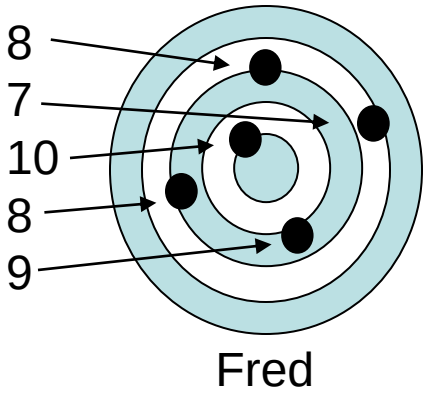
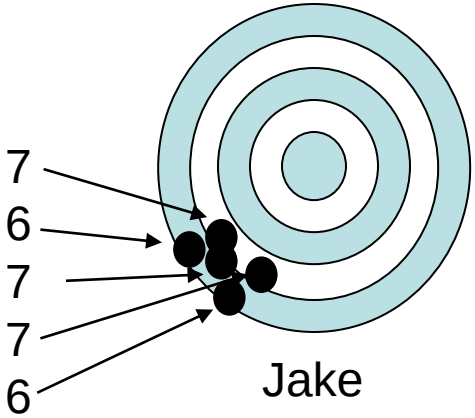
Level 5 – Continuous Improvement with Industry 4.0

Measure 4 – Variation, Capability recap and OEE

Deviation

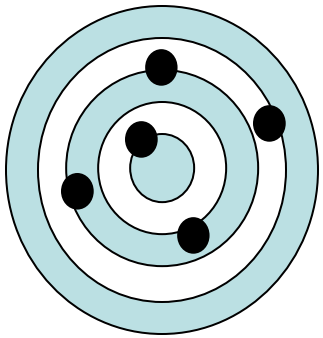
distance between observations and the mean *(or average)*



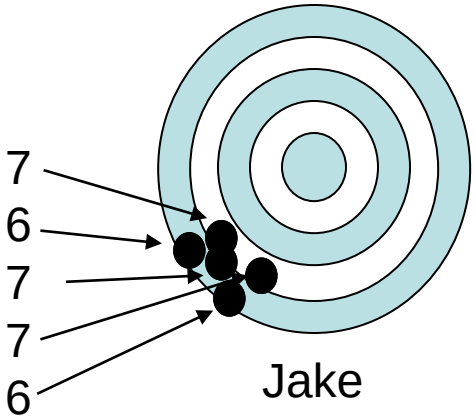


Measure - Variation

- Variance = average distance between observations and the mean squared



Fred



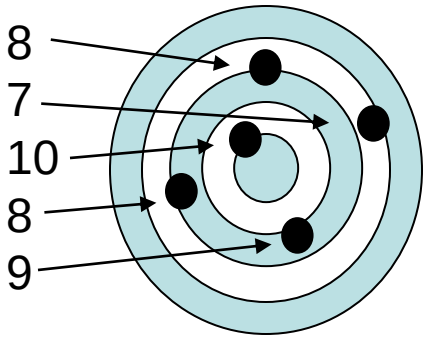
Jake

	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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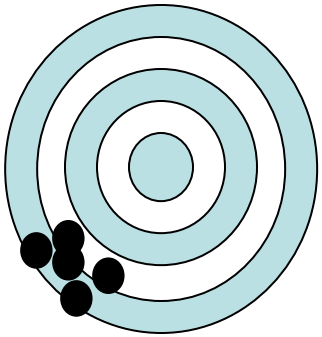


Jake

	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

Consider a <u>sample</u> 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 - Standard Deviation

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

The Standard Deviation is

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

Note The above n-1 is used when taking a sample from a population.

