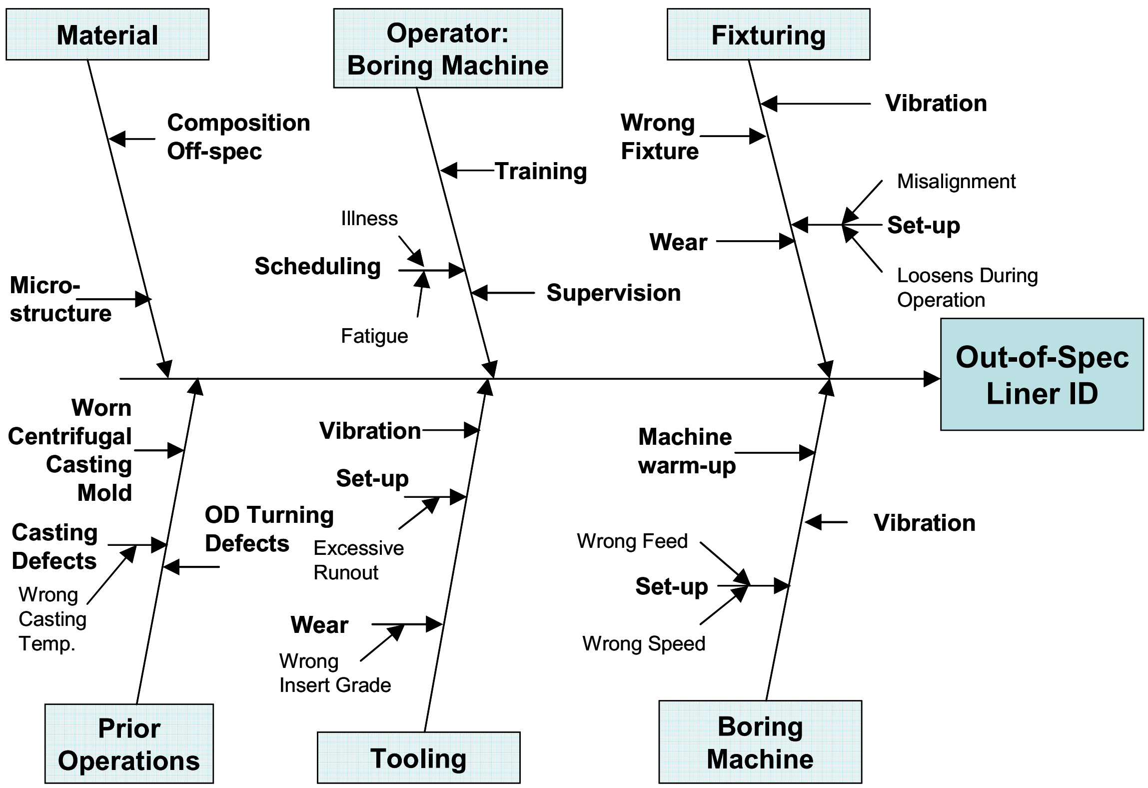


Figure 6.26 Cause and Effect Diagram for Out-of-Specification Liner ID Quality Concern

Initial Control Charts

Forty samples were collected to construct the control charts, as shown in Table 6.1. Samples were collected approximately every half hour. Each value in the table is the average of three diameter measurements made at various positions inside the liner bore. The measurements are of the form 3.5XXX inch, and the table provides only the last three digits of the recorded value. As is evident from the table, in addition to collecting information on the inner diameter (ID) produced by the boring process, information on when the sample was collected from the process was also recorded. It is important to record data such as the time of production, operator name, operating conditions, material batch, and other measures of the "process state" because such measures are vital to diagnosing the root cause of signals manifested on the charts. In the absence of process state information, it is extremely difficult to "do the detective work" and determine what process changes produced signals evident on the charts. The data in Table 6.1 was used to construct initial control charts.

