

Determining Process Capability of an Industrial Process in Laboratory Using Computer Aided Hardware and Software Tools

Abstract

Quality means suitability for use and it is inversely proportional to variability of product, service, people, processes, and environment. However, it is the dynamic state that is associated with each of the above and that meets or exceeds expectations of a customer. Quality improvement is therefore the progressive reduction of variability. The gradual reduction of process and product variability can be done by successive determination and removal of the causes responsible for the variability.

For a process industry, causes of product variability happen generally due to two reasons: (1) The process itself (2) Personnel that runs the process. Whatever the reasons are -- in order to rectify, they need to be determined. Since product and process variability can be described in statistical terms, determination of this in quantitative form using statistical methods will point us to the obvious direction of rectification. Process Capability is a measure of the uniformity of a process output. To estimate this, engineering and statistical analyses have to be launched. If a process is determined to be incapable of producing product within the required specification, Statistical Process Control (SPC) will not fix it or control it; however, it will exhibit that the process is incapable.

Often time's workers are blamed for their poor workmanship even when the process machinery is incapable of producing the product to meet the newer and tighter specification. In such situation management tend to think, what can go wrong with the process? The thing the workers need to do is to run the machinery and produce the product of required specification. It is like someone have given you felt-tip pen having one millimeter thick tip and tell you to make a 0.1 millimeter thick line on a paper. No matter how hard you try it is quite impossible to do so. Similarly if a process is incapable of meeting the standard, no matter how well one tries to control it, it will not produce the product of desired specification.

Determination of Process Capability is not hard, but it is frequently overlooked. It should be done first in any quality improvement program. It must be repeated on a periodic basis to ensure that the process stay fit to produce product of desired specification. If the process is incapable, then it is management's responsibility to either improve the process or accept poor quality product. The workers cannot be held responsible for failure to meet standards, if they do not have any means to achieve those specifications. Process Capability of a certain process is determined by collecting a set of data sample of an output product specification from the process that is under optimal control. Then calculating the upper and lower natural tolerance limits that is within 6σ (6-sigma, σ = standard deviation) spread in the distribution. In other words collected data samples should reveal that the product specification is within 6σ distribution limit. If μ (mu) is the target specification, then the 99.73% of the product produced by the process under

investigation must fall within $\mu + 3\sigma$ and $\mu - 3\sigma$. If so, the process is said to be capable. If it is not within these two limits, the process is not quite profitable and is a candidate for improvement.

This paper analyses and outlines the procedure for the determination of Process Capability of an industrial process in a laboratory using computer hardware and software tools.

In order to communicate the understanding of process capability determination to the students we have prepared a statistical software tool coupled with a digital micrometer that is interfaced with the software tool through USB port for collecting data samples. After collecting a set of data sample students will then use the statistical software tools to determine the process capability of the industrial process that produced the product. Data collected from an industrial process can also be entered manually in to the statistical software tools to determine the process capability, normal distribution charts, process capability ratio, X-bar, and R-charts. Determination of process capability and generating statistical charts using software and hardware tools are part of a process control course.

I. INTRODUCTION

Causes of product variability for a process industry happen generally due to two reasons:

(1) The process itself. (2) Personnel that runs the process. Whatever the reasons are, in order to rectify, they need to be determined. Since product and process variability can be described in statistical terms, determination of this in quantitative form using statistical methods will point us to the obvious direction of rectification. *Process Capability* is a measure of the uniformity of a process output. To estimate this, an engineering and statistical analysis has to be launched. If a process is determined to be incapable of producing product within the required specification, Statistical Process Control (SPC) will not fix it or control it, however it will exhibit that the process is incapable.

Often time's workers are blamed for their poor workmanship even when the process machinery is incapable of producing the product to meet the newer and tighter specification. In such situation management tend to think, what can go wrong with the process? The only thing the workers need to do is to run the machinery and produce the product of required specification. It is like someone has given you a felt-tip pen having one-millimeter thick tip and tell you to draw a 0.1 millimeter thick line on a paper. No matter how hard you try it is quite impossible to do so. Similarly if a process is incapable of meeting the standard, no matter how well one tries to control it, it will not produce the product of desired specification.

A. *What is Process Capability?*

Process Capability is a measure of the uniformity of a process output. Uniformity of the process output is measured by its variability. This variability in the output product is the relative deviation in the product specification and requirement. The variability in the output can happen due to two reasons: 1) The inherent variability of the process. 2) The special causes.

B. Normalized Expression

Process Capability Ratio (PCR), or, C_p , is a measure of the ability of the process to manufacture product that meets the specification. It is a normalized factor that is a measure of the rejects from the process. In other words it is the rate of process output fallout. If the ratio is larger than equal to unity the rate of process reject is considered to be normal. If on other hand the ratio is less than unity the rate of process reject is considered to be abnormal. As PCR increases from unity, process rejects decreases. Also, as PCR decreases from unity, the process rejects increases. Figure 1 show how higher values of Process Capability Ratio, C_p , decreases process rejects. This means larger the PCR number from unity better the process. The *Process Capability Ratio (PCR)* can be expressed as:

$$PCR = (USL-LSL)/ 6\sigma \quad (1)$$

Where:

- σ = Standard Deviation
- USL = Upper Specification Limit
- LSL = Lower Specification Limit

Since the actual value of the standard deviation is not known at the beginning, estimated value of the ratio can be calculated by using the estimated value of the standard deviation, $\hat{\sigma}$ (sigma-hat). Thus, to find the estimated value of the Process Capability Ratio, PCR-hat, use the following relationship.