You can use N if you are sure the data is the whole population i.e arrows shot into target

The Specification Value approach (VoC)

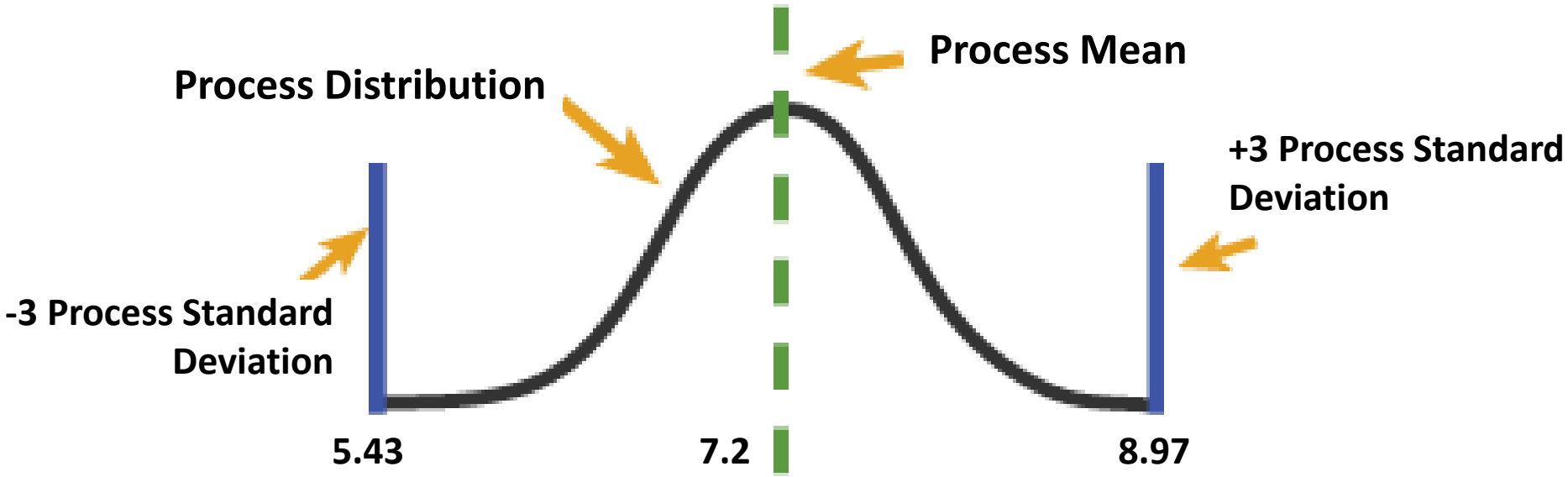
Unfavourable result – in trouble – do something	Favourable result – doing OK – do nothing	Unfavourable result – in trouble – do something

Lower customer requirement

Higher customer requirement

Measure - 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.

