Level 5 – Continuous Improvement with Industry 4.0

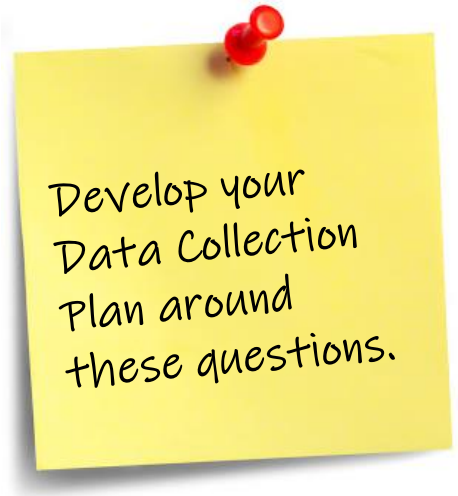
Measure 3 – Variation and Statistical Process Control (SPC)

Measure - Where are we?

Define	Measure	Analyse	Improve	Control
✔ Introduction	✔ Measurement	☐ Root Cause	☐ PDCA	☐ Auditing
✔ Y=(f)x	✔ MSA	☐ Regression	☐ Risk Management	☐ Lessons Learnt
✔ SIPOC	✔ Data Collection	☐ Hypothesis Testing	☐ FMEA	☐ SOPs
✔ Pareto	☐ Variation	☐ t-tests	☐ Value Stream Mapping	☐ SMED
✔ Cause & Effect	☐ SPC	☐ ANOVA	☐ Solution Selection Matrix	☐ TPM
✔ 5 Whys	☐ Process Capability	☐ DoE	☐ Five S	☐ Control Case Study
✔ Is it? Is it not?	☐ Charting		☐ Benchmarking	
✔ Project Charter	☐ OEE		☐ Control Plans	
✔ VoC & QFD				
✔ Team Working				
✔ Critical to Quality (CTQ)				

Measure - Data Collection Plan

1. What data will be collected?
2. Why is it needed?
3. Who is responsible?
4. How will it be collected?
5. When will it be collected?
6. Where will it be collected?



Measure - Data Collection Plan

What data will be collected?

Will you be measuring inputs (x) to a process or outputs (y)

	Y	X1	X2	X3
Existing data				
New Data				

Data Collection Sheets – why?

- Standardize the data collection process
- Organises the data into an acceptable format (by product, operator, time, dept etc)
- Allows team to collect any additional comments during the process

Data Collection Sheets – why?

- Consider all the characteristics you want to collect (different inputs and outputs)
- Talk to people who are collecting the data (if not you) to explain the reason for this
- Test the form before you implement

Data Collection Sheets – example continuous data

date	operator	product	machine	Size off MC	comments
10/3/21	DJ	ABC123	Press 5	253.25	No issues

Data Collection Sheets – example attribute data

date	operator	product	machine	Scratch Y/N	Coating OK Y/N	comments
10/3/21	DJ	ABC123	Press 5	Y	N	No issues

Measure - Data Collection Plan

A well-prepared collection plan will help to ensure successful analysis of the problem by ensuring useful data has been captured

“In God we trust, everybody else bring data”

What is variation?

variation

/vɛːrɪˈeɪʃ(ə)n/

See definitions in:

All | Astronomy | Mathematics | Physics | Biology | Music | Ballet

noun

1. a change or slight difference in condition, amount, or level, typically within certain limits.
   "regional variations in house prices"

   Similar: difference | dissimilarity | disparity | inequality | contrast | discrepancy

2. a different or distinct form or version of something.
   "hurling is an Irish variation of hockey"

   Similar: variant | form | alternative | alternative form | other form | different form

Definitions from Oxford Languages

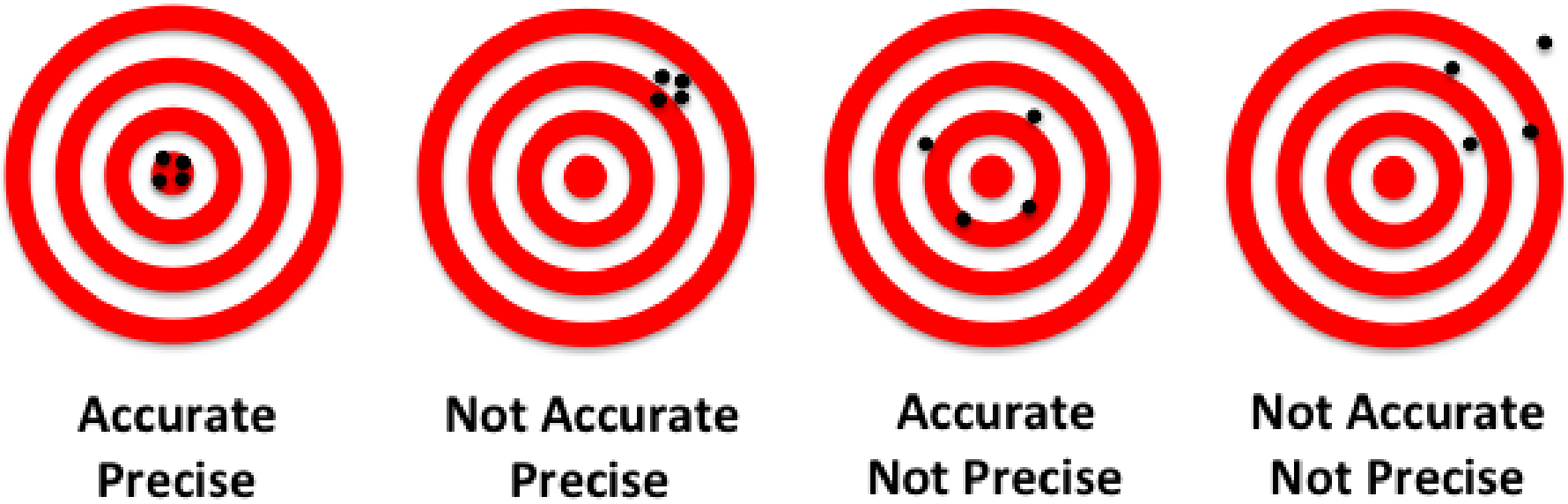
Feedback

Measure - Variation

Some terms to help us understand:-

- Mean – commonly called the average
- Median – mid-point of a distribution
- Mode – most frequently occurring number
- Range – maximum value – minimum value
- Standard Deviation – unit of measure of distance from the mean

Measure - Variation

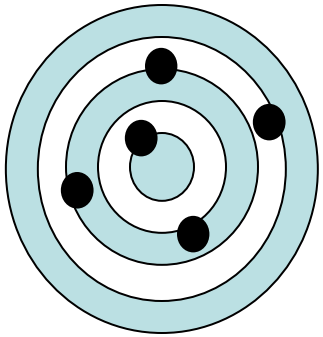


- **How's your aim? Are you accurate?**
- Is your aim precise; that is, are all the shots clustered around the target, or are they distributed all over the place?

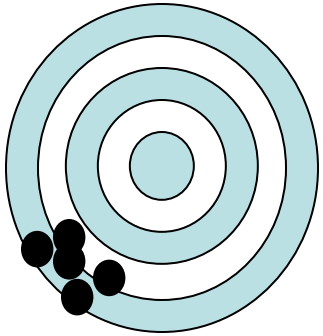
Have you ever…

- Shot a rifle?
- Played darts?
- Shot a round of golf?

- Who is the better shot?



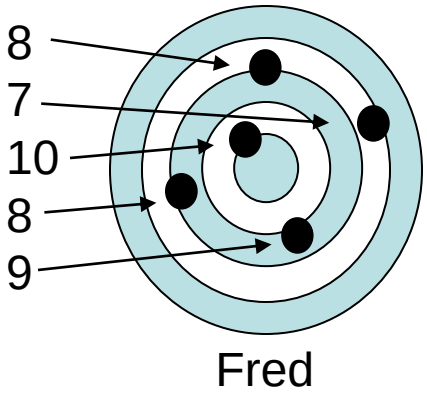
Fred

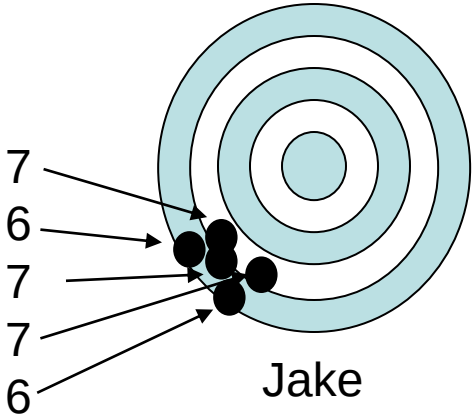


Jake

Deviation

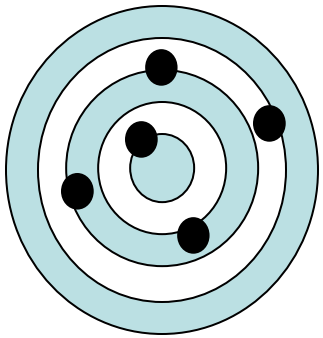
distance between observations and the mean *(or average)*





Measure - Variation

- Deviation = distance between observations and the mean (or average)



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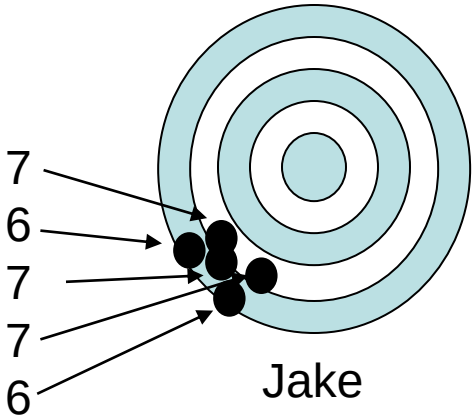
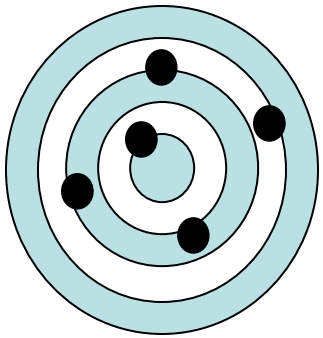