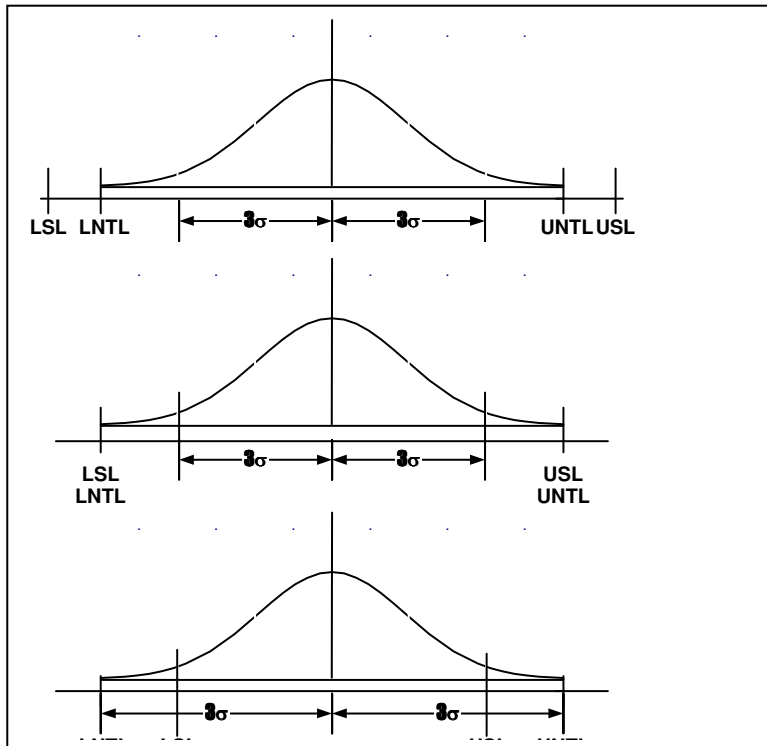


Figure 1: Effect of PCR on Process Rejects

$$\text{PCR-hat} = (\text{USL}-\text{LSL})/ 6 \hat{\sigma} \quad (2)$$

C. Process Capability Study

Process Capability analysis is the central theme of quality engineering program. It is studied by measuring the functional parameter on the product of a process under tight control. For example, a tree is judged by its fruit, flower, or other pertinent characteristics that it outputs. Statistical Process Control (SPC) is a primary tool for this analysis. Control charts and other statistical techniques are used to determine the natural capability of a process. Control charts are tools for studying of process capability in real time.

II. OUTPUT VARIABILITY

A. Types of Output Variability

Variability in the process is a measure of the uniformity of the output. The non-uniformity of the output can happen generally due to two reasons:

1) The natural or intrinsic process variability that is equal to 6σ (σ = standard deviation). This means that the output of a stable, in control, process can be expected to diverge within a range of $\pm 3\sigma$ from its mean. This much of deviation is inherent to the process or also called the variability due to random causes. For a stable and normally distributed process 99.73% of the output product specification will lie within this $\pm 3\sigma$ range from its population mean, μ . The process output mean, μ is estimated from \bar{X} , which in turn is calculated from the collected data samples. Mean value of a data sample, \bar{X} , the mean value of all the data samples, $\bar{\bar{X}}$, Range, R, and the average of the Range, \bar{R} are calculated using the following formulas:

$$\bar{X} = \frac{1}{n} \sum_{i=1}^n X_i = \frac{X_1 + X_2 + X_3 + \dots + X_n}{n} \quad (3)$$

$$\bar{\bar{X}} = \frac{1}{k} \sum_{j=1}^k \bar{X}_j = \frac{\bar{X}_1 + \bar{X}_2 + \bar{X}_3 + \dots + \bar{X}_k}{k} \quad (4)$$

$$R = (X_{\max} - X_{\min}) \quad (5)$$

$$\bar{R} = \frac{1}{k} \sum_{j=1}^k R_j = \frac{R_1 + R_2 + \dots + R_k}{k} \quad (6)$$

Also the sample mean, μ , will fall between two conforming limits. These limits can be expressed as:

$$X_L - Z_{\alpha/2} \frac{\sigma}{\sqrt{n}} \leq \mu \leq X_U + Z_{\alpha/2} \frac{\sigma}{\sqrt{n}} \quad (7)$$

Where:

X_L and X_U = Lower and Upper Specification limit

σ = Standard Deviation

$Z_{\alpha/2}$ = Percentage point of Normal Distribution, Customarily it is 3.

2) The variability in the output product specification can also happen due to assignable causes. When data points fall outside either lower or upper control limits or when the data points show periodic pattern, there are identifiable causes for the variation.

B. Variability due to Natural Causes

In a production process, the output product specification of all the item will not be on the mean (\bar{x}). Regardless of how well the system was designed, carefully controlled, and maintained, there is a certain amount of natural variability in the process. This random variability of the process is the cumulative effect of many small, essentially unavoidable causes. This natural variability causes a $\pm 3\sigma$ deviation in output product specification. This process variability cannot be eliminated completely. This natural variability can only be minimized.

C. Variability due to Assignable Causes

Another kind of variability may present in the output product due to some unusual causes. This kind of variability in the process output has three sources: mal-adjusted machinery, operator error, and/or defective raw material. This variability is generally large compared to the variability that happens due to natural or random causes. One can assign valid causes to these kinds of variability. The effect of this variability is felt at the output in the form of a shift in the process average, μ , from the target average, μ_0 , and also in the form of a larger standard deviation, σ_1 . That is $\sigma_1 > \sigma_0$. Where σ_0 is the desired standard deviation of the output under well-controlled condition. Often variability due to assignable causes put the process output to an unacceptable level. The shift in process average, μ and increased value of standard deviation, σ , both put higher portion of the process output outside the desired specification limits. This decreases the quality of some of the output product. If this condition persists it will increase the process rejects and thus will generate unmarketable product.

Figure 2 shows the three conditions. The top curve describes a process where the standard deviation, σ_0 and process mean, μ_0 both have in-control values. The most of the process output fall within the upper and lower specification limit. The middle curve describes the process where process mean has shifted from μ_0 to μ_1 . This shift caused some portion of the output to fall outside the upper specification. This means there are some rejects. The bottom curve describes that the standard deviation σ_0 has changed from σ_0 to σ_1 . This increase in standard deviation, σ , also caused some portion of the output to fall outside the upper and lower specification limit.

D. Reduction of Variability by Quality Engineering Program

To obtain greater and sustained uniformity in the specification of a product, a quality engineering program need to be implemented.

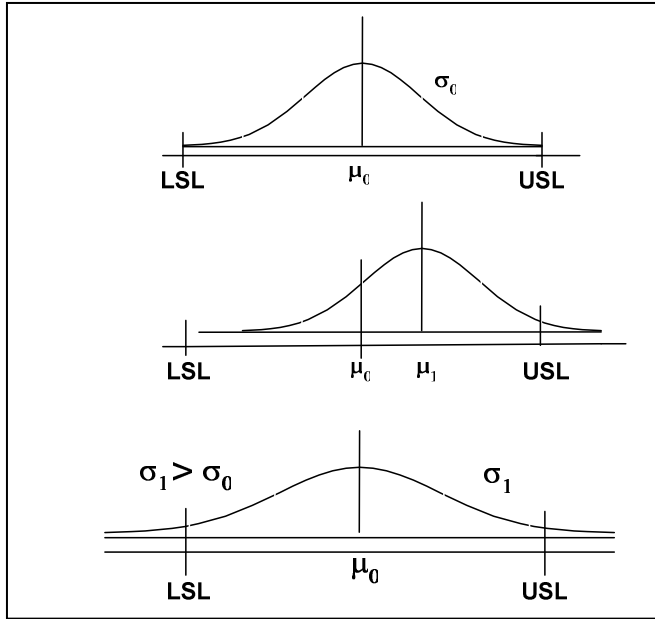


Figure 2: Effect of Standard Deviation and Process Average Shift

The primary objective of a quality engineering effort is to gradually reduce the variability in the key quality characteristics of the product by a systematic process. Figure 3 shows the systematic reduction of variability in the output product specification. The first curve to the left was drawn based on the data samples collected before the application of quality engineering program.