Table 6.1 Initial Set of Cylinder Liner Boring Process Data

Sample Number	Sample Collection time	1	2	3	4	5	$\overline{X}$	R
1	8:00 AM	205	202	204	207	205	204.6	5
2	8:25 AM	202	196	201	198	202	199.8	6
3	8:50 AM	201	202	199	197	196	199.0	6
4	9:15 AM	205	203	196	201	197	200.4	9
5	9:40 AM	199	196	201	200	195	198.2	6
6	10:05 AM	203	198	192	217	196	201.2	25
7	10:30 AM	202	202	198	203	202	201.4	5
8	10:55 AM	197	196	196	200	204	198.6	8
9	11:20 AM	199	200	204	196	202	200.2	8
10	11:45 AM	202	196	204	195	197	198.8	9
11	1:00 PM	205	204	202	208	204	204.6	6
12	1:25 PM	200	201	199	200	201	200.2	2
13	1:50 PM	205	196	201	197	198	199.4	9
14	2:15 PM	202	199	200	198	200	199.8	4
15	2:40 PM	200	200	201	205	201	201.4	5
16	3:05 PM	201	187	209	202	200	199.8	22
17	3:30 PM	202	202	204	198	203	201.8	6
18	3:55 PM	201	198	204	201	201	201.0	6
19	4:20 PM	207	206	194	197	201	201.0	13
20	4:45 PM	200	204	198	199	199	200.0	6
21	8:10 AM	203	200	204	199	200	201.2	5
22	8:35 AM	196	202	197	201	195	198.2	7
23	9:00 AM	197	199	203	200	196	199.0	7
24	9:25 AM	202	197	196	199	206	200.0	10
25	9:50 AM	202	198	201	199	197	199.4	5
26	10:15 AM	203	197	199	197	201	199.4	6
27	10:40 AM	204	203	199	199	197	200.4	7
28	11:05 AM	198	201	201	195	200	199.0	6
29	11:30 AM	201	196	197	204	200	199.6	8
30	11:55 AM	203	207	201	195	201	201.4	12
31	1:05 PM	206	206	199	200	203	202.8	7
32	1:30 PM	197	194	199	200	199	197.8	6
33	1:55 PM	200	201	200	197	200	199.6	4
34	2:20 PM	199	198	201	202	201	200.2	4
35	2:45 PM	200	204	197	197	199	199.4	7
36	3:10 PM	195	203	202	210	197	201.4	15
37	3:35 PM	205	199	202	201	200	201.4	6
38	4:00 PM	193	200	202	196	199	198.0	9
39	4:25 PM	195	199	199	198	198	197.8	4
40	4:50 PM	201	204	203	202	204	202.8	3

Determination of Control Limits

For each sample in Table 6.1, the sample mean, $\overline{X}$, and sample range, R, were calculated using Equations (6.1) and (6.2). The grand average, $\overline{\overline{X}}$, and average range, $\overline{R}$, were calculated using Equations (6.3) and (6.4).

$$\overline{\overline{X}} = 200.25$$

$$\overline{R} = 7.60$$

The control limits for the $\overline{X}$ and R charts were determined using Equations (6.10) and (6.11). These calculations are summarized below.

For the $\overline{X}$ chart,

$$UCL = \overline{\overline{X}} + A_2\overline{R} = 200.25 + (0.577)(7.60)$$

$$LCL = \overline{\overline{X}} - A_2\overline{R} = 200.25 - (0.577)(7.60)$$

$$UCL = 204.64, \qquad LCL = 195.86.$$

For the R chart,

$$UCL = D_4\overline{R} = (2.115)(7.60)$$

$$LCL = D_4\overline{R} = (0)(7.60)$$

$$UCL = 16.074, \qquad LCL = 0.0.$$

The appropriate values for A_2, D_3, and D_4 are obtained from Table A.2. Figure 6.27 shows the $\overline{X}$ and R charts based on the trial limits determined above.

