# Corrective Actions and Process Capability Index

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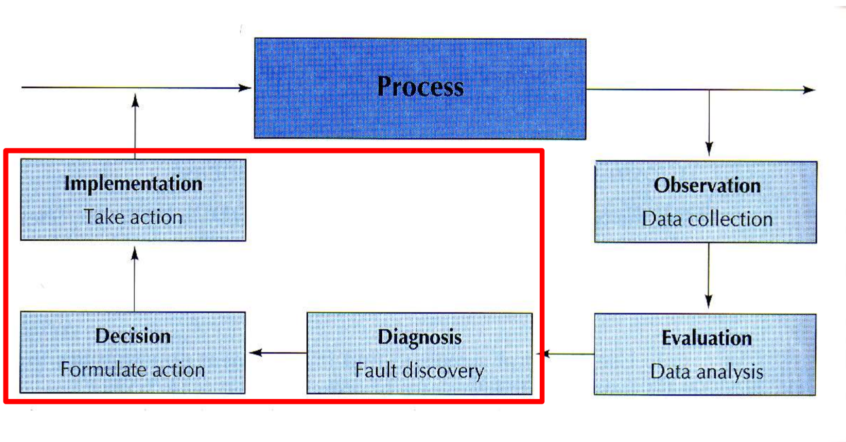
## Classical Control System View of SPC Implementation



# Closing Control Loop: Causes and Actions

- Step 1: Find the relevant causes/factors:
  - Scatter Plot
  - Regression Analysis and Classification Tree
  - Machine learning
- Step 2: Prioritize defects/causes
  - Pareto Diagram
- Step 3: Find the root causes
  - Cause-and-Effect Diagram
- Step 4: Close the control loop
  - Out-of-Control Action Plans (OCAPS)
  - Advanced Process Control (APC/Run-to-Run Control)




# Scatter Plot

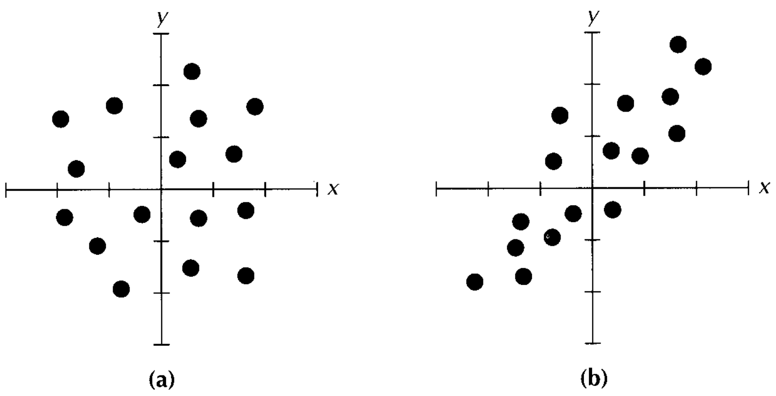



**Figure 6.18** Examples of No Correlation (a) and Positive Correlation (b)

# Regression Analysis and Decision Trees Learning

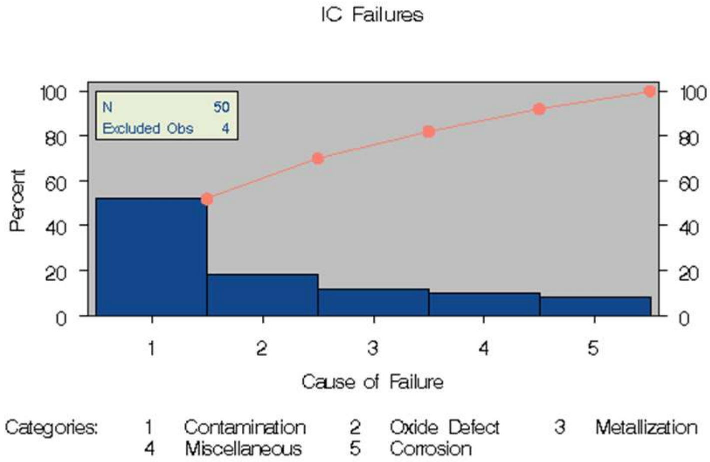
- Regression analysis:
  - Simple and multiple regression will be covered
  - Stepwise, ridge, LASSO, etc.
- Decision trees: Data Mining courses
  - CART classification and Regression Tree
    - Gini Index/variance reduction
  - ID3/C4.5
    - Information Entropy/Information Gain/Information Gain Ratio
- Supervised machine learning




# Pareto Principle

- Also known as the **80/20 rule**, the **law of the vital few**, or the principle of **factor sparsity**
- Named after Italian economist Vilfredo Pareto who noted the 80/20 connection by showing that approximately 80% of the land in Italy was owned by 20% of the population
- Axiom of business management: “80% of sales come from 20% of clients”
- In computer science, Microsoft noted that by fixing the top 20% of the most-reported bugs, 80% of the related errors and crashes in a given system would be eliminated.