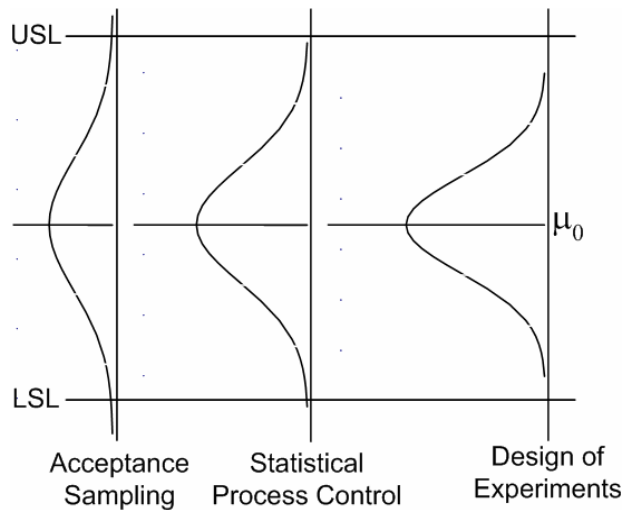


Figure 3: Systematic Reduction of Output Variability

It shows that some portion of the output product that came out of the process does not meet the given specification. Thus there is process fallout. The second curve shows that by applying the Statistical Process Control (SPC) techniques, variability of the process output has reduced and most of the process output falls within the upper and lower specification limit. The third curve to the right shows that further reduction of the process variability is achieved through design of

experiments. Design of experiment is a systematic statistical approach to optimize the controllable input factors to achieve reduced variability of the output.

E. Monitoring Causes of Variability

The main objective of Statistical Process Control (SPC) is to detect the cause of the output shift quickly and accurately. If one tries to investigate the cause of output variability by studying the process average, μ and standard deviation, σ , it will unnecessarily produce products that are nonconforming and in turn are unmarketable. Best way to find the cause is to study the control charts. Control charts are typical quality characteristics of the output plotted in real-time frame. The horizontal line at the centerline represents the instantaneous average, $\bar{\bar{x}}$ of the samples. The Upper Control Limit (UCL) and the Lower Control Limit (LCL) are the two calculated values of the output limits. If the specification of the sample points fall within these two limits, the process is considered to be under control. Products produced over this period are conforming. If, however, in \bar{x} control chart some data points fall outside the control limits, causes can be attributed to each of the data points that fall outside the control limits. Process supervisor can study the control charts on a continuous basis. He/she should look for the following behavior in the control charts:

- 1) Data points that are outside the UCL and LCL
- 2) Identifiable unusual trend in \bar{x} or R charts or both
- 3) Data points are distributed about the $\bar{\bar{x}}$ line in such way that shows periodic nature about the mean.

All the above conditions indicate that there are some assignable causes for each of those problems.

III. PROCESS CAPABILITY ANALYSIS

A thorough knowledge of the manufacturing process coupled with good understanding about the control charts is necessary to analyze the process capability of an industrial system. Let us analyze the following two sets of \bar{X} and R charts. In Figure 4a the \bar{X} chart looks quite stable. The individual points in the \bar{X} chart appear to be randomly distributed about the $\bar{\bar{x}}$ line. On the other hand, in Figure 4b, Range values in R chart is oscillating about the range mean, \bar{R} -line. Although no data points exceed the UCL and LCL, it appears to be something is obviously wrong. This oscillating behavior of R chart clearly indicates that range has increased to an undesirable level. This also means that the individual output products are too much different from each other. In other words non-uniformity of the output has increased to an unwanted level. The problem is not visible from the \bar{X} chart, because the average of 8 and 12 is 10 and also average of 0 and 20 is 10.

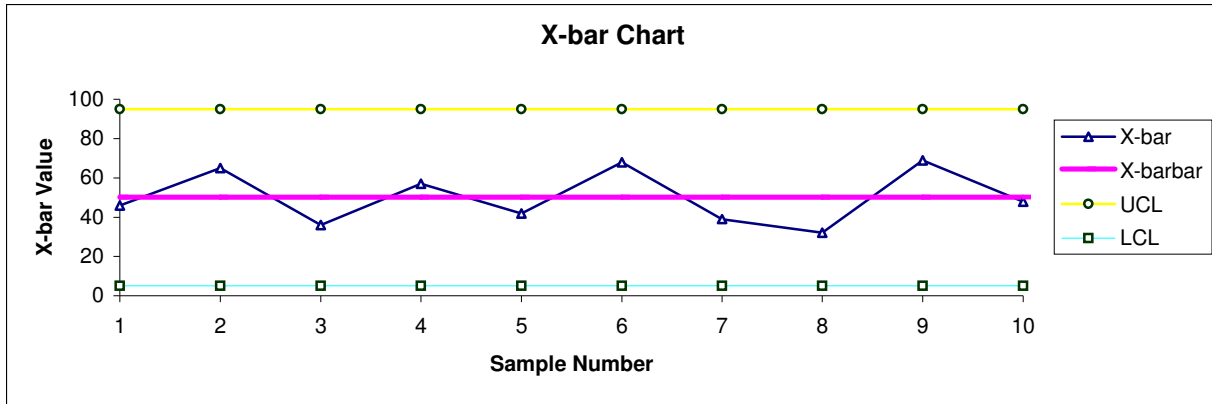


Figure 4a

In Figure 5 the R chart looks stable and the points are randomly distributed about the \bar{R} line. \bar{X} chart appears to be unstable. Some of the individual data points are either on the control limits or very close to the limits. A typical reason for such a distribution is two different operators on the same machine. This may happen due to shift change. Providing uniformity in the operator training can reduce this kind of problem.

IV. DETERMINATION OF CONTROL LIMITS

Specifying the control limits is one of the critical decisions that must be made in designing the control charts. By moving the control limits further from the centerline, \bar{X} , decreases probability of false alarm but increases the possibility of not been able to detect the real out-of-control condition. On the other hand, by moving the control limits closer to the centerline will increase the probability of false alarm but decreases the possibility of not been able to detect the out-of-control condition. Since for normal distribution pattern $\pm 3\sigma$ spread encompasses 99.73% of the of the material, many company in the United States determines the upper and lower control limits as a multiple of standard deviation, σ . Thus for most companies the two control limits are:

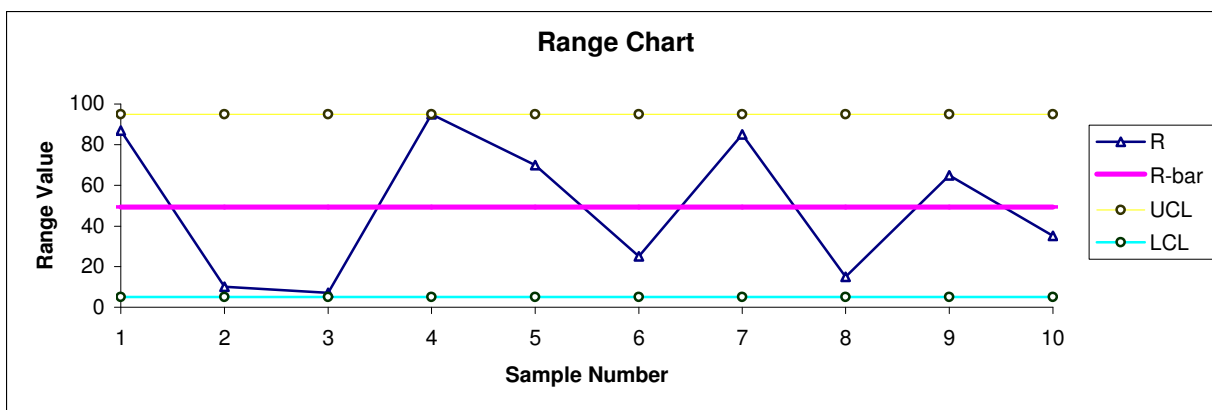


Figure 4b

Figure 4: Process Capability Analysis Using Control Charts, Case #1

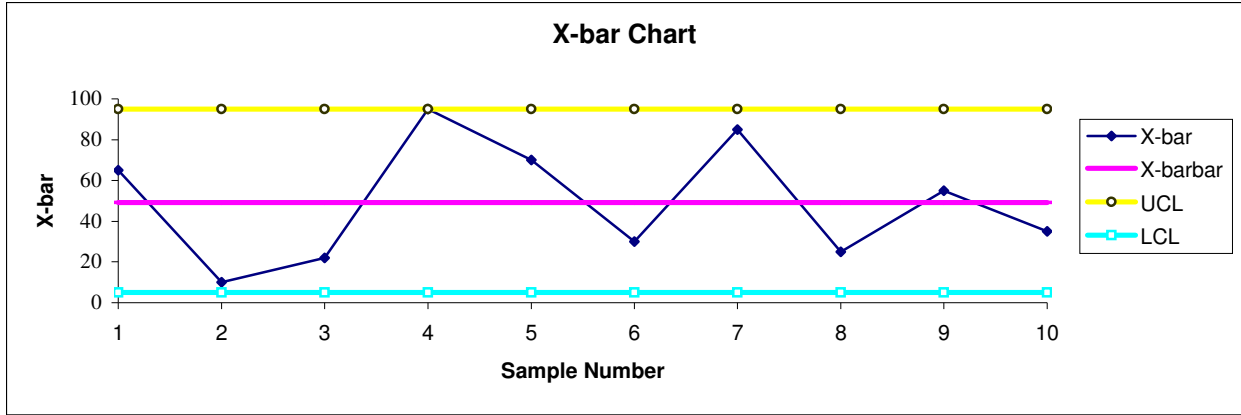


Figure 5a

$$UCL = \bar{\bar{X}} + 3\sigma \quad (8)$$

$$LCL = \bar{\bar{X}} - 3\sigma \quad (9)$$

However, some companies have higher quality control standard than others and may use values other than $\pm 3\sigma$ for their control limits. Also there are production processes that require two other kinds of limits and they are Upper Warning Limit (UWL) and Lower Warning Limit (LWL). These limits are generally set at 2σ point. They are expressed as:

$$UWL = \bar{\bar{X}} + 2\sigma \quad (10)$$

$$LWL = \bar{\bar{X}} - 2\sigma \quad (11)$$

In a real industrial setting, the actual values of μ and σ are not known at the beginning. So they must be estimated from the primary group of samples taken when the process was thought to be in control. They should be based on at least 25 to 30 samples having sample size of 4 to 6. They are calculated using the following formulas:

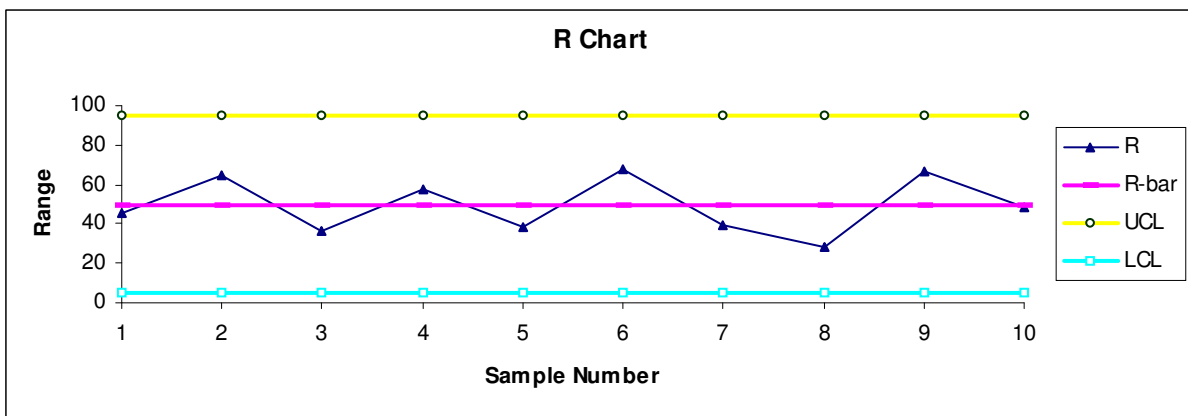


Figure 5b

Figure 5: Process Capability Analysis Using Control Charts, Case #2

$$\text{Standard Deviation, } \sigma = \frac{\bar{R}}{d_2} \quad (12)$$

Control Limits for \bar{X} Charts:

$$UCL = \bar{\bar{X}} + A_2 \bar{R} \quad UCL = \bar{\bar{X}} + \frac{3}{d_2 \sqrt{n}} \bar{R} \quad (13a)$$

$$LCL = \bar{\bar{X}} - A_2 \bar{R} \quad LCL = \bar{\bar{X}} - \frac{3}{d_2 \sqrt{n}} \bar{R} \quad (13b)$$

Control Limits for R Charts:

$$UCL = D_4 \bar{R} \quad UCL = \bar{R} + 3\hat{\sigma}_R = \bar{R} + 3d_3 \frac{\bar{R}}{d_2} \quad (14a)$$

$$LCL = D_3 \bar{R} \quad UCL = \bar{R} - 3\hat{\sigma}_R = \bar{R} - 3d_3 \frac{\bar{R}}{d_2} \quad (14b)$$

UCL and LCL calculated in this way are treated as trial control limits, UTCL and LTCL, for \bar{X} and R control charts. After running the process \bar{X} and R charts are constructed using another set of collected data. These data are compared against the trial control limits. If none of the data points fall outside the trial control limits then these control limits are suitable for controlling the future production and they become the established control limit for the process. If, however, any of the data points fall outside the trial control limits in \bar{X} and R charts then the trial control limit must be revised. First, for each of the \bar{X} and R-value that are outside the control limits are analyzed for assignable causes. If an assignable cause is found, it must be removed from the process and the data point is discarded and trial control limits are recalculated based only on the remaining data. This new control limits are tighter than the previous limits. This process should be continued until all \bar{X} and R-values are within the trial control limits. At that point, the trial limits are adopted for future control.