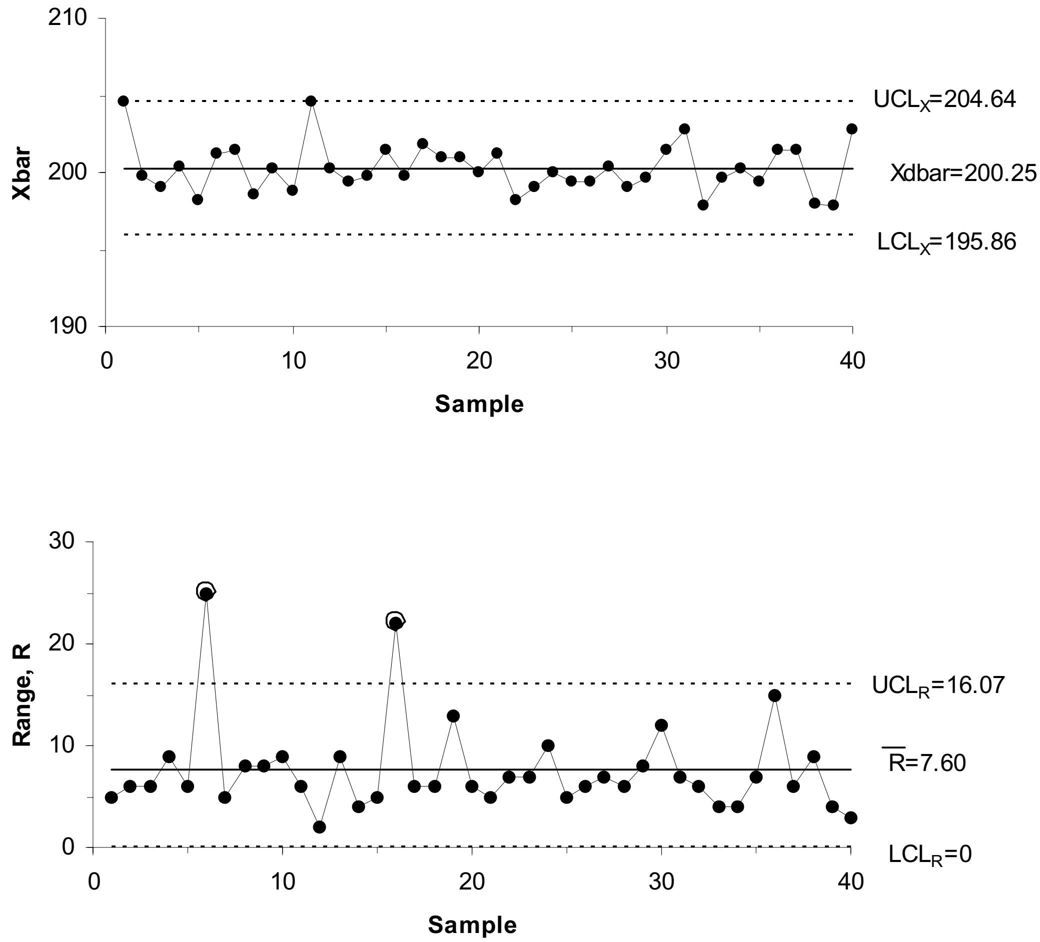


Figure 6.27 Initial Control Charts for Cylinder Liner Boring Process

<u>Interpretation of the Initial Charts</u>

Initially, as we examine the R chart, we see that two points exceed the upper control limit. From this, it may be concluded that there are special causes producing an increase in the process variability, at least at those points. The study team closely examined these points – samples 6 and 16 – to see if they could identify a reason (special cause) for these statistical signals. To focus discussions related to potential special cause(s), the previously constructed cause and effect diagram was employed. Discussions relative to the fishbone diagram suggested that the periodic replacement of the regular operator with a substitute was a strong candidate for the root cause of the R chart signals. The study team found the data that they had collected on the process state to be especially useful in checking this hypothesis. The records show that a substitute operator filled in for the regular operator during the mid-morning and mid-afternoon breaks (i.e., 10:00-10:15am and 3:00-3:15pm). An examination of the control chart data reveals that samples 6, 16, and 36 were produced while the substitute operator was in charge. It may be noted that only samples 6 and 16 manifested themselves as out-of-control conditions on the R chart. Nevertheless, if the substitute operator is indeed the root cause of the increased process variability, then, in fact, all three samples are subject to the same special cause. This data supports the hypothesis that the substitute operator is the root cause of the R chart signals.