Jake

	Observations	Deviations
	7	7 – 6.6 = 0.4
	7	7 – 6.6 = 0.4
	7	7 – 6.6 = 0.4
	6	6 – 6.6 = -0.6
	6	6 – 6.6 = -0.6
averages	**6.6**	

Measure - Variation

- Variance = average distance between observations and the mean squared



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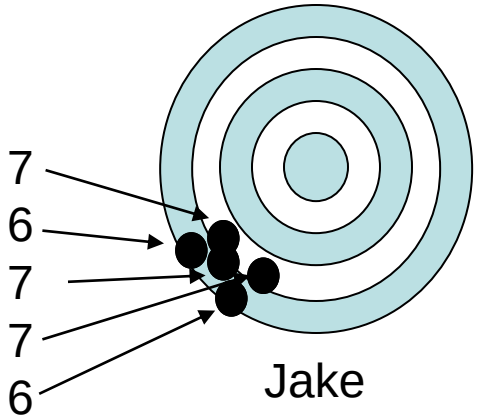


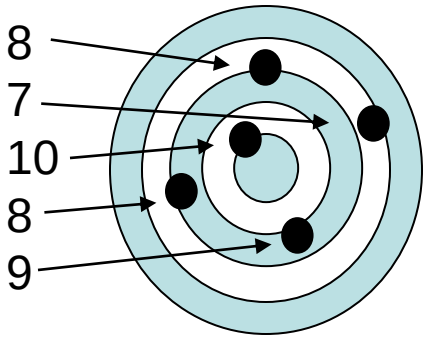
Jake

	Observations	Deviations	Squared Deviations
	7	7 - 6.6 = 0.4	0.16
	7	7 - 6.6 = 0.4	0.16
	7	7 - 6.6 = 0.4	0.16
	6	6 – 6.6 = 0.6	0.36
	6	6 – 6.6 = -0.6	0.36
averages	**6.6**		**0.24**

Variance

Measure - Variation

- Variance = average distance between observations and the mean squared



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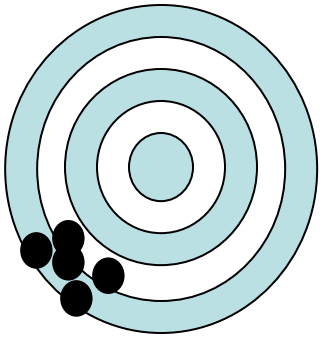


Jake

	Observations	Deviations	Squared Deviations
	10	10 - 8.4 = 1.6	2.56
	9	9 – 8.4 = 0.6	0.36
	8	8 – 8.4 = -0.4	0.16
	8	8 – 8.4 =-0.4	0.16
	7	7 – 8.4 = -1.4	1.96
averages	**8.4**		**1.0**

Variance

Measure - Standard Deviation

- Standard Deviation is a measure of how close the numbers are to the mean. If the standard deviation is big, then the data is more "dispersed" or "diverse" as it serves as a measure of uncertainty.

- We use Standard Deviation of assessments grades; it gives us an indication of the spread of marks over a module.

- Its symbol is **σ** (the greek letter sigma)

- The formula is straightforward; it is the **square root** of the **Variance.**

Measure - Standard Deviation

Consider a sample of 5 data points; 6.5, 7.5, 8.0, 7.2, 6.8

The **Range** is the highest minus the lowest; 8.0 – 6.5 = 1.5
The **Mean** (X-bar) is 7.2

The Standard Deviation is

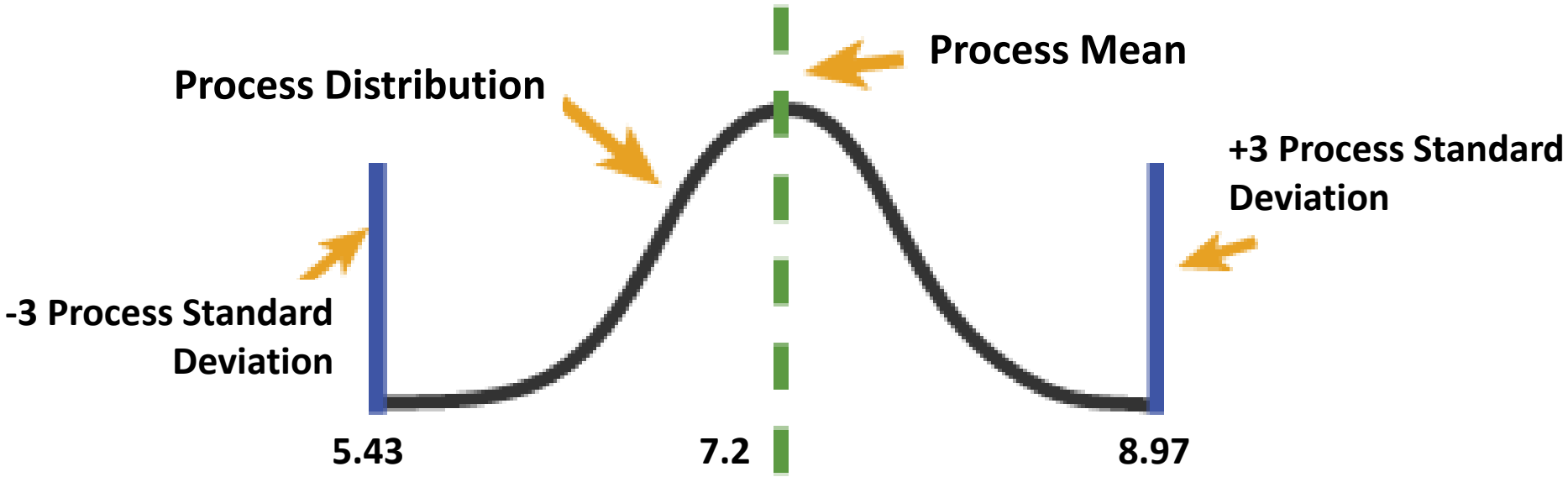
$$stdev = \sqrt{\frac{(6.5-7.2)^2 + (7.5-7.2)^2 + (8.0-7.2)^2 + (7.2-7.2)^2 + (6.8-7.2)^2}{5-1}}$$

$$\boldsymbol{stdev = 0.59}$$

Fortunately, we have Excel!

Measure - Control Limits

- Statistical tables have been developed for various types of distributions that quantify the area under the curve for a given number of standard deviations from the mean.
- Shewhart found that control limits placed at three standard deviations from the mean in either direction provide an economical trade-off between the risk of reacting to a false signal and the risk of not reacting to a true signal.



Measure - 3 Standard Deviations

- We want to calculate three-sigma, which is three standard deviations above the mean.