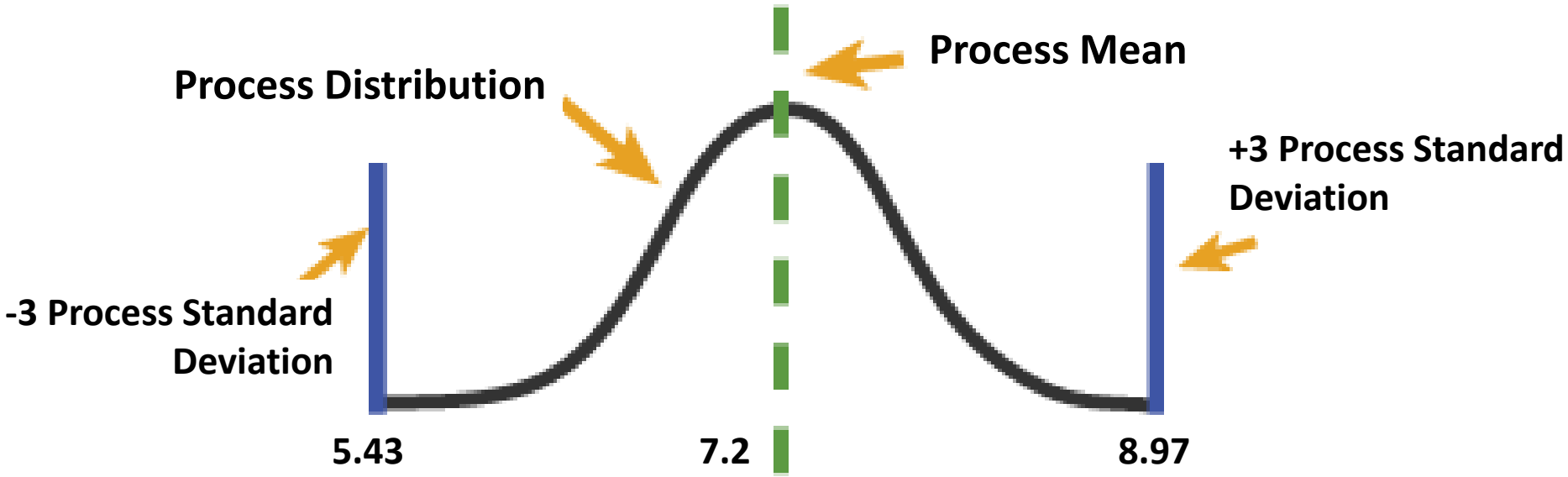
- 3x STDEV + Mean

- $\boldsymbol{stdev = 0.59}$

⇢(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.