The diagnosis step in the *Process of SPC* has identified the substitute operator as a strong candidate for the source of the R chart signals. Attention now turns to the formulation of a corrective action and implementation of said action. Discussion with line supervisors, and regular and substitute operators uncovered the fact that the substitute operator had received virtually no training in the operation of the cylinder boring machine. The substitute was inexperienced and had not been instructed on how to apply coolant, position the tool, etc. As a corrective action, the study team worked to ensure that the substitute was provided with training on proper machine operation. Of course, only by collecting additional samples from the process can it truly be determined that i) the substitute was the true root cause of the R chart signals, and ii) that the corrective action is effective in removing special causes from the process.

Control Charts after Addressing Operator Special Cause

Once the substitute operator had received training regarding proper operation of the boring machine, the study team collected an addition 40 samples from the liner boring process, as shown in Table 6.2. Data on the process conditions under which each sample was collected were again recorded.

Table 6.2 Cylinder Liner Boring Data after Operator Special Cause Removed

Sample Number	Sample Collection time	1	2	3	4	5	$\overline{X}$	R
41	8:10 AM	204	201	206	207	204	204.4	6
42	8:35 AM	200	204	203	205	202	202.8	5
43	9:00 AM	204	197	204	203	202	202.0	7
44	9:25 AM	202	203	194	195	200	198.8	9
45	9:50 AM	202	199	200	205	206	202.4	7
46	10:15 AM	197	199	201	199	198	198.8	4
47	10:40 AM	199	197	196	202	198	198.4	6
48	11:05 AM	192	200	198	201	200	198.2	9
49	11:30 AM	197	204	206	199	200	201.2	9
50	11:55 AM	197	199	197	198	197	197.6	2
51	1:05 PM	204	200	208	206	205	204.6	8
52	1:30 PM	203	200	200	203	202	201.6	3
53	1:55 PM	201	202	201	202	206	202.4	5
54	2:20 PM	200	194	197	201	202	198.8	8
55	2:45 PM	191	196	201	203	198	197.8	12
56	3:10 PM	198	203	199	199	197	199.2	6
57	3:35 PM	199	199	197	201	201	199.4	4
58	4:00 PM	198	194	198	201	194	197.0	7
59	4:25 PM	199	195	203	200	201	199.6	8
60	4:50 PM	196	198	197	201	196	197.6	5
61	8:15 AM	203	202	204	206	204	203.8	4
62	8:40 AM	208	204	199	200	205	203.2	9
63	9:05 AM	202	201	201	201	198	200.6	4

Sample Number	Sample Collection time	1	2	3	4	5	$\overline{X}$	R
64	9:30 AM	193	203	202	197	196	198.2	10
65	9:55 AM	199	201	205	198	201	200.8	7
66	10:20 AM	202	199	201	201	204	201.4	5
67	10:45 AM	200	201	200	201	202	200.8	2
68	11:10 AM	197	197	200	198	201	198.6	4
69	11:35 AM	205	198	201	200	196	200.0	9
70	11:59 AM	199	201	195	198	197	198.0	6
71	1:00 PM	207	207	203	204	205	205.2	4
72	1:25 PM	197	202	208	201	206	202.8	11
73	1:50 PM	199	205	205	199	200	201.6	6
74	2:15 PM	194	200	199	206	201	200.0	12
75	2:40 PM	197	198	201	196	201	198.6	5
76	3:05 PM	200	197	201	200	197	199.0	4
77	3:30 PM	201	198	195	201	201	199.2	6
78	3:55 PM	198	199	203	202	199	200.2	5
79	4:20 PM	201	199	193	197	196	197.2	8
80	4:45 PM	192	199	199	203	196	197.8	11