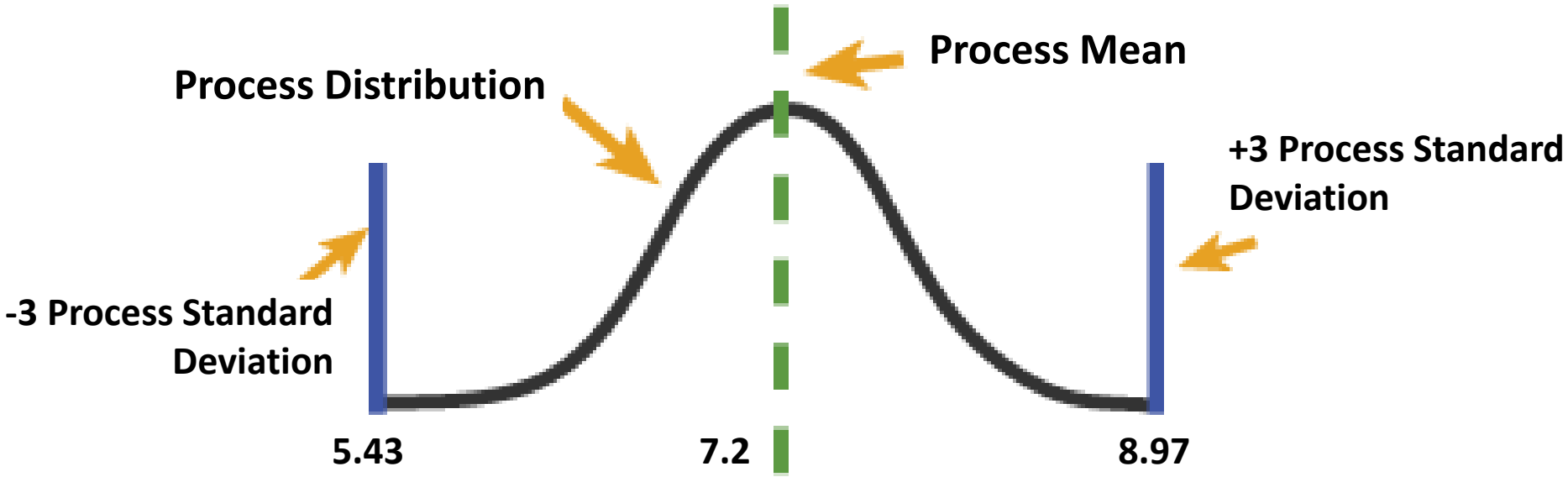
- 3x STDEV + Mean

- $\boldsymbol{stdev = 0.59}$

⇢(3 x 0.59) + 7.2 = 8.97

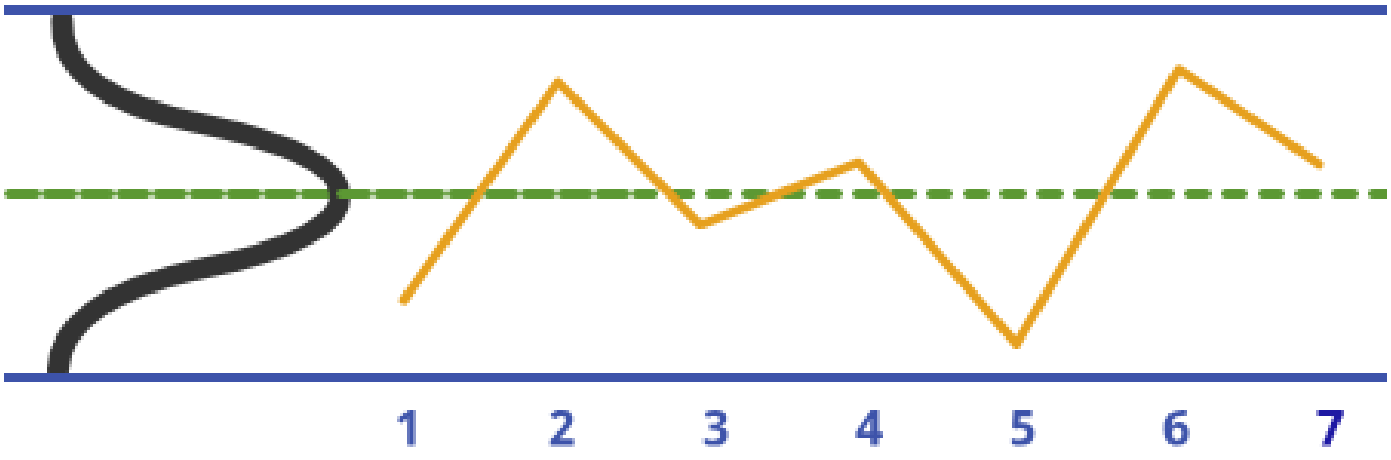
Measure - Control Limits

- The illustration below shows a normal curve for a distribution with a mean of 7.2, a mean less 3 standard deviations value of 5.43, and a mean plus 3 standard deviations value of 8.97. Values, or measurements, less than 5.43 or greater than 8.97 are extremely unlikely.
- These laws of probability are the foundation of the control chart.



Measure - Control Limits

- Consider that the distribution is turned sideways, and the lines denoting the mean and ±3 standard deviations are extended.
- This construction forms the basis of the Control chart.
- Time series data plotted on this chart can be compared to the lines, which now become control limits for the process.
- Comparing the plot points to the control limits allows a simple probability assessment.



Brief history of (industrial) statistics

Pre 1920	Population & government statistics
1920s	Gossett: t-test (Brewing industry) Fisher: Experimental design (Agriculture)
1930s	W.A. Shewhart: Quality control (Bell Labs) Tippet: application of Fisher's ideas in industry
1940s	Developments in acceptance sampling
1950s	Developments in design of experiments (e.g. George Box) and reliability methods: (e.g. Waloddi Weibull) W. Edwards Deming & Joseph Juran visit Japan
1960s & 1970s	Growth of Japanese industry and their use of statistical techniques including experimental design in quality management. (especially Genichi Taguchi).
1980s & 1990s	'Quality revolution' in U.S.A. and Europe. Recognition of the value of statistical techniques and quality management techniques for quality improvement. Many 'Quality gurus' established. E.g. W. Edwards Deming, Joseph Juran, Feigenbaum, Crosby, Joiner, Kaoru Ishikawa, Ohno. Many quality programmes and standards (and acronyms!) established: E.g. TQM, JIT, ISO9000, Zero-defects, Six Sigma.

Control Charts

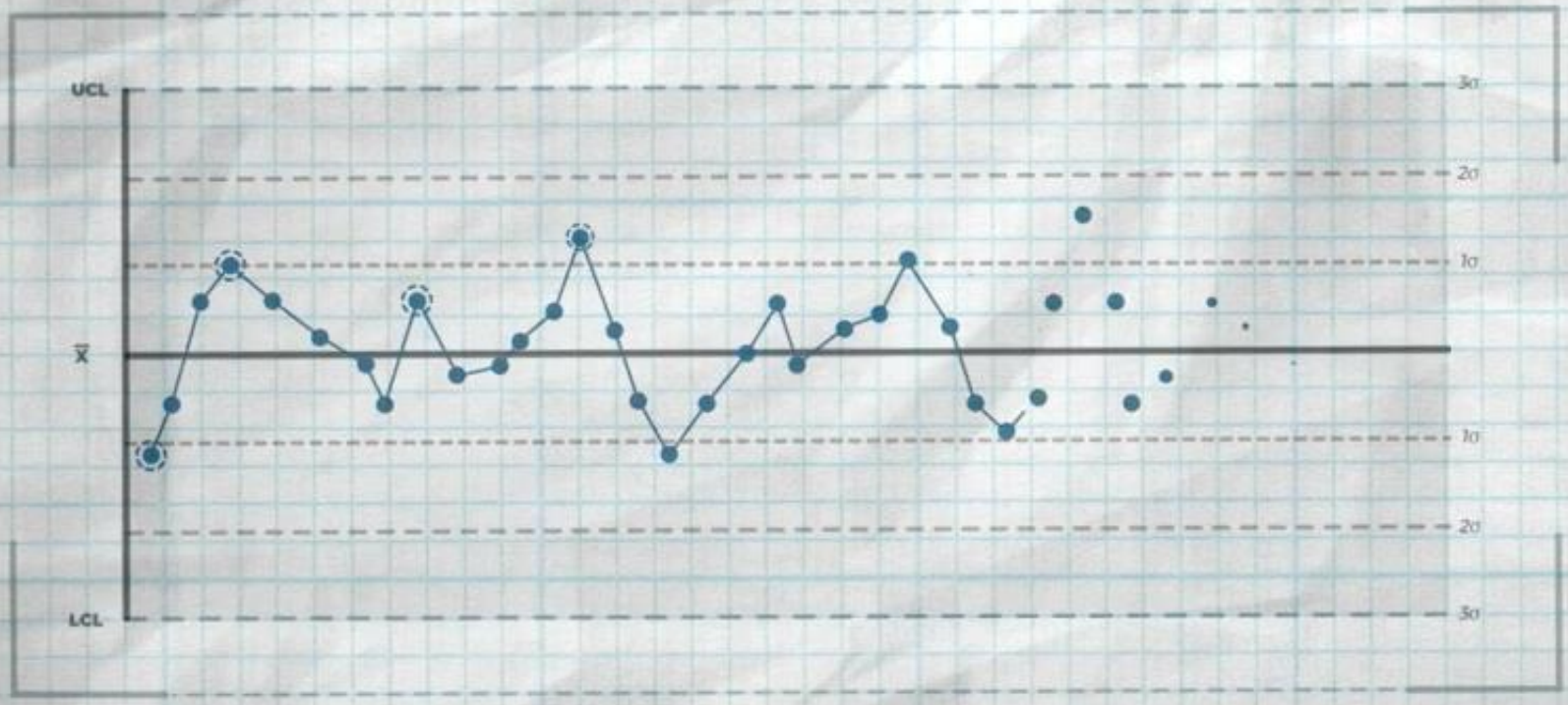
- Control charts are also known as Shewhart charts, named after Walter A. Shewhart, an American physicist, engineer and statistician (1891–1967)
- Control charts were devised as simple, but powerful, graphical ways of monitoring a process to check whether any assignable causes of variation are present.
- Measurements of product quality are made at regular intervals of time and plotted on the vertical axis of the graph versus time on the horizontal axis.
- Prior to this the natural variation of the product will have been estimated and the 'expected' range of natural variation is also shown on the chart - usually as two horizontal lines - called control lines or action lines.

Control Charts

- Points outside the range of natural variation indicate the likely presence of assignable cause variation and appropriate action should then be taken to bring the process back into control.
- Control charts are tools used to determine whether a process is in a state of statistical control or whether special causes of variation are present.
- When there is evidence that special causes of variation are present, action is initiated to bring the process back into control.
- Sometime SPC is used retrospectively to identify where problems occurred and the reasons for these are traced so that these problems may be avoided in the future.

Measure Phase

- In SPC, when we talk about the *distribution of the process*, we are referring not to the process itself but to data collected **from** the process—for example, data on widths of pieces coming out of a woodworking machine—and to the way those data are *distributed* when plotted on a chart or graph.