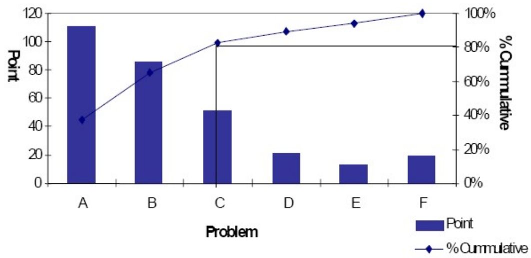
# Pareto Diagram





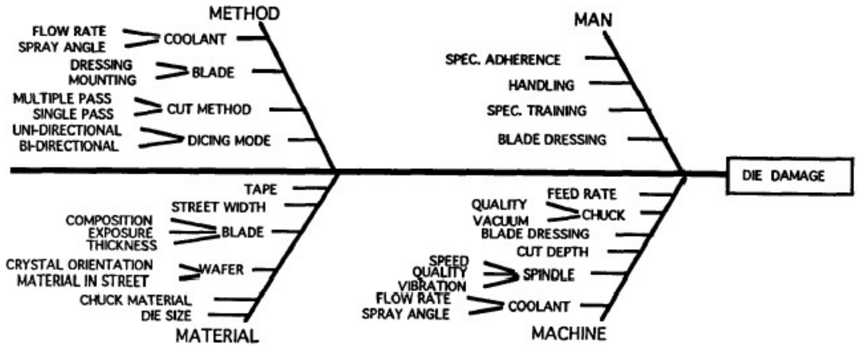

# Pareto Diagram Example
# Long Waiting Time

| No | Case | Problems | Score | Percentage | Cummulative (%) |
|---|---|---|---|---|---|
| 1 | A | Registration Time | 111 | 37 | 37 |
| 2 | B | Insufficient Doctors | 85 | 28 | 65 |
| 3 | C | Insufficient Counter Staff | 51 | 17 | 82 |
| 4 | D | Problem mixing with 'follow-up' patients | 21 | 7 | 89 |
| 5 | E | Too many patients at the same time | 13 | 4 | 94 |
| 6 | F | Others | 19 | 6 | 100 |
| | | Total | 300 | 100 | |




Source: Mohamad Hanaffi Abdullah, "Study on Outpatients' Waiting Time in Hospital University Kebangsaan Malaysia (HUKM) Through the Six Sigma Approach"

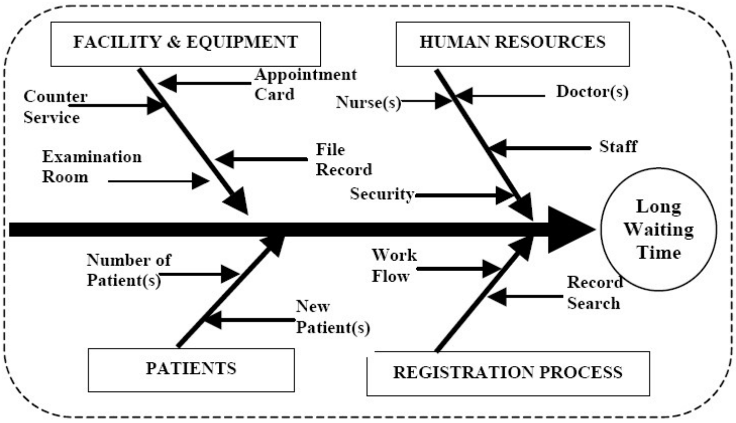
## Cause-and-Effect (Ishikawa Fishbone) Diagram




Source: Harry Shah and Satish Ram, "CHARACTERIZATION OF THE WAFER DICING PROCESS USING TAGUCHI METHODOLOGY," IEEVSEMI Advanced Semiconductor Manufacturing Conference , 200-205, 1992