Determination of Control Limits

The centerlines and the control limit calculations for the charts based on the data in Table 6.2 are

$$\overline{\overline{X}} = 200.24$$
$$\overline{R} = 6.55$$

For the $\overline{X}$ chart,

$$UCL = \overline{\overline{X}} + A_2\overline{R} = 200.24 + (0.577)(6.55)$$
$$LCL = \overline{\overline{X}} - A_2\overline{R} = 200.24 - (0.577)(6.55)$$
$$UCL = 204.02, \qquad LCL = 196.46.$$

For the R chart,

$$UCL = D_4\overline{R} = (2.115)(6.55)$$
$$LCL = D_4\overline{R} = (0)(6.55)$$
$$UCL = 13.85, \qquad LCL = 0.0.$$

A quick examination of the centerlines based on the new data reveals that the value for $\overline{\overline{X}}$ is virtually unchanged, and that the value for $\overline{R}$ has decreased by approximately 15%. This suggests that the substitute versus regular operator issue did indeed influence the level of process variability. Figure 6.28 shows the $\overline{X}$ and R charts based on the data in Table 6.2 and the control limits determined above.

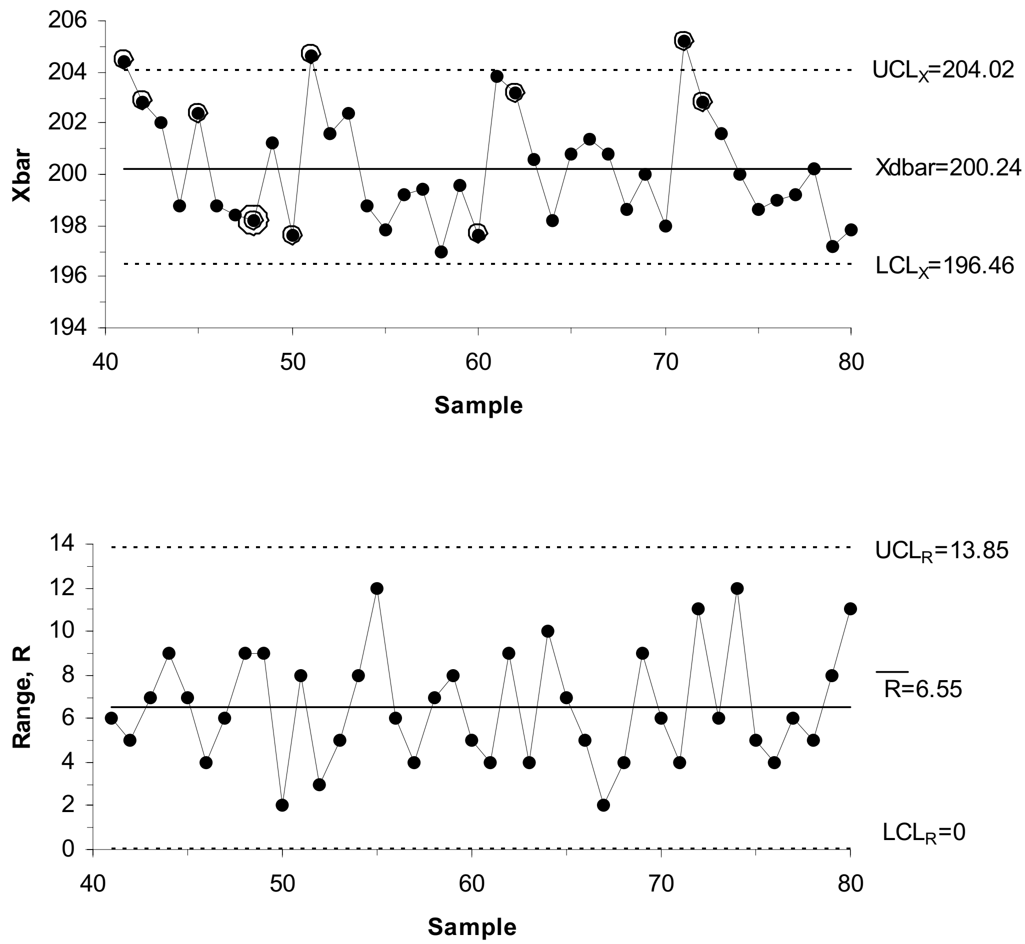


Figure 6.28 Control Charts for Boring Process after Operator Special Cause Removed