V. ESTIMATING PROCESS CAPABILITY

The \bar{X} and R charts provide information about the performance or capability of the process in real time frame. These charts work like a window into the process and provide a quantitative measure of the product quality. One must at least go through the following steps to determine the process capability.

1) After all the assignable causes have been eliminated from the process as far as it is practical, check to see that the process is stable and under tight control, collect at least 25 to 50 samples, 3 to 6 reading per sample.

2) Record the data set in a time ordered sequence. After calculating \bar{X} 's, R's, $\bar{\bar{X}}$'s, and $\bar{\bar{R}}$'s. estimate the values of Upper Control Limit ($UCL = \bar{\bar{X}} + A_2 \bar{\bar{R}}$) and Lower Control Limit ($LCL = \bar{\bar{X}} - A_2 \bar{\bar{R}}$) for \bar{X} chart and Upper Control Limit ($UCL = D_4 \bar{\bar{R}}$) and Lower Control Limit ($LCL = D_3 \bar{\bar{R}}$) for R charts. A_2 , D_3 , and D_4 are control charts constants. The estimated value of these UCL and LCL are little tighter than the $\pm 3\sigma$ values. Due to the tighter control limit, it may appear that the process is out of control. However, this is necessary for some process to achieve the target rapidly.

3) The \bar{X} and \bar{R} charts need to be analyzed to verify that the data points are randomly distributed about the \bar{X} and \bar{R} line and within the UCL and LCL control limits.

4) Standard deviation, σ needs to be estimated (estimated value of σ is denoted by $\hat{\sigma}$) by using the following formula:

$$\hat{\sigma} = \frac{\bar{R}}{d_2} \quad (15)$$

For greater accuracy $\hat{\sigma}$ can also be estimated by using the following formula and the initial set of data.

$$\hat{\sigma} = \sqrt{\frac{n \sum X_i^2 - (\sum X_i)^2}{n(n-1)}} \quad (16)$$

Where: $\hat{\sigma}$ = Estimated value of the standard deviation

n = total number of reading taken and not number of samples

\sum = Mathematical symbol which means to sum all of the following

X_i^2 = Square of every reading taken

$(\sum X_i)^2$ = Sum of all the reading values added together and then squared.

5) Once the reasonable value of σ has been estimated, Process Capability is found by comparing the target specification limits with the Upper Natural Tolerance Limit, UNTL = $\mu + 3\sigma$ and Lower Natural Tolerance Limit, LNLT = $\mu - 3\sigma$ calculated from the collected process data.

6) The percentage of the product that will be within the target limits can be calculated from the cumulative normal distribution defined by the following formula.

$$F(a) = \int_{-\infty}^a \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2} dx \quad (17)$$

Since it is difficult to evaluate this integral, easier approach to this problem is to find the positive and negative values of Z and then find the percentage of conformity from the cumulative standard normal distribution table or simply called Z-charts. The positive and negative values of Z can be found from the following two formulas:

$$Z^+ = \frac{X_U - \mu}{\sigma} \quad (18a)$$

$$Z^- = \frac{X_L - \mu}{\sigma} \quad (18b)$$

Where:

X_U = Upper Specification Limit

X_L = Lower Specification Limit

μ = Process average, estimated from \bar{X}

σ = Standard Deviation, calculated from the process data

VI. COMPUTER AIDED HARDWARE AND SOFTWARE TOOLS USED FOR THE DETERMINATION OF PROCESS CAPABILITY

Computer aided hardware tools used for precision measurement and computer communication are performed by a Mitutoyo digital micrometer having USB interface. Data logging, analysis and determination of process capability are completed by software tools called *Statit Express QC* produced by *Statware, Inc.* Data can also be entered manually in to *Statit Express QC* software tools through keyboard. In this case every time a measurement is made by the micrometer, an entry in to data table is completed by pressing a button on the micrometer. Once the data is entered in to the table, *Statit Express QC* software tools are used for the desired analysis. Charts in Figure 6, 7, 8 and 9 are developed by the software tools. Once we entered the desired value of the *Upper and Lower Specification Limit (USL and LCL)* and the most desirable specification, μ the software tools generated outputs as shown in Figure 7 and 8. The chart includes many analytical figures for the data entered such as standard deviation, $\pm 3\sigma$ values, process capability index, C_p and percentage of product above and below the specification. The hardware and the software tools are very easy to use and also inexpensive. We have seven setups for our laboratory.

VII. DETERMINING PROCESS CAPABILITY OF AN INDUSTRIAL SYSTEM IN LABORATORY

To understand the process capability determination procedure in a laboratory environment, printed circuit board (PCB) samples of one manufacturer are gathered by each student group. Students are also instructed about how samples should be collected from a manufacturing process. In addition to PCB samples each group of student has a digital micrometer whose output is directly connected to a computer station. Each computer has software called *Statit Express QC*. Although, each student knows how to calculate the process capability using formulas and steps provided in this paper, software like *Statit Express QC* is a fast and easy way to calculate the process capability and other statistical variable with a few key strokes. It also makes the normal distribution curve and other curves plots easier than ever. Being able to use a software tools students have more time to play with the numbers other than engaging in cumbersome and prone to error calculation using calculators.

Data shown in Table I are thickness of twenty five samples (sample length = 3) of bare PCB that are entered directly in to a computer using micrometer setup by a group of students. From the manufacturer data the target PCB thickness is 63 mil (1mil = $1/1000$ inch). Since the PCBs used for Table I data are gather from a PCB manufacturer, the analysis is based on the fact that the process was under optimal control while these boards were produced. This analysis will illustrate the capability of the process that manufactured the boards. If a hypothetical range of the desired thickness (USL and LSL) is set one can analyze process capability and percentage of conforming from the entered data. For this paper only \bar{X} 's, $\bar{\bar{X}}$'s, R's, \bar{R} 's, are calculated and tabulated in Table II. Estimated value of the UCL, LCL, σ , and percentage of conforming output for the given values of thicknesses are also calculated using Z-charts and tabulated in Table II. Figure 6 shows \bar{X} and R control charts drawn from the data set using a statistical software tools. The control charts reveal that the PCB manufacturing process is under proper control. However, the purpose

of this exercise is to determine the Process Capability, C_p of the PCB manufacturing facility. C_p of the process indicates the percentage of the PCB produced by the manufacturing process that will be below and above the desired thickness limit. If the thickness limit specified by the electronic product manufacturing industry (PCB buyer) is narrower than 6σ , C_p will be less than unity and more than 0.27% of the PCB thickness will be nonconforming and in turn will be rejected. If, however, the specification limit is same the natural variability, $\pm 3\sigma$, of the process, only 0.27% of the material will be rejected or in other word C_p will be unity.