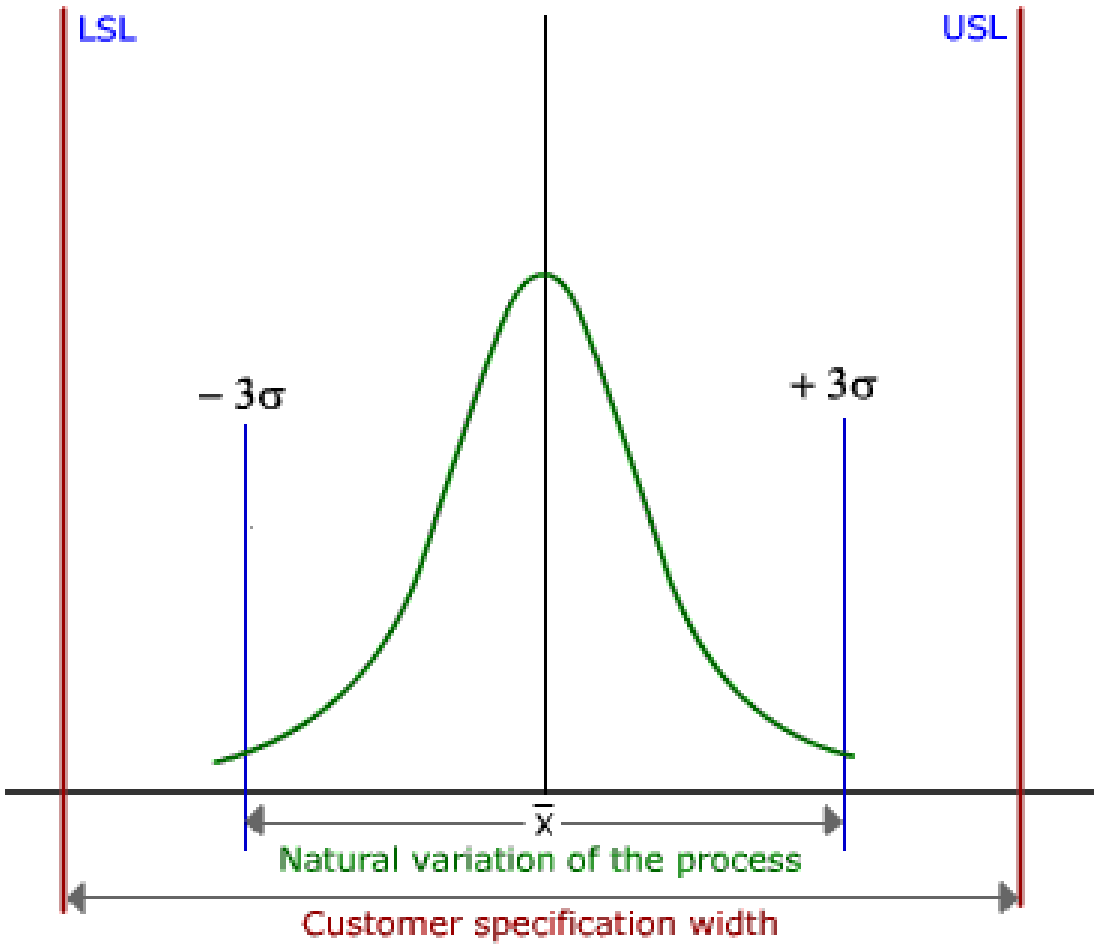
Measure - Control Limits Vs Tolerances

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

- Upper and Lower Control Limits

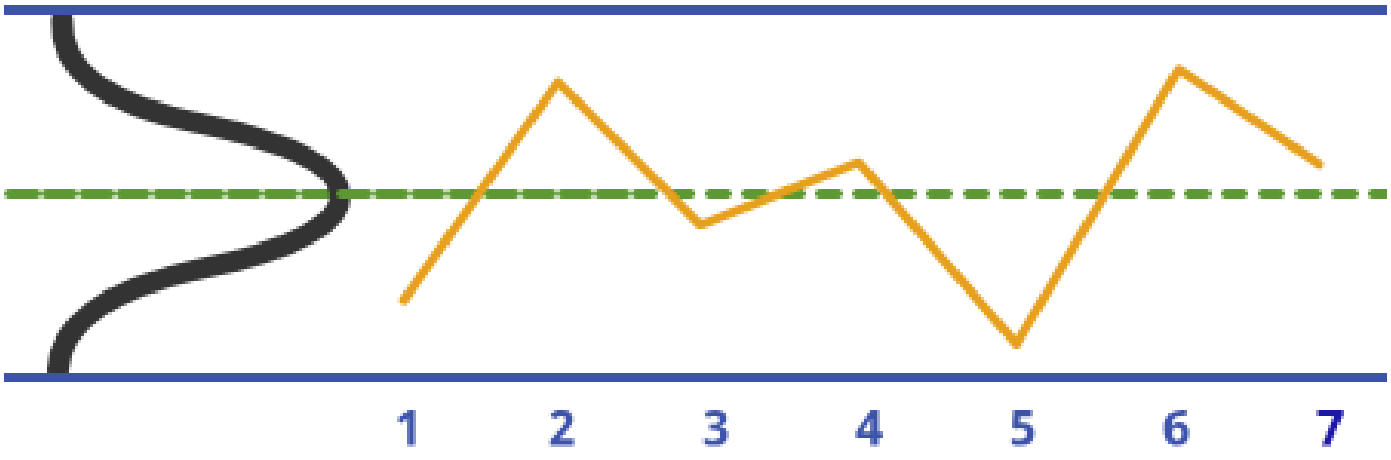
Tolerances are part of the Customer specification, and therefore the 'Voice of the Customer' Identified as;

- Upper and Lower Specification Limits (LSL & USL)



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.



Sampling Strategies

Robust method on deciding when to take samples:-

- Random sampling – nos 4,17,22,24,32,43,57,68 etc
- Sequential sampling – 5 samples per hour, every hour

Two worst ways to take samples:-

- Judgement – based on someone’s knowledge of process
- Convenience – easiest to measure or at convenient times

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
- Don’t combine data (or mix product)
- Have out-of-control procedures (what do I do now?)
- Actual production volume matters (Average Run Length)

Sampling Strategies

Rough sample size guidelines:-

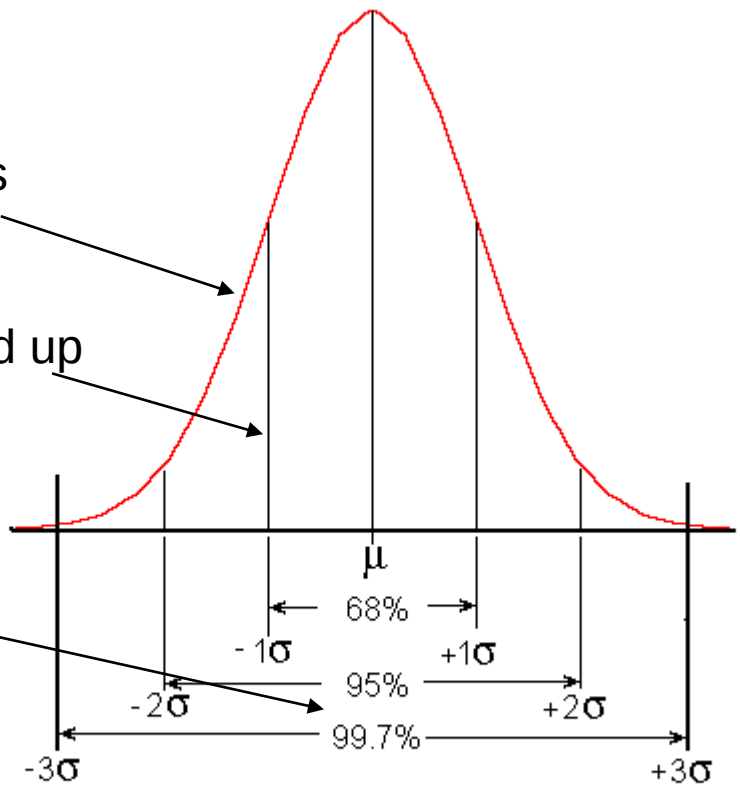
- Variable data minimum 25 to 30 measurements
- Attribute data 50 to 100 samples
- We can understand optimizing sample sizes during ‘Analyse’ phase