<u>Interpretation of the Control Charts</u>

Again, we first examine the R chart of Figure 6.28. No statistical signals are evident in the chart (none of the tests discussed previously have been violated). This confirms that the decisions made by the study team related to the substitute operator were correct. Clearly, efforts to better train the substitute operator were effective. The variability associated with the liner boring process is now in good statistical control. With the variability of the process stable, attention may now turn to an examination of the $\overline{X}$ chart. It is evident that there are a number of statistical signals on the $\overline{X}$ chart. The samples that represent signals and the tests for control chart interpretation that have been violated are shown in Table 6.3.

Table 6.3 $\overline{X}$ Chart Test Violations for Figure 6.28

Sample	Test(s) Violated
41	Point Above the Upper Control Limit
42	2 out of 3 Points in Zone A or Beyond Above the Mean
45	4 out of 5 Points in Zone B or Beyond Above the Mean
48	Run of 8 Points that Avoid Zone C
	4 out of 5 Points in Zone B or Beyond Below the Mean
50	4 out of 5 Points in Zone B or Beyond Below the Mean
51	Point Above the Upper Control Limit
60	2 out of 3 Points in Zone A or Beyond Below the Mean
62	2 out of 3 Points in Zone A or Beyond Above the Mean
71	Point Above the Upper Control Limit
72	2 out of 3 Points in Zone A or Beyond Above the Mean

The signals on the $\overline{X}$ chart indicate the presence of a special cause in the process. The root cause for the signals evident on the chart must now be identified. The study team must do the detective work, and diagnose the cause for the behavior reflected on the chart. With this in mind, the study team returned to the cause and effect diagram of Figure 6.26. During discussion of the diagram, it was suggested that machine warm up might be the cause of the behavior. In other words, parts produced early in the day (shortly after the machine is turned on at 8am) and right after lunch (the machine is shut down for the 12-1pm lunch hour) may deviate from the desired size. An examination of the $\overline{X}$ chart does reveal that $\overline{X}$ values produced during the 8-9am and 1-2pm time-periods are generally larger than many of the other $\overline{X}$ values.

To ascertain the extent to which the warm up is related to the liner ID, the study team prepared a scatter plot as shown in Figure 6.29. The $\overline{X}$ values for samples 41-80 were plotted as a function of the elapsed time since machine start-up. An examination of figure showed that the liner inner diameter (ID) appears to reduce in size as the machine warms up. The warm up period seems to last for about 60 to 90 minutes, after which the liner ID stabilizes at a value near 200.

With some evidence that machine warm up affects the liner ID, the study team brainstormed strategies to avoid/manage the warm up effect. The first strategy suggested was to change the operating parameters during the warm up period of the machine. The second strategy was to have the machine go through an accelerated warm up procedure and not produce any parts during this period. The final suggested approach to address the machine warm up issue was to leave the machine on over the lunch hour, and have a worker arrive at the facility early to start up the machine in the morning. This final strategy was selected for implementation owing to its simplicity and cost effectiveness. Of course, only by collecting additional samples from the process can it be determined whether the warm up issue is the true root cause, and whether the proposed corrective action will eliminate the instability in the process mean behavior displayed on the $\overline{X}$ chart.