VIII. DISCUSSION OF RESULTS

\bar{X} and R Charts in Figure 6, Process Capability chart along with C_p and product beyond specification data in Figure 7, 8 and 9 all are computed using Statit Express QC Software tool. Statit Express QC is a SPC software product produced by Statware, Inc., Analyzing the process capability charts in Figure 7, 8 and 9, for various values of specification limits. It is interesting to notice that as the desired thickness of the PCBs used by the electronic product manufacturer becomes narrower, C_p gets smaller and total parts beyond specification or rejects becomes greater. If the reject goes beyond 5% to 6%, PCB bare board manufacturer must raise their price as an immediate measure to make profit. However, as a long term solution the industry must improve their machinery that produces PCBs with lower thickness tolerance.

In Figure 7 for a given thickness limits of $USL=64.8129$ mil and $LSL=61.0511$ mil, Process Capability has been computed to be equal to $C_p = 1$ and the product beyond specification limit is 0.27% (estimated). This also indicates that 97.73% PCBs have conforming thickness. This demonstrates that PCBs produced by the current machinery of the manufacturing facility is up-to-date with the current thickness requirements by electronic product manufacturer. This 0.27% (or, approximately 3 out of 1000) rejection rate is quite normal and falls under the category of natural deviation. These limits are for $\pm 3\sigma$ points.

However, if the thickness limits get too tight as in Figure 8, at $USL= 63.559$ mil and $LSL= 62.3050$ mil, C_p becomes 0.333 and 31.73% (actual) or 31.58% (estimated) of the PCB thicknesses will be beyond the specified limit or will not be acceptable by the electronic product manufacturing industry. This means that 68.27% (estimated) of the PCB thicknesses would be conforming. If, however, thickness is moderately tightened as shown in Figure 9 ($USL =64.186$ mil and $LSL = 61.678$), that is more natural course of the demand, C_p will become 0.667 and 7.89% (actual) or 4.55% (estimated) of the PCB thicknesses will be beyond the specified limit or will not be acceptable by the electronic product manufacturing industry. These later two thickness limits are $\pm 1\sigma$ and $\pm 2\sigma$ points respectively. These values $\pm 1\sigma$, $\pm 2\sigma$, or $\pm 3\sigma$ do not have to be rounded number like 1, 2, or 3. They can also be $\pm 1.75\sigma$ and $\pm 2.5\sigma$ and can be used for the determination of process capability and percentage nonconforming.

TABLE I			
Bare PCB thickness in Mils (1Mil = 1/1000 inch)			
PCB samples were collected from a manufacturer			
Sample#	Thickness in Mil		
1	62.90	63.60	64.00
2	63.00	63.10	62.20
3	62.20	62.80	63.10
4	63.30	63.40	63.00
5	63.10	61.90	62.80
6	63.00	61.30	62.90
7	63.40	63.00	63.90
8	62.50	62.80	62.60
9	62.20	62.30	63.30
10	63.10	63.10	63.30
11	63.50	63.00	63.80
12	62.30	63.00	63.00
13	63.50	64.00	63.00
14	64.50	63.10	61.90
15	64.40	63.20	61.60
16	62.70	63.00	62.30
17	63.10	63.00	63.00
18	62.60	63.60	63.10
19	62.90	64.00	63.50
20	62.90	62.80	62.50
21	61.60	61.50	62.50
22	61.90	63.00	63.20
23	63.00	63.50	62.90
24	63.50	62.30	62.90
25	62.30	62.90	63.00

TABLE II

Sample#	X-bar	Range	X-barbar	62.93200				
1	63.50	1.10						
2	62.77	0.90	R-bar	0.98800				
3	62.70	0.90						
4	63.23	0.40	X-UCL	63.93976				
5	62.60	1.20						
6	62.40	1.70	X-LCL	61.92424				
7	63.43	0.90						
8	62.63	0.30	R-UCL	2.53916				
9	62.60	1.10						
10	63.17	0.20	R-LCL	0.00000				
11	63.43	0.80						
12	62.77	0.70	Sigma	0.62698	Based on the entire population			
13	63.50	1.00						
14	63.17	2.60	Sigma-hat	0.5846154	Estimated value			
15	63.07	2.80						
16	62.67	0.70			% Conforming outputs			
17	63.03	0.10						
18	63.10	1.00	USP	LSP	P-Val	N-Val	% Conf	
19	63.47	1.10	64.8129	61.0511	0.9987	0.0228	97.5899	±3 σ
20	62.73	0.40	64.1860	61.6780	0.9772	0.0228	95.4498	±2σ
21	61.87	1.00	63.5590	62.3050	0.8413	0.1587	68.2686	±1σ
22	62.70	1.30	64.0000	62.0000	0.9558	0.0686	88.7177	
23	63.13	0.60	63.5000	62.5000	0.8175	0.2454	57.2104	
24	62.90	1.20	63.2500	62.2500	0.6940	0.1384	55.5636	
25	62.73	0.70	64.8140	61.0520	0.9987	0.0014	99.7301	