## Cause-and-Effect (Ishikawa Fishbone) Diagram Example – Long Waiting Time




Source: Mohamad Hanaffi Abdullah, "Study on Outpatients' Waiting Time in Hospital University Kebangsaan Malaysia (HUKM) Through the Six Sigma Approach"

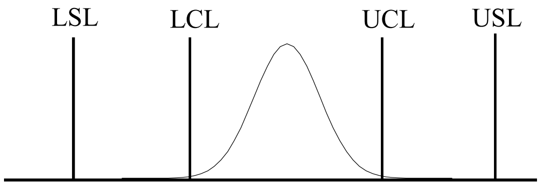
# Taking Actions and Making Adjustments

- **Out-of-Control Action Plans (OCAPS)**
  - Detail the action to be taken once an out-of-control situation is detected.
  - A specific flowchart, that leads the process engineer through the corrective procedure, may be provided for each unique process
- **Advanced Process Control:** Run-to-Run adjustments made to the process that are programmed to compensate for the size of the out-of-control measurement




# Process Capability Assessment

- What is a capable process?
- Assess process capability **in terms of control chart application**
- Comparing 6-s control window of *X*-chart to the specification window:




$$C_p = \frac{USL - LSL}{6\hat{\sigma}}$$

# Process Capability

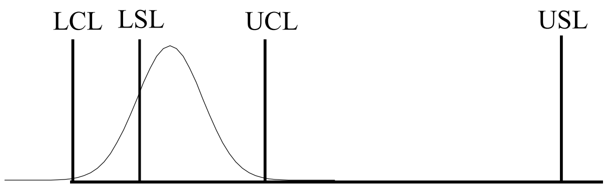
- The ability of the process to produce parts that conform to the engineering specifications (spec).
- A good process should
  - maintain a good statistical control
  - conform to engineering spec
- A process in statistical control but not meeting the spec?
  - the process is off-center from the nominal
  - the process variation is too large



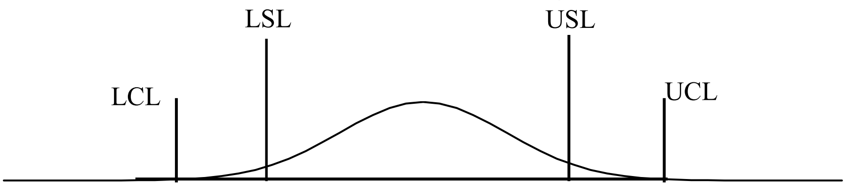


# Incapable Processes

- Process is off-center from the nominal



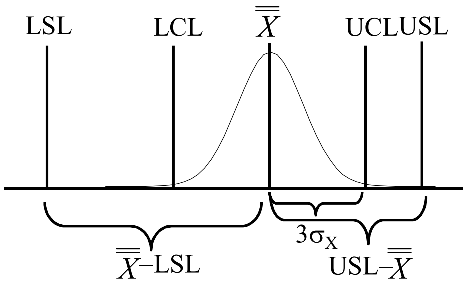

- Process variation is too large



# Process Capability Index

$$C_p = \frac{USL - LSL}{6\sigma_X}$$

$$C_{pk} = \min\left[\frac{\bar{\bar{X}} - LSL}{3\sigma_X}, \frac{USL - \bar{\bar{X}}}{3\sigma_X}\right]$$




- **Cp index measures potential capability (variation)**
  **Cpk index reflects the current process performance (mean and variation)** and for process with asymmetric spec limits
- Cpk ≤Cp [Cpk = Cp when $\bar{\bar{X}}$ = (USL+LSL)/2 ]




# Estimating Cp from Control Chart

- If a process is in statistical control,

$$C_p = \frac{USL - LSL}{6\hat{\sigma}_X} \qquad \hat{\sigma}_x = s_x$$

- Example: $s_x$= 0.00237, n=6, spec=(0.253, 0.263)

$$\hat{\sigma}_x = s_x = 0.00237$$

$$C_p = \frac{USL - LSL}{6\hat{\sigma}_X} = \frac{0.263 - 0.253}{6 \cdot 0.00237} = 0.72$$