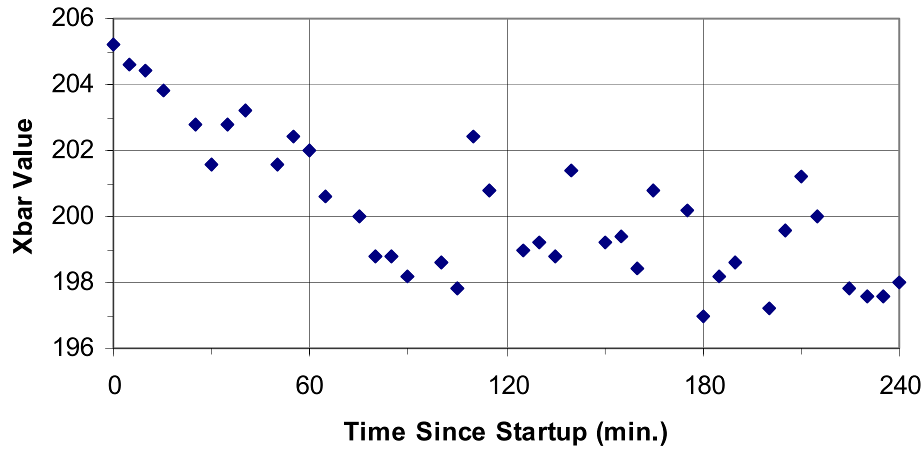


Figure 6.29 Scatter Plot for $\overline{X}$ versus Time since Startup

Control Charts after Addressing Warm Up Special Cause

Following the implementation of the boring machine operation scheme designed to address the machine warm up issue, 40 additional samples were collected from the process. This data is shown in Table 6.4.

Table 6.4 Cylinder Liner Boring Data after Warm Up Special Cause Removed

Sample Number	Sample Collection time	1	2	3	4	5	$\overline{X}$	R
81	8:05 AM	203	200	200	198	201	200.4	5
82	8:30 AM	195	203	203	193	199	198.6	10
83	8:55 AM	206	200	198	199	202	201.0	8
84	9:20 AM	197	202	200	199	202	200.0	5
85	9:45 AM	205	194	203	198	201	200.2	11
86	10:10 AM	207	202	204	198	204	203.0	9
87	10:35 AM	199	198	197	199	199	198.4	2
88	11:00 AM	201	206	202	203	198	202.0	8
89	11:25 AM	197	202	200	197	200	199.2	5
90	11:50 AM	197	199	197	202	193	197.6	9
91	1:00 PM	203	194	202	200	200	199.8	9
92	1:25 PM	201	202	201	197	202	200.6	5
93	1:50 PM	204	195	208	202	202	202.2	13
94	2:15 PM	199	202	196	201	195	198.6	7
95	2:40 PM	200	201	201	197	198	199.4	4
96	3:05 PM	200	200	203	201	201	201.0	3
97	3:30 PM	196	201	199	198	197	198.2	5
98	3:55 PM	197	202	198	196	197	198.0	6
99	4:20 PM	205	193	202	200	196	199.2	12
100	4:45 PM	203	200	199	204	202	201.6	5
101	8:00 AM	201	205	201	202	199	201.6	6

Sample Number	Sample Collection time	1	2	3	4	5	$\overline{X}$	R
102	8:25 AM	200	203	200	200	203	201.2	3
103	8:50 AM	201	203	199	200	201	200.8	4
104	9:15 AM	196	201	200	199	204	200.0	8
105	9:40 AM	199	199	201	203	201	200.6	4
106	10:05 AM	202	201	200	203	201	201.4	3
107	10:30 AM	197	201	199	196	199	198.4	5
108	10:55 AM	195	200	205	202	195	199.4	10
109	11:20 AM	201	202	200	195	201	199.8	7
110	11:45 AM	196	200	200	196	196	197.6	4
111	1:15 PM	206	200	197	196	198	199.4	10
112	1:40 PM	202	198	205	201	196	200.4	9
113	2:05 PM	200	198	198	200	197	198.6	3
114	2:30 PM	199	201	204	200	205	201.8	6
115	2:55 PM	201	201	198	197	198	199.0	4
116	3:20 PM	199	206	197	198	201	200.2	9
117	3:45 PM	201	197	191	200	201	198.0	10
118	4:10 PM	202	198	199	200	204	200.6	6
119	4:35 PM	201	203	204	197	202	201.4	7
120	5:00 PM	200	204	199	203	199	201.0	5