NELSØNS RULES

Nelson's Rules

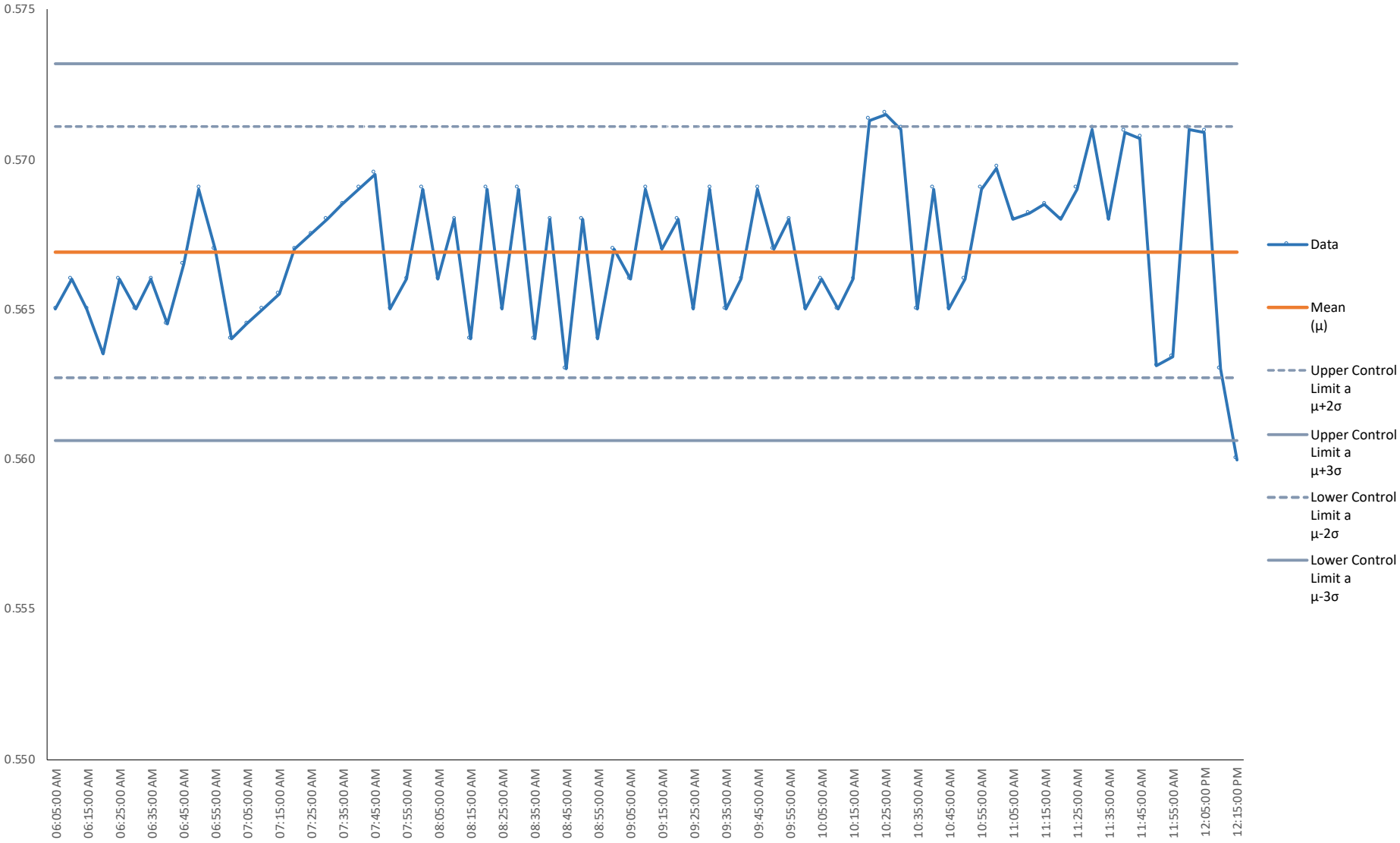
Western Electric Rules

1. One point above UCL or below LCL
2. Two points above/below 2 sigma
3. Four out of five points above/below 1 sigma
4. Eight points in a row above/below the center line

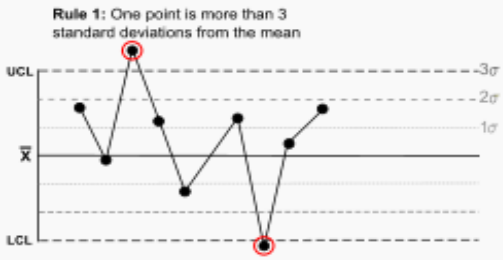
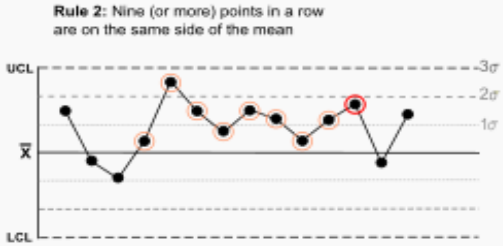
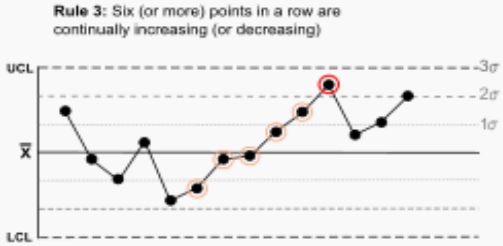
Work of Lloyd S Nelson, published in October 1984;

1. One point above UCL or below LCL
2. Two points above/below 2 sigma
3. Three out of four points above/below 1 sigma
4. Eight points in a row above/below the center line
5. Six points in a row ascending or descending (trend)
6. 15 points in a row "hugging" the center line (between -1 and +1 sigma)
7. 14 points in a row alternating up and down
8. Eight points in a row above 1 sigma or below -1 sigma

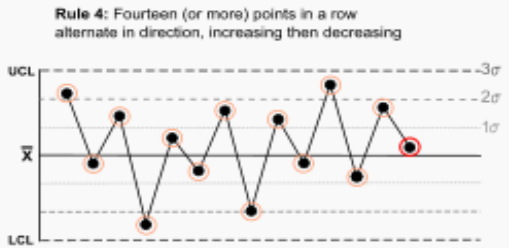
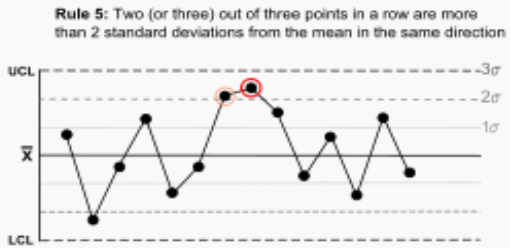
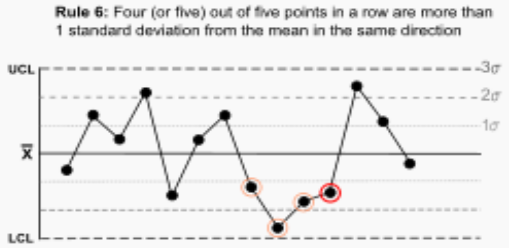
Control Chart



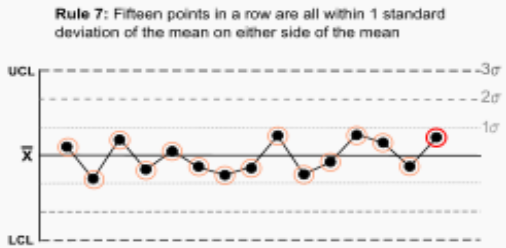
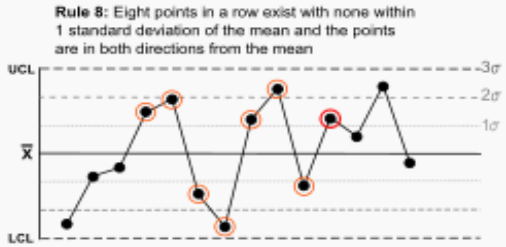
Nelson's Rules 1 to 3

Rule	Description	Chart Example	Problem Indicated
Rule 1	One point is more than 3 standard deviations from the mean.		One sample (two shown in this case) is grossly out of control.
Rule 2	Nine (or more) points in a row are on the same side of the mean.		Some prolonged bias exists.
Rule 3	Six (or more) points in a row are continually increasing (or decreasing).		A trend exists.

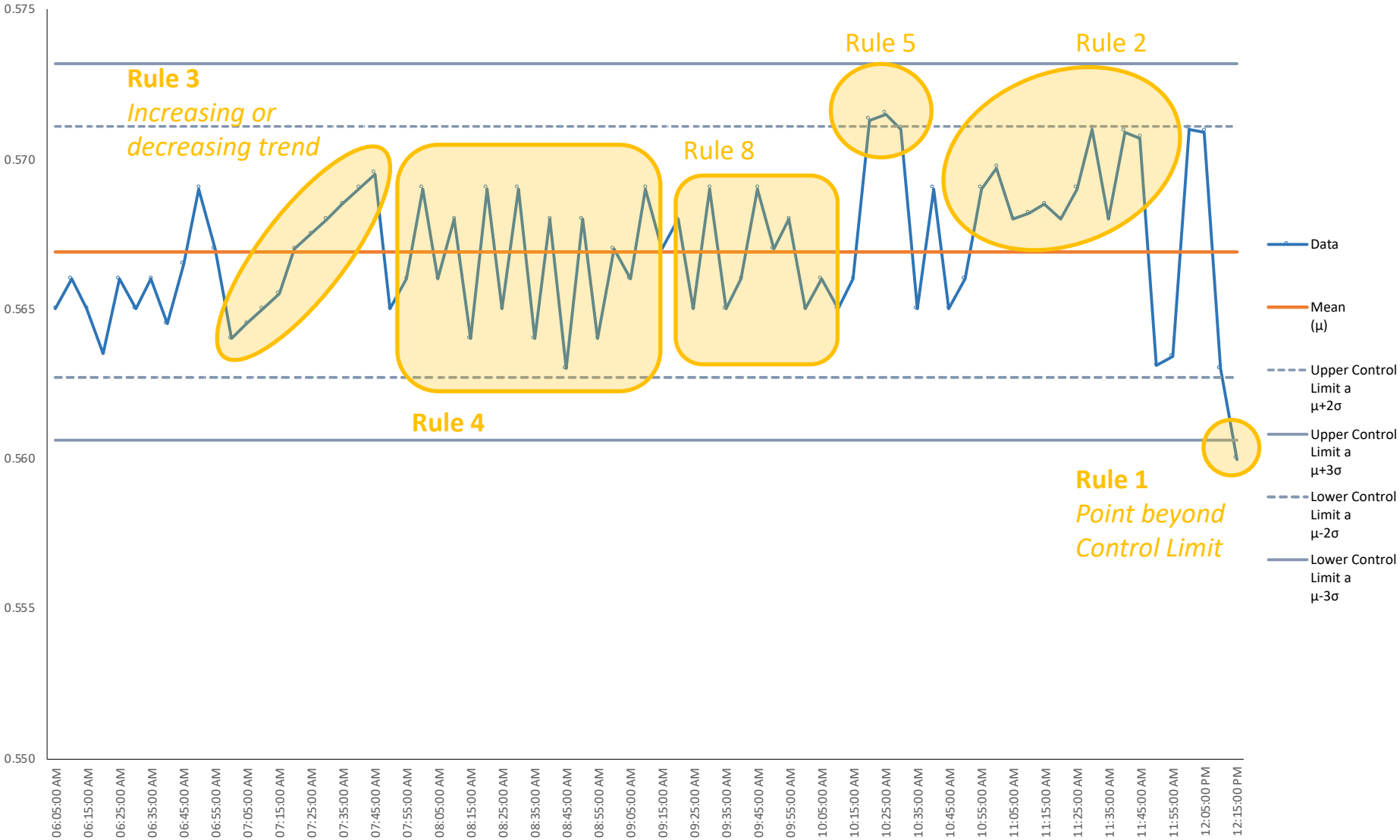
Nelson's Rules 4 to 6

Rule 4	Fourteen (or more) points in a row alternate in direction, increasing then decreasing.		This much oscillation is beyond noise. This is directional and the position of the mean and size of the standard deviation do not affect this rule.
Rule 5	Two (or three) out of three points in a row are more than 2 standard deviations from the mean in the same direction.		There is a medium tendency for samples to be mediumly out of control. The side of the mean for the third point is unspecified.
Rule 6	Four (or five) out of five points in a row are more than 1 standard deviation from the mean in the same direction.		There is a strong tendency for samples to be slightly out of control. The side of the mean for the fifth point is unspecified.