# An Integrated PCI - $C_{pm}$

$$C_{pm} = \frac{USL - LSL}{6\tilde{\sigma}}$$

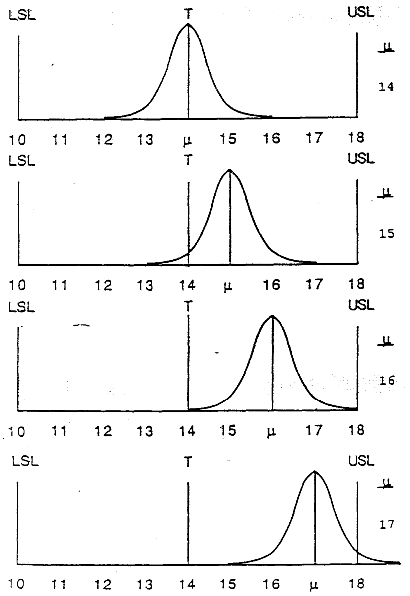
where $\tilde{\sigma} = \sqrt{E(X-T)^2} = \sqrt{\sigma^2 + (\mu - T)^2}$

$$\hat{\tilde{\sigma}} = \sqrt{\frac{\sum_{i=1}^{n}(X_i - T)^2}{n}} = \sqrt{\hat{\sigma}^2 + (T - \bar{X})^2}$$

$$C^*_{pm} = \frac{\min[USL - T, T - LSL]}{3\tilde{\sigma}}$$



# Comparison of PCI's

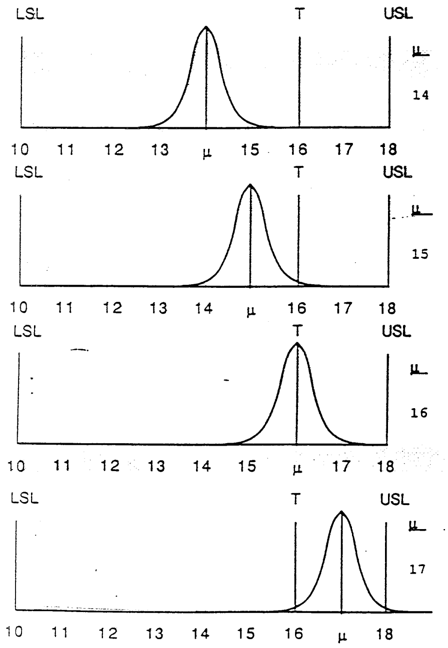



σ=0.5 μ=T

σ=0.5 μ=T+1

σ=0.5 μ=T+2

σ=0.5 μ=T+3




$3\sigma=1$ $\mu=T-2$

$3\sigma=1$ $\mu=T-1$

$3\sigma=1$ $\mu=T$

$3\sigma=1$ $\mu=T+1$



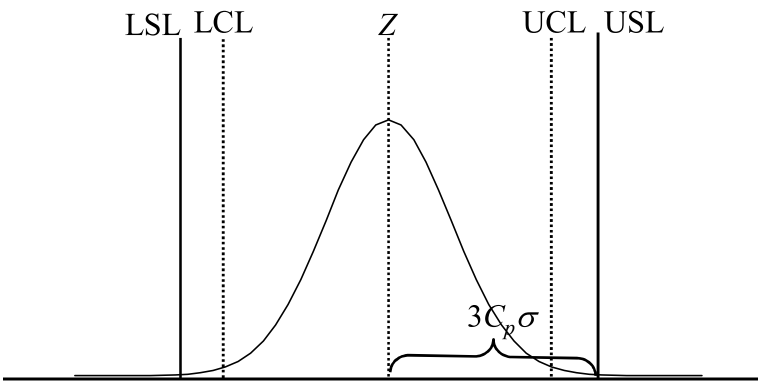

## Calculation of Out-of-Spec %

Assuming normally distributed $X$: $Z=\dfrac{X-\bar{\bar{X}}}{\hat{\sigma}_X}\sim N(0,1)$

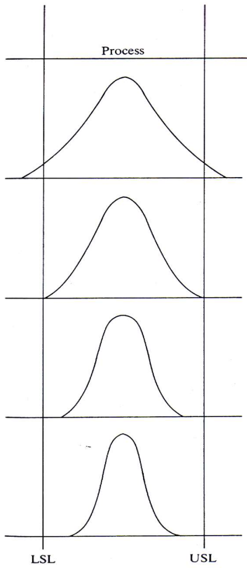
When $\bar{\bar{X}}$=(LSL+USL)/2

Out-of –spec%=[$P$($X$≥USL)+$P$($X$≤LSL)]×100%

=[$P(Z\geq 3C_p)+P(Z\leq -3C_p)$]×100%



# Four Examples of Process Capability




| $C_p$ | Total amount outside limits | Typical actions to be taken |
|---|---|---|
| <1.0 | ≥5.0% | Heavy process control, sorting, rework, etc. |
| 1.0 | 0.3% | Heavy process control, inspection |
| 1.33 | 64 ppm | Reduced inspection, selected use of control charts |
| 1.63 | 1 ppm | Spot checking, selected use of control charts |