“Normal data” 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

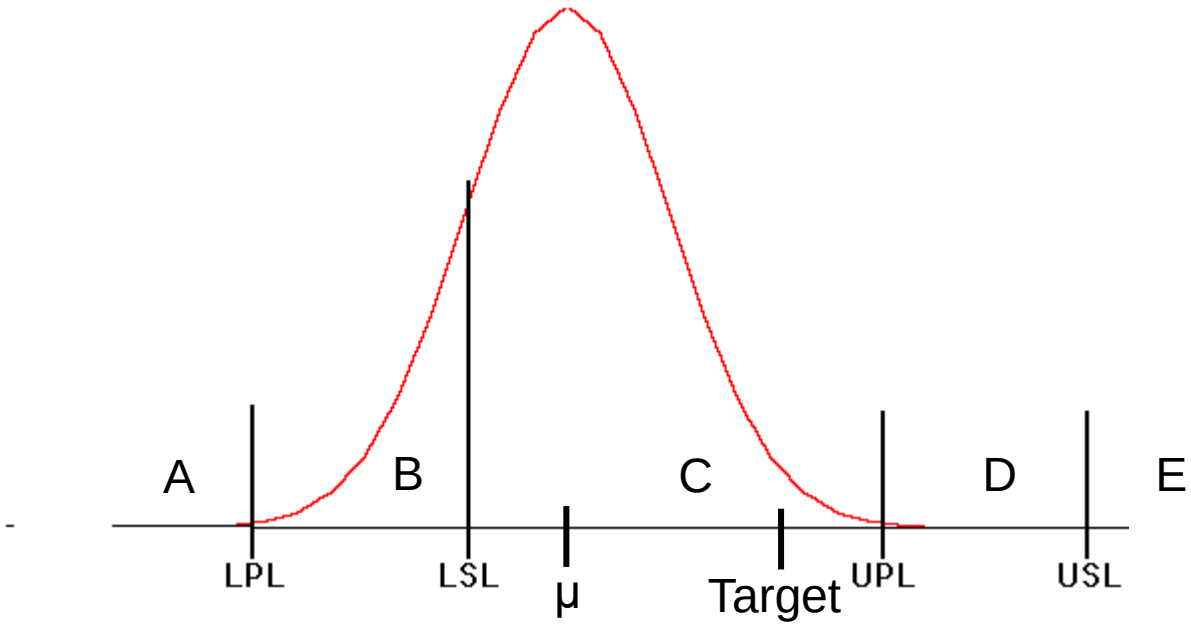
- Common Causes:
  - Random variation (usual)
  - No pattern
  - Inherent in process
  - adjusting the process increases its variation
- Special Causes
  - Non-random variation (unusual)
  - May exhibit a pattern
  - Assignable, explainable, controllable
  - adjusting the process decreases its variation