Nelson's Rules 7 and 8

Rule 7	Fifteen points in a row are all within 1 standard deviation of the mean on either side of the mean.		With 1 standard deviation, greater variation would be expected.
Rule 8	Eight points in a row exist with none within 1 standard deviation of the mean and the points are in both directions from the mean.		Jumping from above to below whilst missing the first standard deviation band is rarely random.

Control Chart



Process in Control when…

- No sample points outside the limits
- Most points close to process average.
- An equal number of points above and below the centerline.
- All points appear randomly distributed.

Adapted from Russell R,. and Taylor, B,. (2010) Operations Management: Creating Value Along the Supply Chain , 7th Ed

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Excel Template

SPC Template

Data Table - ONLY ENTER DATA INTO YELLOW CELLS

Time Period	Data	Mean (μ)	Moving range	Average of moving ranges	Upper Control Limit a μ+2σ	Upper Control Limit a μ+3σ	Lower Control Limit a μ-2σ	Lower Control Limit a μ-3σ
6:05:00 AM	0.565	0.567		0.002	0.571	0.573	0.563	0.561
6:10:00 AM	0.566	0.567	0.001	0.002	0.571	0.573	0.563	0.561
6:15:00 AM	0.565	0.567	0.001	0.002	0.571	0.573	0.563	0.561
6:20:00 AM	0.564	0.567	0.001	0.002	0.571	0.573	0.563	0.561
6:25:00 AM	0.566	0.567	0.002	0.002	0.571	0.573	0.563	0.561
6:30:00 AM	0.565	0.567	0.001	0.002	0.571	0.573	0.563	0.561
6:35:00 AM	0.566	0.567	0.001	0.002	0.571	0.573	0.563	0.561
6:40:00 AM	0.565	0.567	0.001	0.002	0.571	0.573	0.563	0.561
6:45:00 AM	0.567	0.567	0.002	0.002	0.571	0.573	0.563	0.561
6:50:00 AM	0.569	0.567	0.002	0.002	0.571	0.573	0.563	0.561
6:55:00 AM	0.567	0.567	0.002	0.002	0.571	0.573	0.563	0.561
7:00:00 AM	0.564	0.567	0.003	0.002	0.571	0.573	0.563	0.561
7:05:00 AM	0.565	0.567	0.001	0.002	0.571	0.573	0.563	0.561
7:10:00 AM	0.565	0.567	0.000	0.002	0.571	0.573	0.563	0.561
7:15:00 AM	0.566	0.567	0.001	0.002	0.571	0.573	0.563	0.561
7:20:00 AM	0.567	0.567	0.001	0.002	0.571	0.573	0.563	0.561
7:25:00 AM	0.568	0.567	0.001	0.002	0.571	0.573	0.563	0.561
7:30:00 AM	0.568	0.567	0.000	0.002	0.571	0.573	0.563	0.561
7:35:00 AM	0.569	0.567	0.001	0.002	0.571	0.573	0.563	0.561
7:40:00 AM	0.569	0.567	0.000	0.002	0.571	0.573	0.563	0.561
7:45:00 AM	0.570	0.567	0.001	0.002	0.571	0.573	0.563	0.561
7:50:00 AM	0.565	0.567	0.005	0.002	0.571	0.573	0.563	0.561
7:55:00 AM	0.566	0.567	0.001	0.002	0.571	0.573	0.563	0.561
8:00:00 AM	0.569	0.567	0.003	0.002	0.571	0.573	0.563	0.561
8:05:00 AM	0.566	0.567	0.003	0.002	0.571	0.573	0.563	0.561
8:10:00 AM	0.568	0.567	0.002	0.002	0.571	0.573	0.563	0.561
8:15:00 AM	0.564	0.567	0.004	0.002	0.571	0.573	0.563	0.561
8:20:00 AM	0.569	0.567	0.005	0.002	0.571	0.573	0.563	0.561
8:25:00 AM	0.565	0.567	0.004	0.002	0.571	0.573	0.563	0.561
8:30:00 AM	0.569	0.567	0.004	0.002	0.571	0.573	0.563	0.561
8:35:00 AM	0.564	0.567	0.005	0.002	0.571	0.573	0.563	0.561
8:40:00 AM	0.568	0.567	0.004	0.002	0.571	0.573	0.563	0.561
8:45:00 AM	0.569	0.567	0.003	0.002	0.571	0.573	0.563	0.561
8:50:00 AM	0.568	0.567	0.005	0.002	0.571	0.573	0.563	0.561
8:55:00 AM	0.564	0.567	0.004	0.002	0.571	0.573	0.563	0.561
9:00:00 AM	0.567	0.567	0.003	0.002	0.571	0.573	0.563	0.561
9:05:00 AM	0.566	0.567	0.001	0.002	0.571	0.573	0.563	0.561
9:10:00 AM	0.569	0.567	0.003	0.002	0.571	0.573	0.563	0.561
9:15:00 AM	0.567	0.567	0.002	0.002	0.571	0.573	0.563	0.561
9:20:00 AM	0.568	0.567	0.001	0.002	0.571	0.573	0.563	0.561
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9:35:00 AM	0.565	0.567	0.004	0.002	0.571	0.573	0.563	0.561
9:40:00 AM	0.566	0.567	0.001	0.002	0.571	0.573	0.563	0.561
9:45:00 AM	0.569	0.567	0.003	0.002	0.571	0.573	0.563	0.561
9:50:00 AM	0.567	0.567	0.002	0.002	0.571	0.573	0.563	0.561
9:55:00 AM	0.568	0.567	0.001	0.002	0.571	0.573	0.563	0.561
10:00:00 AM	0.565	0.567	0.003	0.002	0.571	0.573	0.563	0.561
10:05:00 AM	0.566	0.567	0.001	0.002	0.571	0.573	0.563	0.561
10:10:00 AM	0.565	0.567	0.001	0.002	0.571	0.573	0.563	0.561
10:15:00 AM	0.566	0.567	0.001	0.002	0.571	0.573	0.563	0.561
10:20:00 AM	0.571	0.567	0.005	0.002	0.571	0.573	0.563	0.561
10:25:00 AM	0.570	0.567	0.001	0.002	0.571	0.573	0.563	0.561
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10:35:00 AM	0.565	0.567	0.006	0.002	0.571	0.573	0.563	0.561
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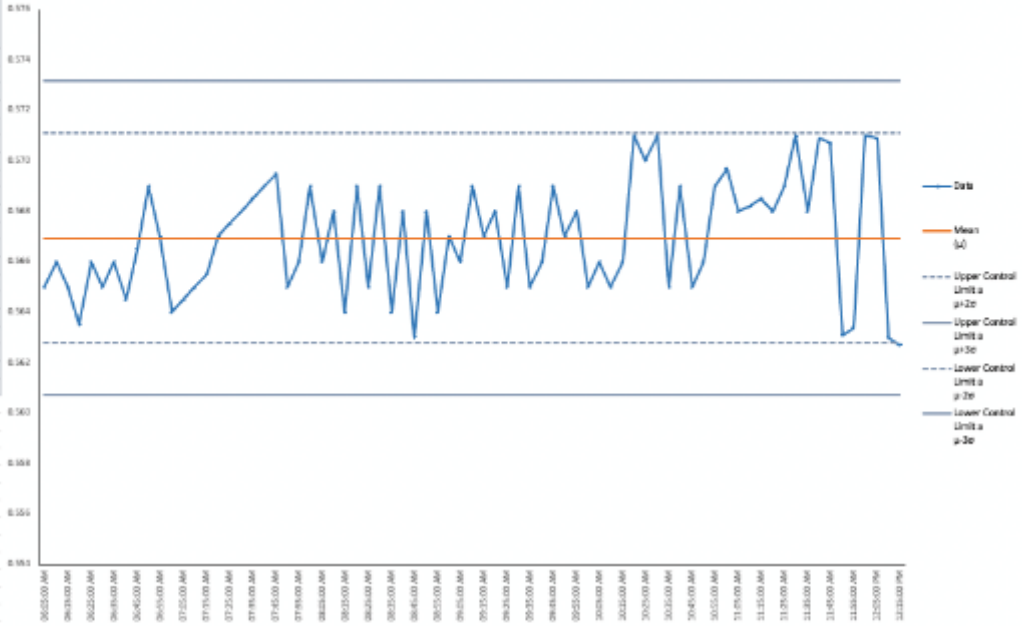
10:50:00 AM	0.566	0.567	0.001	0.002	0.571	0.573	0.563	0.561
10:55:00 AM	0.569	0.567	0.003	0.002	0.571	0.573	0.563	0.561
11:00:00 AM	0.570	0.567	0.001	0.002	0.571	0.573	0.563	0.561
11:05:00 AM	0.568	0.567	0.002	0.002	0.571	0.573	0.563	0.561
11:10:00 AM	0.568	0.567	0.000	0.002	0.571	0.573	0.563	0.561