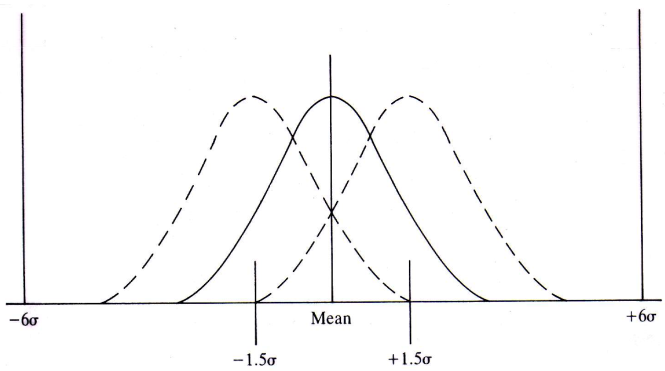
ppm: parts per million




# Six-σ Concept of Process Capability

$C_p = 2$

If mean shifts ±1.5σ, only 3.4 ppm will be beyond spec limits.

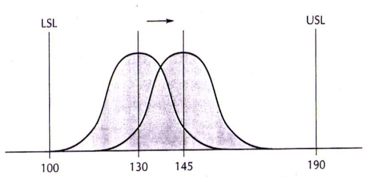


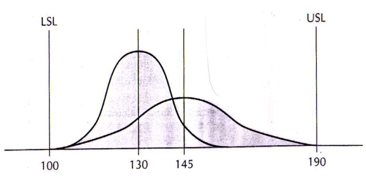
# How to improve $C_{pk}$?

- Reduce variation
  - remove special variation (SPC)
  - reduce common variation (process improvement, robust design)
- Adjust mean to nominal value

If $\sigma_x = 10$ then
Cpk = 1.0 (mean = 130)
Cpk = 1.5 (mean = 145)

mean = 145, $\sigma_x = 15$
mean = 130, $\sigma_x = 10$
then Cpk = 1.0







# Steps in Assessment of Process Capability

- estimate $\sigma_x = s_x$
- calculate $C_p$, $C_{pk}$
- calculate out-of-spec percentage using