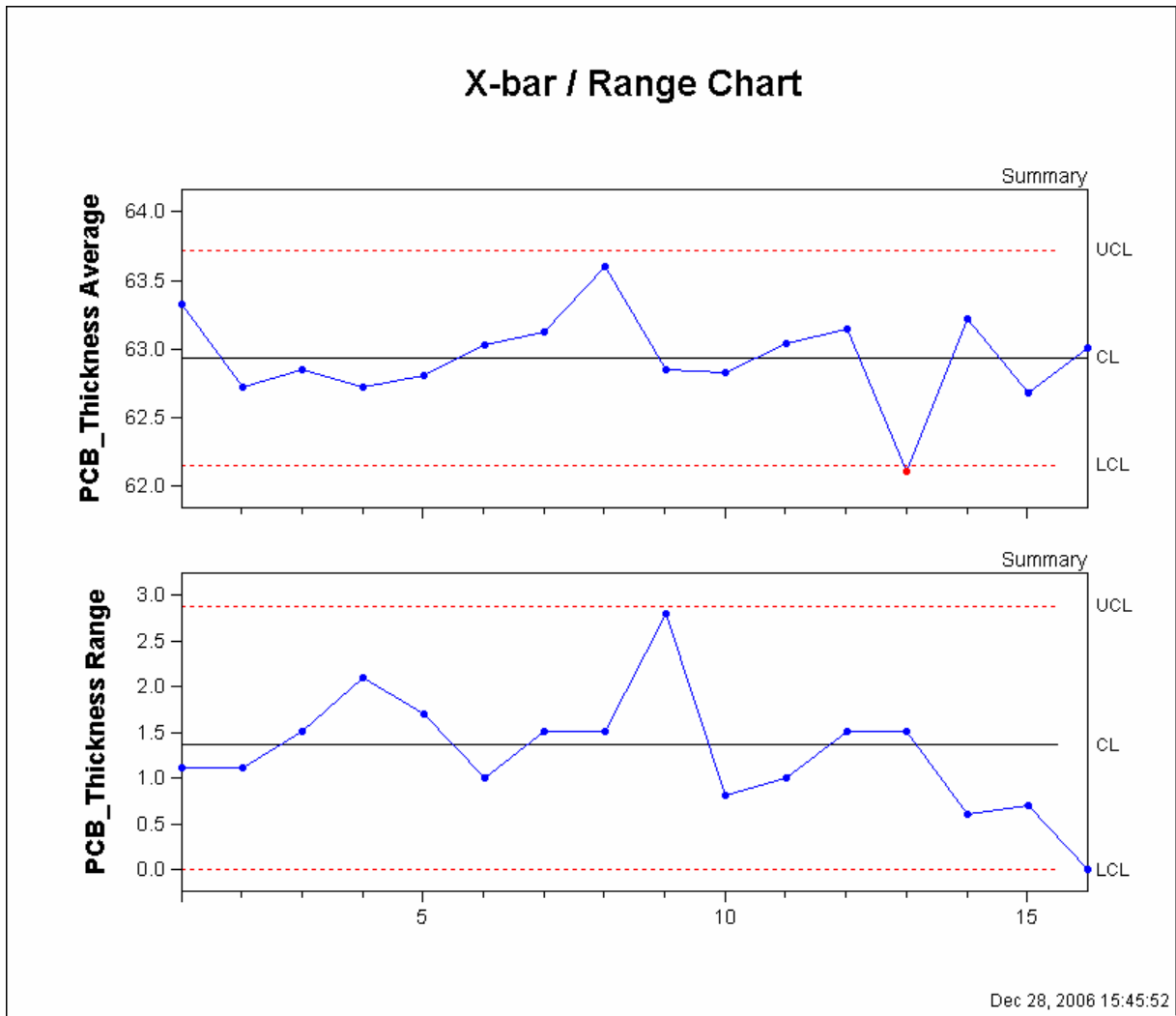


Figure 6: X-bar and R Chart drawn from the Table I PCB thickness data set

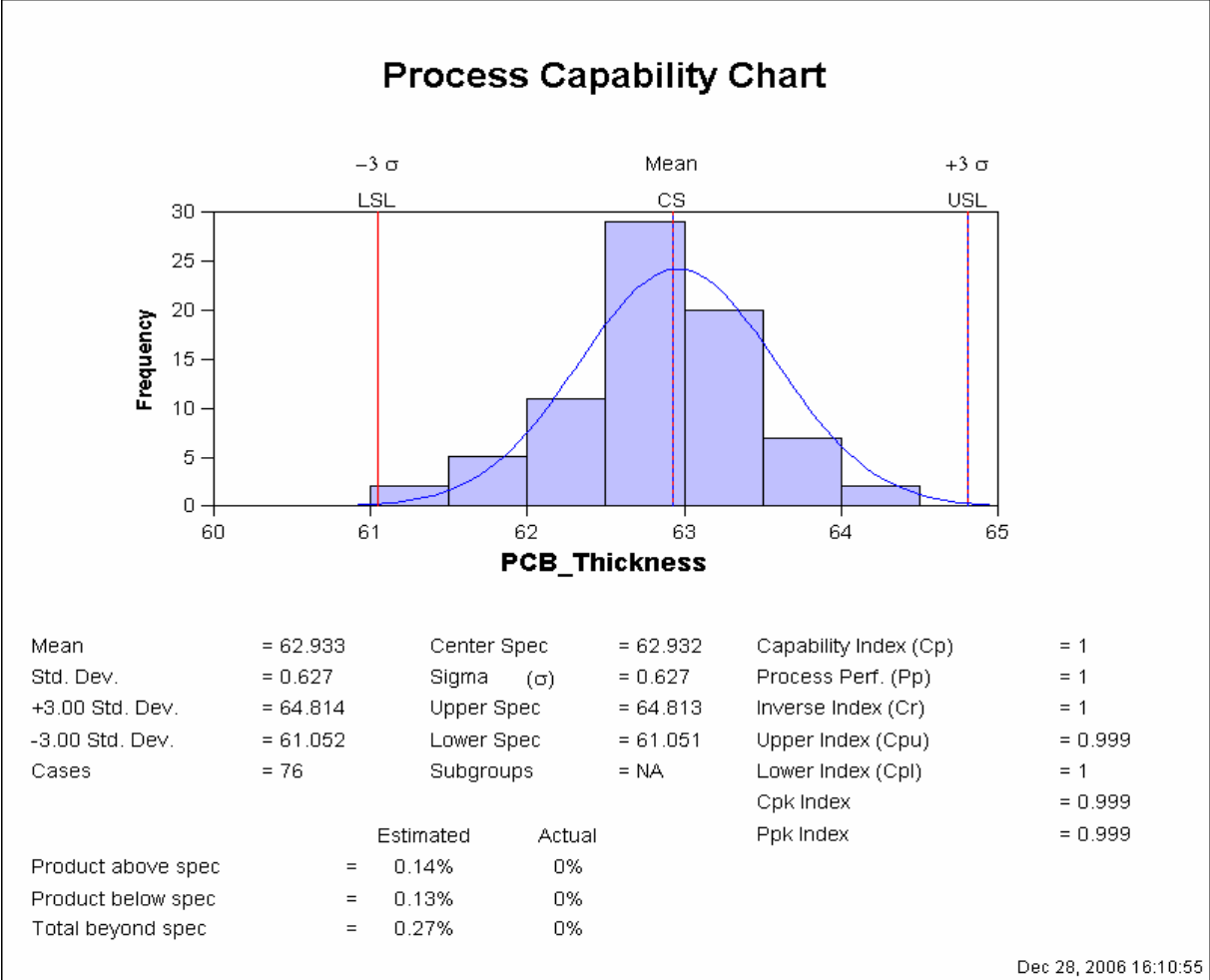


Figure 7: Process capability chart for USL = 64.8129 mil & LSL= 61.0511 mil, $\pm 3\sigma$ point