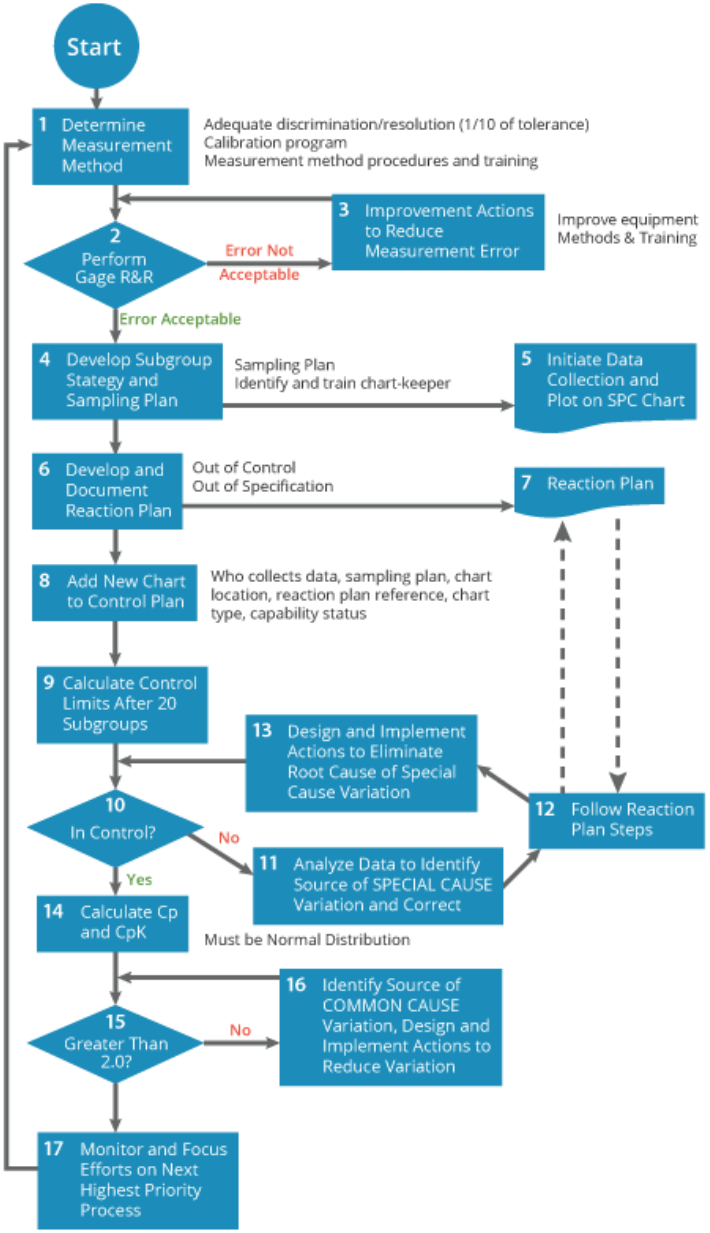
SPC Chart



Implementing Statistical Process Control

- Deploying Statistical Process Control is a process in itself, requiring organizational commitment across functional boundaries.

- The flow-chart below outlines the major components of an effective SPC effort.



https://www.moresteam.com/toolbox/statistical-process-control-spc.cfm

Types of Control Charts?

- Different types of control charts depending on types of data and sample sizes

Variable (measureable, continuous data)

- Mean/Range - (x bar- and R- chart) – sample size up to 10
- Individual/Range (ImR – chart) – best with sample size of one
- Mean/Std Dev – (x bar and S) – larger sub-group sizes over 10

Attribute data

- P-chart/NP-chart/C-chart/U-chart

Adapted from Russell R,. and Taylor, B,. (2010) Operations Management: Creating Value Along the Supply Chain , 7th Ed

Types of Control Charts?

Variable (measureable, continuous data)

- Plots the average or individual points and the range
- Mean/Std Dev – (x bar and S) – larger sub-group sizes over 10

Attribute data

- Plots the proportion or count rather than variable data
- P chart – charts the proportion of defects
- C chart – charts defect count per sample (same sample size each time)
- U chart – charts number of defects per unit (sample size can vary)
- NP chart – number of defects in each sub-group

Adapted from Russell R,. and Taylor, B,. (2010) Operations Management: Creating Value Along the Supply Chain , 7th Ed

Lots of other charts exist

P chart	C charts	U charts	Cusum & EWMA
For yes-no questions like "is it defective?" (binomial data)	For counting number defects where most items have ≥1 defects (eg. custom built houses)	Average count per unit (similar to C chart)	Advanced charts
$\bar{p} \pm 3\sqrt{\frac{\bar{p}(1-\bar{p})}{n}}$	$\bar{c} \pm 3\sqrt{\bar{c}}$	$\bar{u} \pm 3\sqrt{\frac{\bar{u}}{n}}$	"V" shaped or Curved control limits (calculate them by hiring a statistician)

Selecting rational samples

- Chosen so that variation within the sample is considered to be from common causes
- Special causes should only occur between samples
- Special causes to avoid in sampling
  - passage of time
  - workers
  - shifts
  - machines
  - Locations

Chart advice

- Larger samples are more accurate
- Sample costs money, but so does being out-of-control
- Don’t convert measurement data to “yes/no” binomial data (X’s to P’s)
- Don’t combine data (or mix product)
- Have out-of-control procedures (what do I do now?)
- Actual production volume matters (Average Run Length)

Applying SPC to Service Industries

- Nature of defect is different in services.
- Service defect is a failure to meet customer requirements.
- Monitor times, customer satisfaction.

Hospitals?

- Timeliness and quickness of care, staff responses to requests, accuracy of lab tests, cleanliness, courtesy, accuracy of paperwork, speed of admittance.

Airlines?

- Flight delays, lost luggage and luggage handling, waiting time at ticket counters and check-in, agent and flight attendant courtesy, accurate flight information, passenger cabin cleanliness.

Adapted from Russell R,. and Taylor, B,. (2010) Operations Management: Creating Value Along the Supply Chain , 7th Ed

Level 5 – Continuous Improvement with Industry 4.0

Measure 3 – Capability

There are two methods for interpreting data within a manufacturing environment:-

The Specification Value approach (VoC)

Shewharts Control Chart approach (Voice of the Process)

The Specification Value approach (VoC)

Unfavourable result – in trouble – do something	Favourable result – doing OK – do nothing	Unfavourable result – in trouble – do something

Lower customer requirement

Higher customer requirement

Measure - Variation

- In manufacturing, the questions are:
  - Where is the process centered; in other words, is the process on or off target and, if it's the latter, by how much is it off target?
  - How much does the process fluctuate about the center?

Limits

- Process and Control limits (VoP):
  - Statistical
  - Process limits are used for <u>individual items</u>
  - Control limits are used with <u>averages</u>
  - Limits = $\mu \pm 3\sigma$
  - Define usual (common causes) & unusual (special causes)
- Specification limits (VoC):
  - Engineered
  - Limits = target $\pm$ tolerance
  - Define acceptable & unacceptable

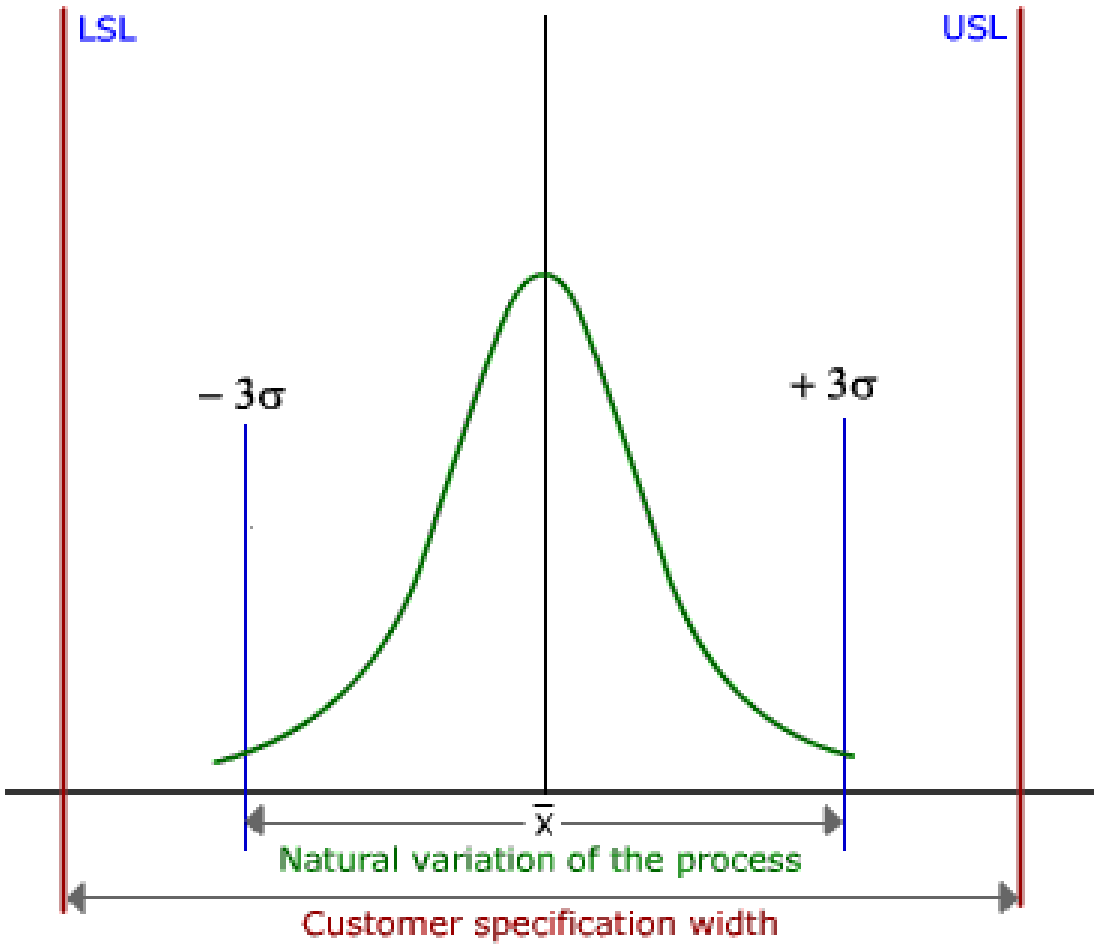
Measure - Control Limits Vs Tolerances

Control limits, are the 'Voice of the Process' Identified as;

- Upper and Lower Control Limits

Tolerances are part of the Customer specification, and therefore the 'Voice of the Customer' Identified as;

- Upper and Lower Specification Limits (LSL & USL)