Determination of Control Limits

The centerlines and the control limit calculations for the charts based on the data in Table 6.4 are

$$\overline{\overline{X}} = 200.005$$
$$\overline{R} = 6.6$$

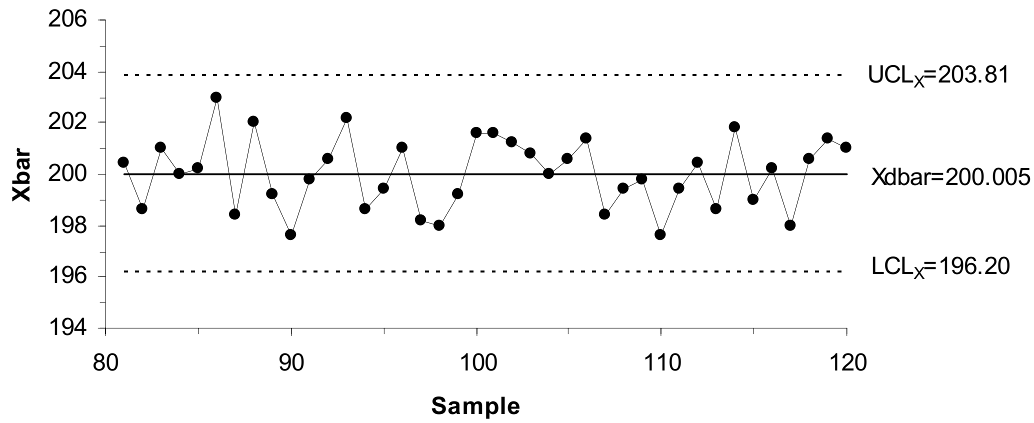
For the $\overline{\mathrm{X}}$ chart,

$$UCL = \overline{\overline{X}} + A_2\overline{R} = 200.005 + (0.577)(6.6)$$
$$LCL = \overline{\overline{X}} - A_2\overline{R} = 200.005 - (0.577)(6.6)$$
$$UCL = 203.81, \qquad LCL = 196.20.$$

For the R chart,

$$UCL = D_4\overline{R} = (2.115)(6.60)$$
$$LCL = D_4\overline{R} = (0)(6.60)$$
$$UCL = 13.96, \qquad LCL = 0.0.$$

Figure 6.30 shows the $\overline{\mathrm{X}}$ and R charts based on the data in Table 6.4 and the centerlines and control limits determined above.



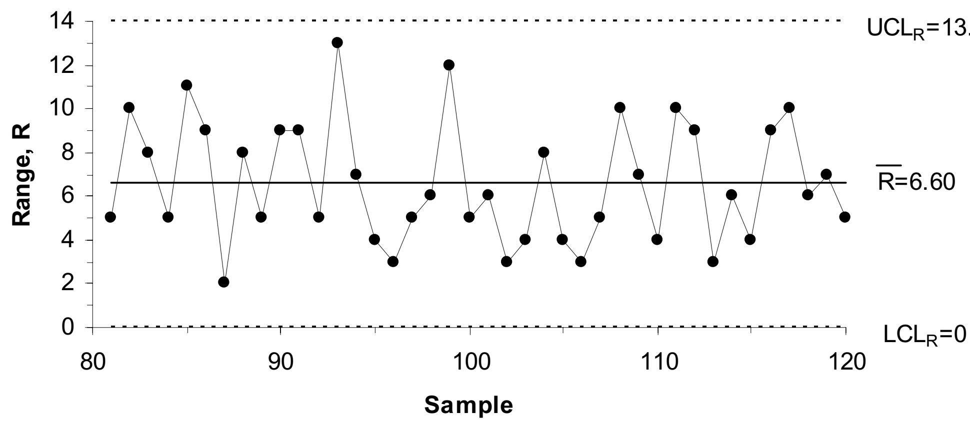


Figure 6.30 Control Charts for Liner Boring Process after Warm Up Cause Removed

Interpretation of the Control Charts

We again, first examine the R chart of Figure 6.30 and discern no statistical signals evident in the chart. This provides further evidence that the action taken to train the substitute operator was effective in removing a special cause. Attention then shifts to the $\overline{X}$ chart in the figure – no statistical signals are apparent. This confirms the effectiveness of the study team's corrective action on how to deal with machine warm up. Both charts demonstrate good statistical control, and the limits may be extended so that the study team can continue monitoring the process.