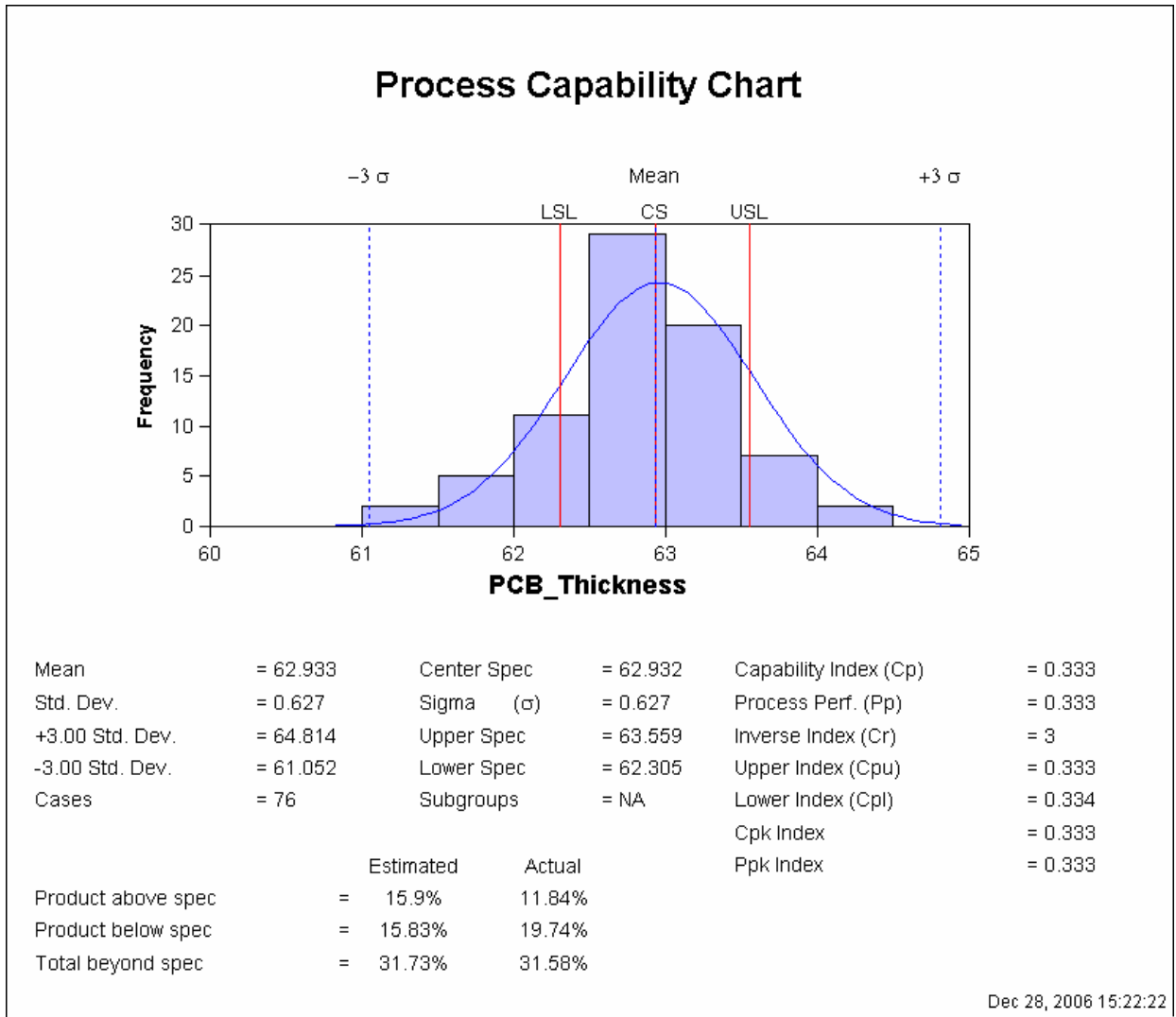


Figure 8: Process capability chart for USL = 63.559 mil & LSL= 61.678 mil, $\pm 1\sigma$ point.

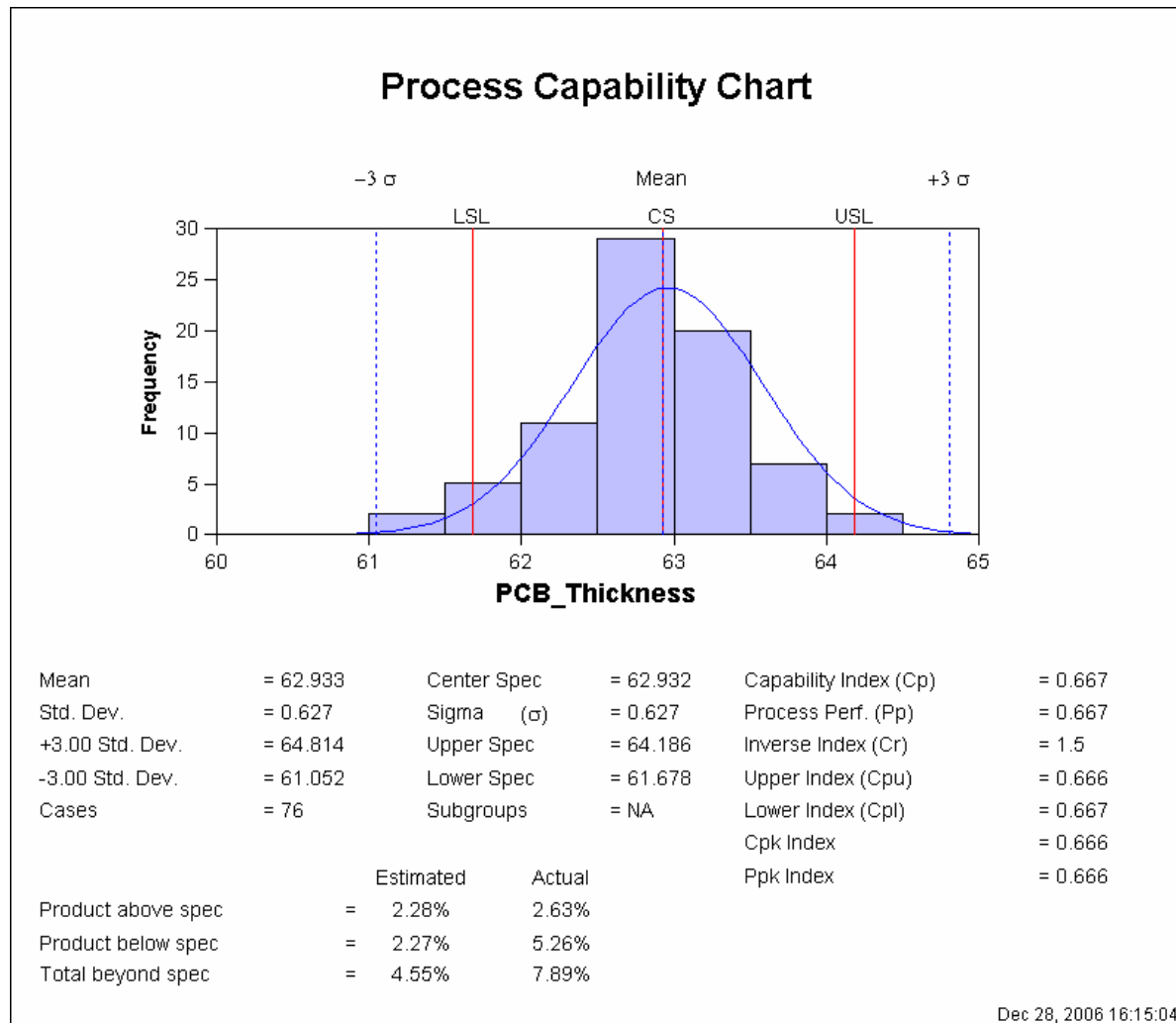


Figure 9: Process capability chart for USL = 64.186 mil & LSL= 61.678 mil, $\pm 2\sigma$ point

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