$$Z = \frac{X - \overline{\overline{X}}}{\hat{\sigma}_X}$$

# Example: Poly CVD Process

| | CD_site1 | CD_site2 | CD_site3 | CD_site4 | CD_site5 | within-wafer average | within-wafer stdev |
|---|---|---|---|---|---|---|---|
| wafer 1 | 60.52 | 59.84 | 59.34 | 60.62 | 59.59 | 59.98 | 0.57 |
| wafer 2 | 61.11 | 60.23 | 60.08 | 61.04 | 60.07 | 60.50 | 0.52 |
| wafer 3 | 60.43 | 60.09 | 59.58 | 59.67 | 59.67 | 59.89 | 0.36 |
| wafer 4 | 60.46 | 60.16 | 59.51 | 60.53 | 59.50 | 60.03 | 0.50 |
| wafer 5 | 61.08 | 60.10 | 59.87 | 61.02 | 60.17 | 60.45 | 0.56 |
| wafer 6 | 60.73 | 60.66 | 59.89 | 60.12 | 60.03 | 60.29 | 0.38 |
| wafer 7 | 60.17 | 59.46 | 58.84 | 60.26 | 59.64 | 59.67 | 0.58 |
| wafer 8 | 60.52 | 59.73 | 59.35 | 60.47 | 59.78 | 59.97 | 0.51 |
| wafer 9 | 60.28 | 60.02 | 59.15 | 59.59 | 59.39 | 59.69 | 0.46 |
| wafer 10 | 60.22 | 59.81 | 59.19 | 60.52 | 59.82 | 59.91 | 0.50 |
| wafer 11 | 60.61 | 59.69 | 59.51 | 60.46 | 59.69 | 59.99 | 0.50 |
| wafer 12 | 60.06 | 60.00 | 59.28 | 59.55 | 59.43 | 59.67 | 0.35 |
| wafer 13 | 60.37 | 59.93 | 59.15 | 60.49 | 59.71 | 59.93 | 0.54 |
| wafer 14 | 60.77 | 60.02 | 59.97 | 60.84 | 59.77 | 60.27 | 0.49 |
| wafer 15 | 60.22 | 59.92 | 59.12 | 59.58 | 59.63 | 59.69 | 0.41 |
| wafer 16 | 60.13 | 59.73 | 59.07 | 60.59 | 60.04 | 59.91 | 0.56 |
| wafer 17 | 60.82 | 60.13 | 59.63 | 60.74 | 59.72 | 60.21 | 0.56 |
| wafer 18 | 60.60 | 60.57 | 59.84 | 60.22 | 60.03 | 60.25 | 0.33 |
| wafer 19 | 60.15 | 59.48 | 59.07 | 60.29 | 59.44 | 59.69 | 0.51 |
| wafer 20 | 60.73 | 60.00 | 59.58 | 60.83 | 60.11 | 60.25 | 0.52 |
| wafer 21 | 60.44 | 60.28 | 59.37 | 59.85 | 59.67 | 59.92 | 0.44 |
| wafer 22 | 60.56 | 60.23 | 59.59 | 60.63 | 59.58 | 60.12 | 0.51 |
| wafer 23 | 60.55 | 59.66 | 59.53 | 60.44 | 59.72 | 59.98 | 0.48 |
| wafer 24 | 60.18 | 60.16 | 59.46 | 59.83 | 59.58 | 59.84 | 0.33 |
| wafer 25 | 60.47 | 59.75 | 59.23 | 60.38 | 59.58 | 59.88 | 0.53 |
| wafer 26 | 60.22 | 59.79 | 59.20 | 60.15 | 59.47 | 59.77 | 0.44 |
| wafer 27 | 60.68 | 60.03 | 59.68 | 60.69 | 59.75 | 60.17 | 0.49 |
| wafer 28 | 60.29 | 60.54 | 59.43 | 59.75 | 60.00 | 60.00 | 0.44 |
| wafer 29 | 60.13 | 59.53 | 58.83 | 60.11 | 59.31 | 59.58 | 0.55 |
| wafer 30 | 60.33 | 59.69 | 59.60 | 60.40 | 59.73 | 59.95 | 0.38 |
| site average | 60.46 | 59.97 | 59.43 | 60.32 | 59.72 | | |
| wafer-to-wafer site Stdev | 0.27 | 0.31 | 0.32 | 0.43 | 0.23 | | |

USL=62
LSL=58




# Overall Process Capability

$$\hat{\sigma}_x = s_x = 0.49$$

$$C_p = \frac{USL - LSL}{6\sigma_X} = \frac{62 - 58}{6 \cdot 0.49} = 1.36$$

$$C_{pk} = \min\left[\frac{\overline{\overline{X}} - LSL}{3\sigma_X}, \frac{USL - \overline{\overline{X}}}{3\sigma_X}\right] = \min\left[\frac{59.98 - 58}{3 \cdot 0.49}, \frac{62 - 59.98}{3 \cdot 0.49}\right] = 1.347$$

# Out-of-Spec Calculation

- $Z_L = \frac{LSL - \overline{\overline{X}}}{\sigma_x} = \frac{58 - 59.98}{0.49} = -4.041 \Rightarrow$ P(X≤ 58) is Ψ(-4.041)=2.66E-5
- $Z_U = \frac{USL - \overline{\overline{X}}}{\sigma_x} = \frac{62 - 59.98}{0.49} = 4.122 \Rightarrow$ P(X≥62) is 1-Ψ(4.122)=1.88E-5
- out-of-spec percentage = 2.66E-5+1.88E-5 =4.54E-5 = 0.0045%

# Site-1 Process Capability

$$\hat{\sigma}_x = s_{\text{site-1}} = 0.27$$

$$C_p = \frac{USL - LSL}{6\sigma_X} = \frac{62 - 58}{6 \cdot 0.27} = 2.47$$

$$C_{pk} = \min\left[\frac{\overline{X} - LSL}{3\sigma_X}, \frac{USL - \overline{X}}{3\sigma_X}\right] = \min\left[\frac{60.46 - 58}{3 \cdot 0.27}, \frac{62 - 60.46}{3 \cdot 0.27}\right] = 1.9$$