SPC uses samples to identify that special causes have occurred

Limits

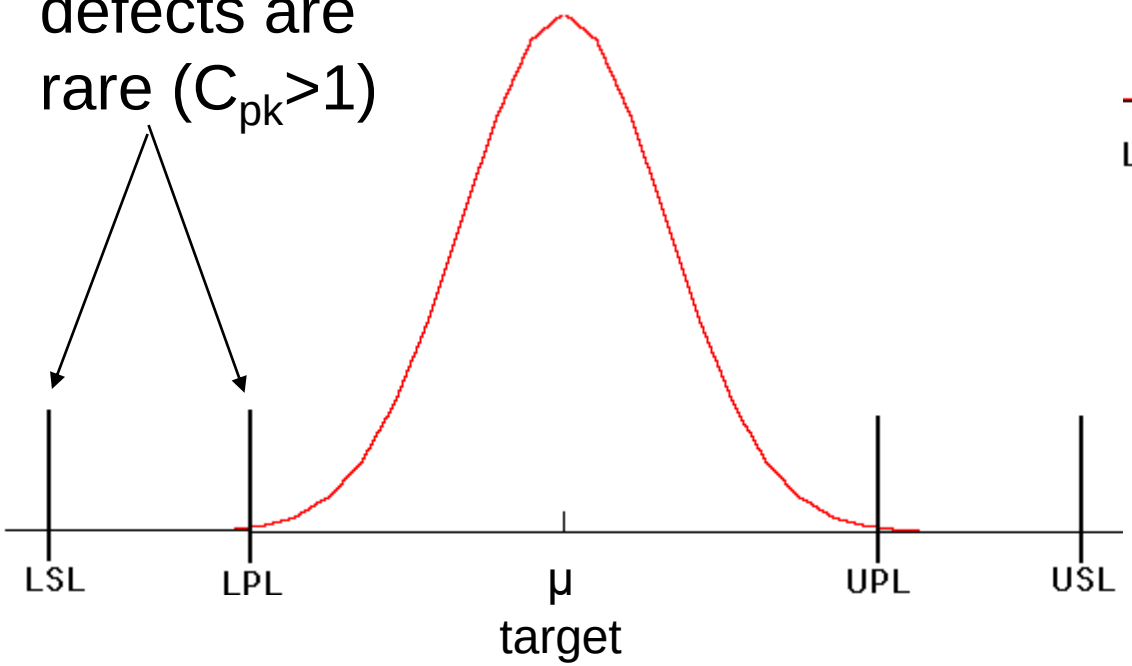
- Process and Control limits (VoP):
  - Statistical
  - Process limits are used for <u>individual items</u>
  - Control limits are used with <u>averages</u>
  - Limits = $\mu \pm 3\sigma$
  - Define usual (common causes) & unusual (special causes)
- Specification limits (VoC):
  - Engineered
  - Limits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

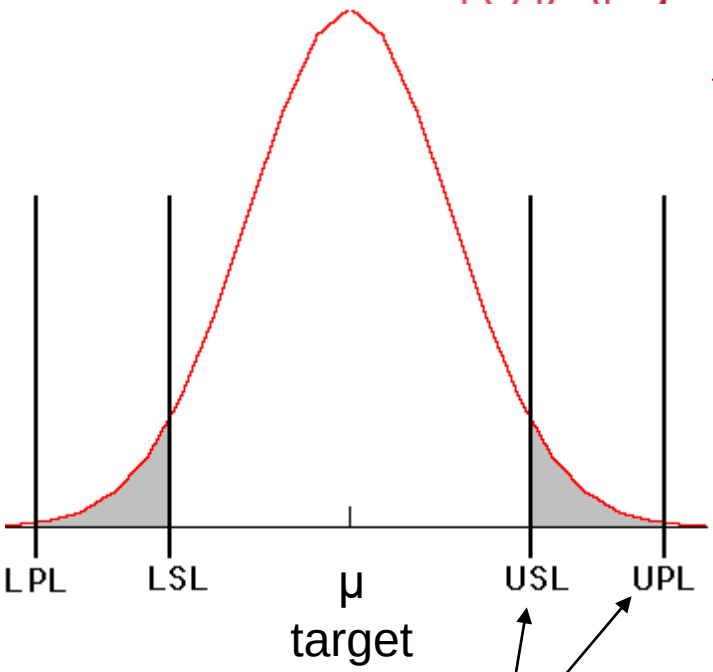
Usual v. Unusual, Acceptable v. Defective