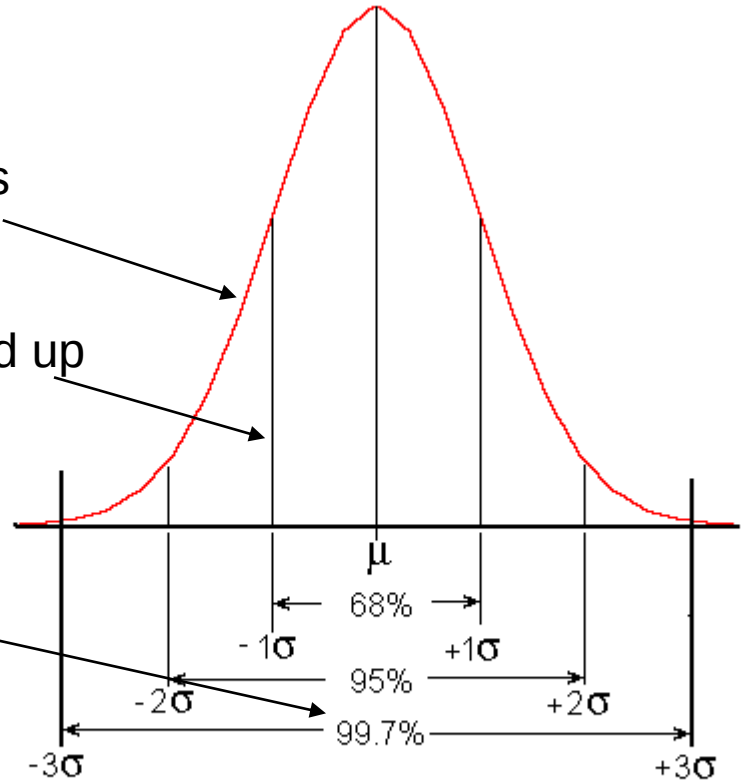


“Normal” bell shaped curve

Add up about 30 of most things
and you start to be “normal”

Normal distributions are divided up
into 3 standard deviations on
each side of the mean

Once you have that, you
know a lot about
what is going on

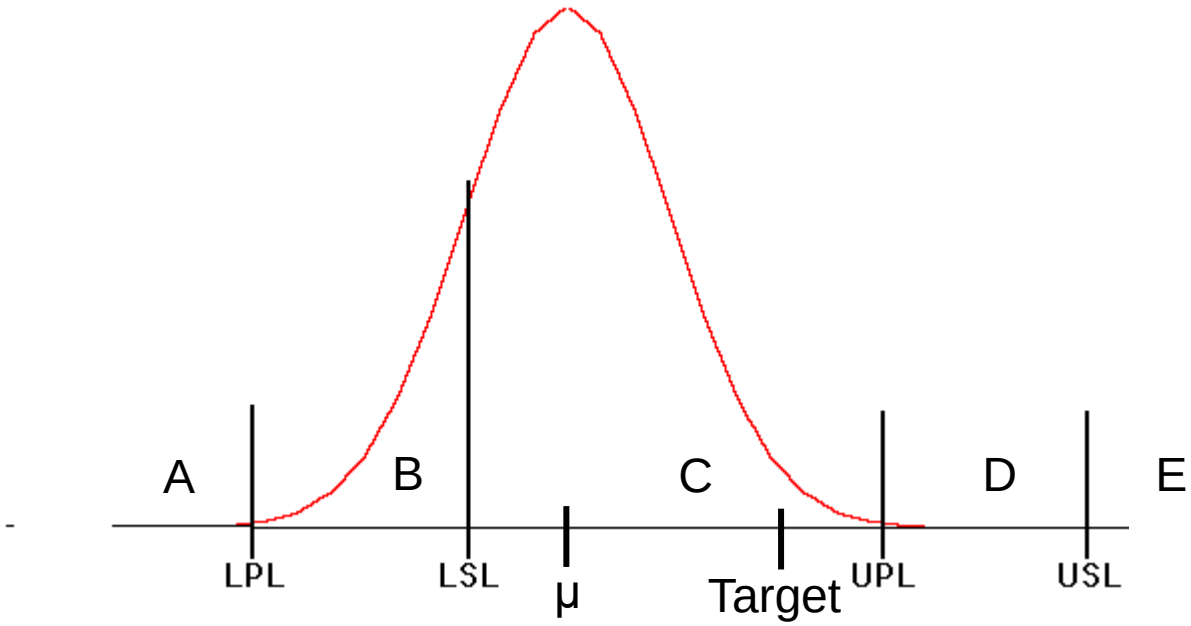


And that is what a standard deviation
is good for

Causes of Variability

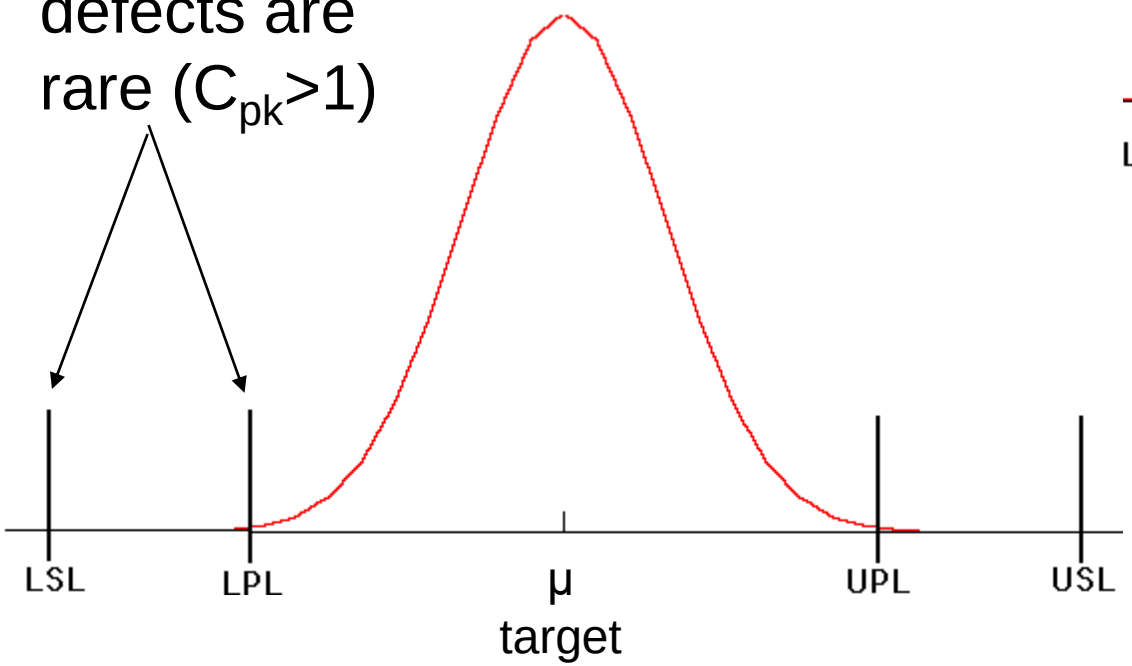
- Common Causes:
  - Random variation (usual)
  - No pattern
  - Inherent in process
  - adjusting the process increases its variation
- Special Causes
  - Non-random variation (unusual)
  - May exhibit a pattern
  - Assignable, explainable, controllable
  - adjusting the process decreases its variation

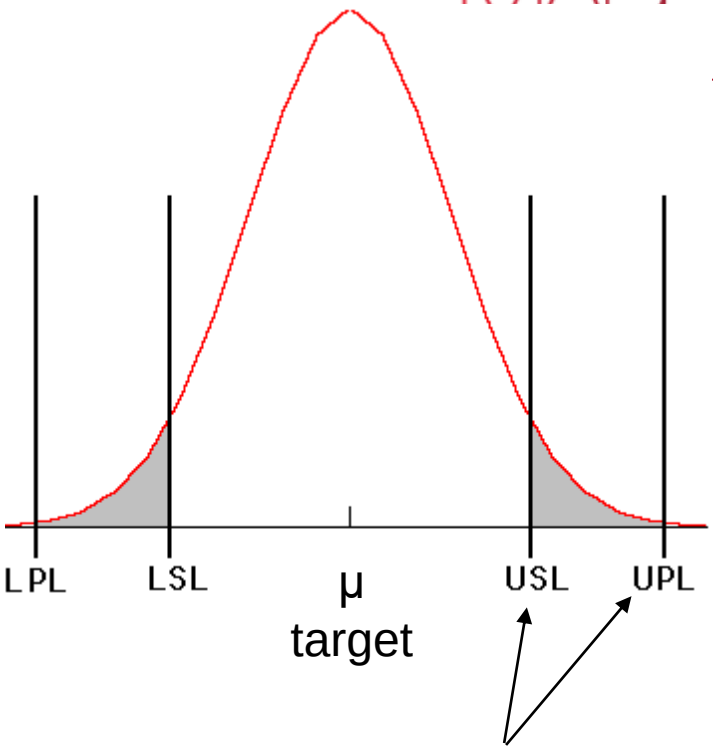
Usual v. Unusual, Acceptable v. Defective



More about limits

Good quality: defects are rare (C_{pk}>1)





Poor quality: defects are common (C_{pk}<1)

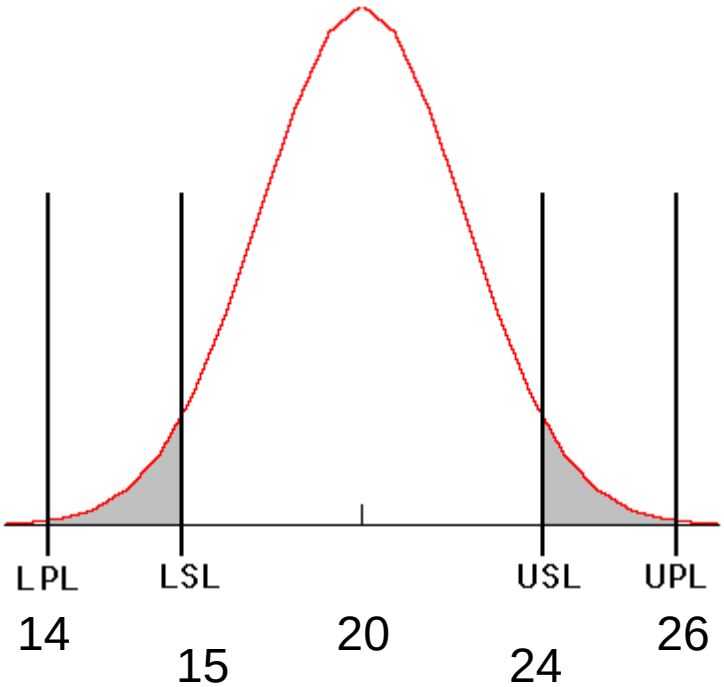
C_{pk} measures "Process Capability"

If process limits and control limits are at the same location, C_{pk} = 1. C_{pk} ≥ 2 is exceptional.

Process capability

Good quality: defects are rare (Cpk>1)
Poor quality: defects are common (Cpk<1)

$$Cpk = \min \begin{cases} \dfrac{USL - \bar{\bar{x}}}{3\sigma} = \dfrac{24 - 20}{6} = .667 \\[2ex] \dfrac{\bar{\bar{x}} - LSL}{3\sigma} = \dfrac{20 - 15}{6} = .833 \end{cases}$$



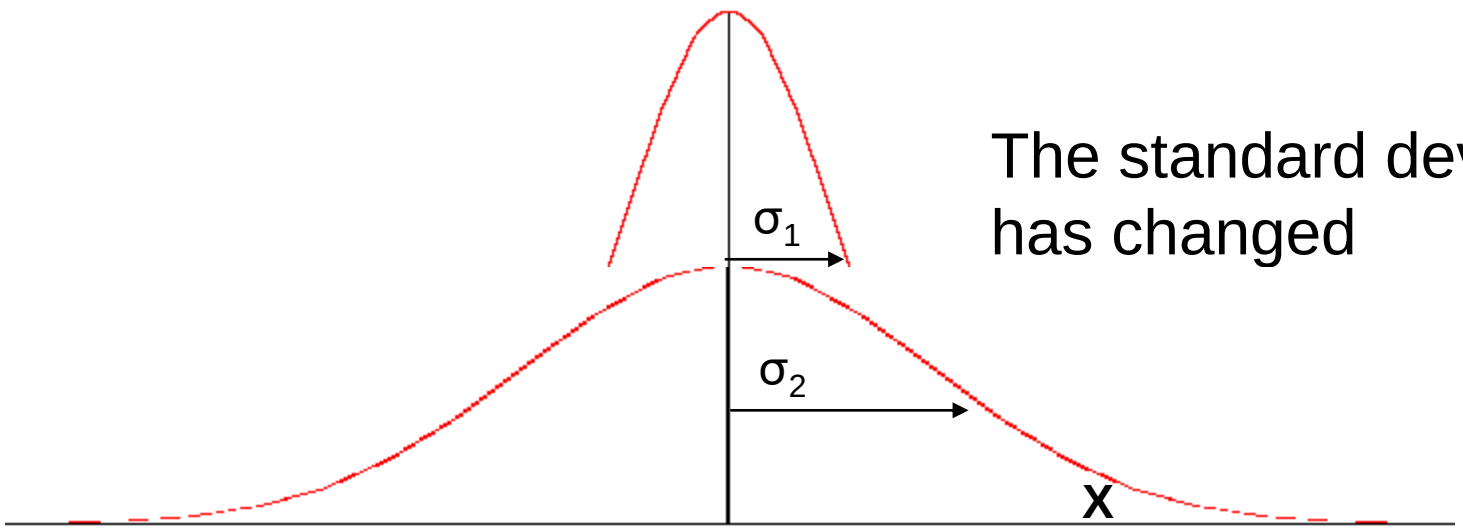
$3\sigma = (UPL - \bar{\bar{x}}, \text{ or } \bar{\bar{x}} - LPL)$

Going out of control

- When an observation is unusual, what can we conclude?

Going out of control

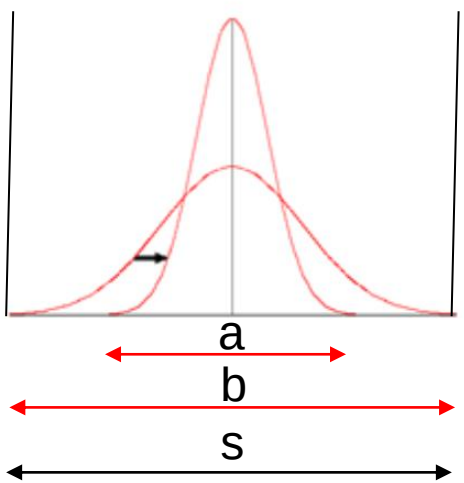
- When an observation is unusual, what can we conclude?



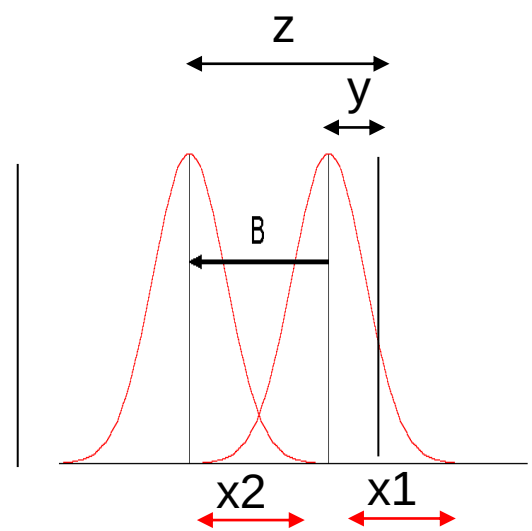
The standard deviation has changed

Summary

- We can now begin to recognise process drift and changes and give them values



a/s = Cp 2
b/s = Cp 1



y/x1 = Cpk .5
z/x2 = approx 3

Cp measures process spread in relation to specification spread

Cpk measures process spread in relation to specification spread and its location relative to process mean and closest spec limit

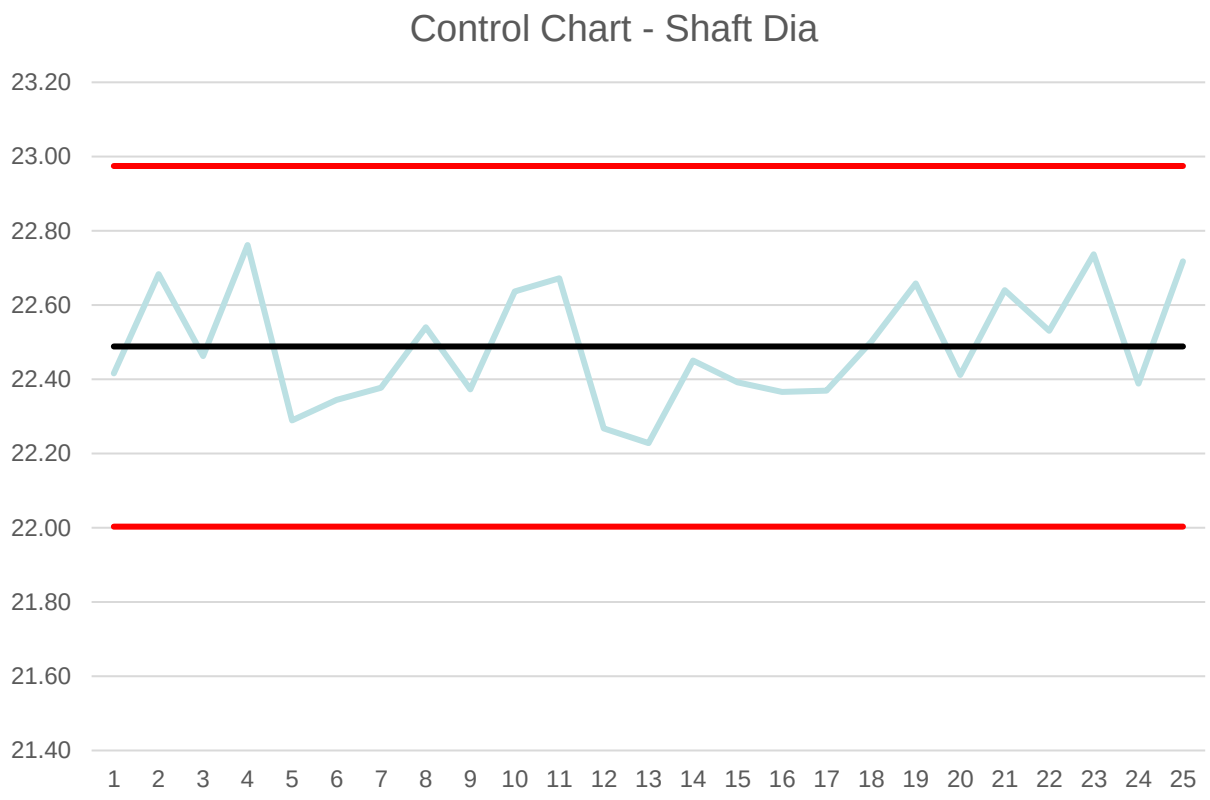
Exercise

- Open the spreadsheet Measure 3 – capability exercise

measurements		average		diff		sq diff		
22.42						0.000		
22.68						0.000		
22.46						0.000		
22.76						0.000		
22.29						0.000		
22.34						0.000		
22.38						0.000		
22.54						0.000		
22.37						0.000		
22.64						0.000		
22.67						0.000		
22.27						0.000		
22.23						0.000		
22.45						0.000		
22.39						0.000		
22.37						0.000		
22.37						0.000		
22.50						0.000		
22.66						0.000		
22.41						0.000		
22.64						0.000		
22.53						0.000		
22.74						0.000		
22.39						0.000		
22.72						0.000		
	ave					0.000	variance	
0.00	UCL					0.000	std dev	
0.00	LCL							
	lower		specification					
22.00	spec		tol		spread			
23.00	upper spec			1.00		0	#DIV/0!	Cp
							#DIV/0!	CpU
							#DIV/0!	CpL

Exercise

- Open the spreadsheet Measure 3 – capability exercise



Summary

- Cp will give you the process capability against the specification but will not give you its location
- Cpk will give you the location to one side of the process in relation to a specification limit but will not give you the other side performance
- You have to use both Cp and Cpk to get the full picture!

Next Week Schedule

- From next week, April 1st lectures will be 1pm – 3pm