More about limits

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





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

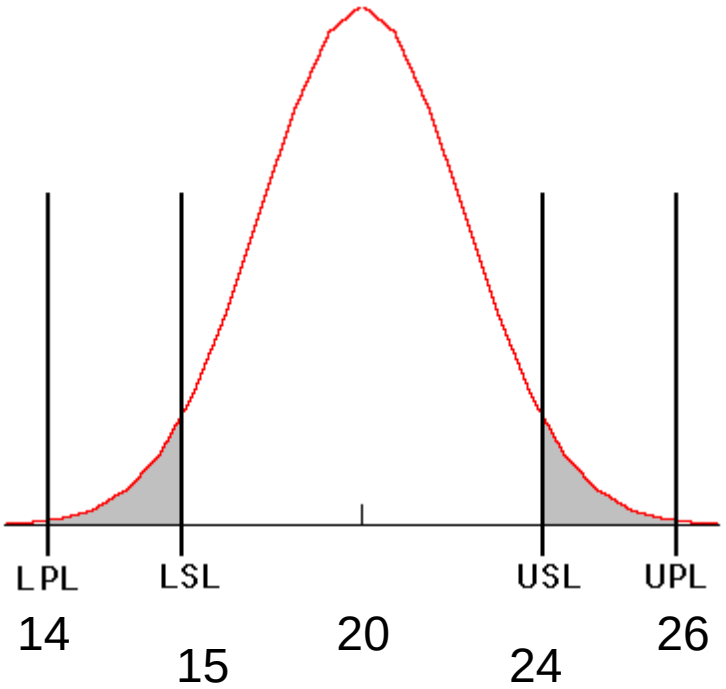
C_{pk} measures "Process Capability"

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)

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



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

Going out of control

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

Going out of control

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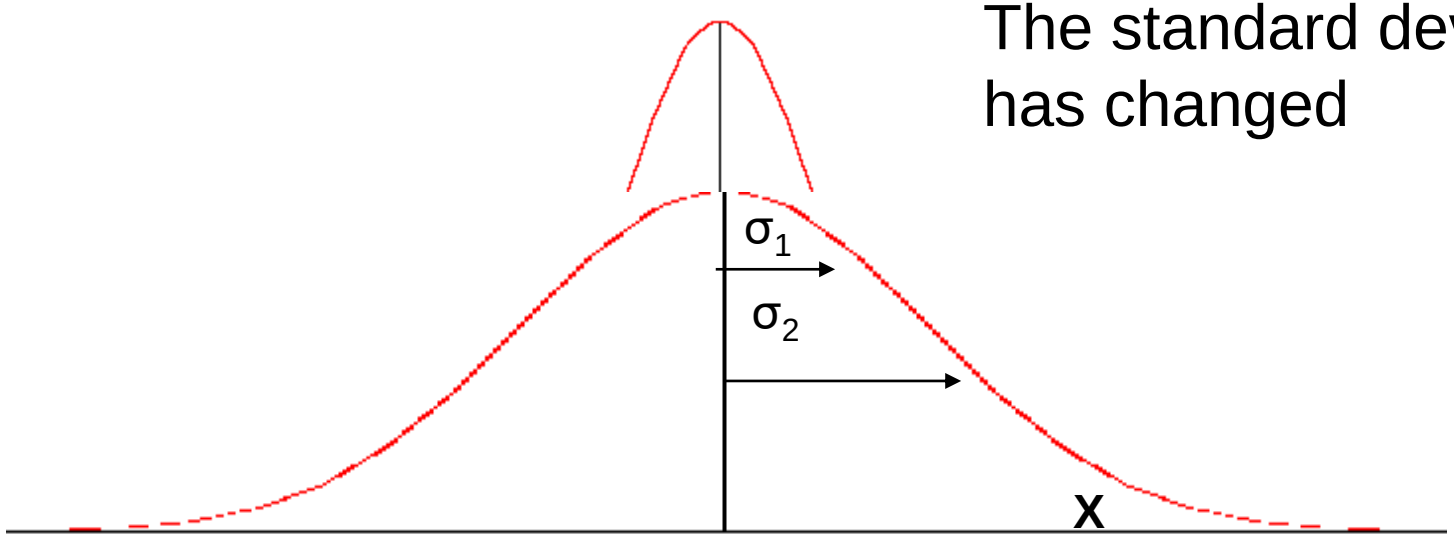
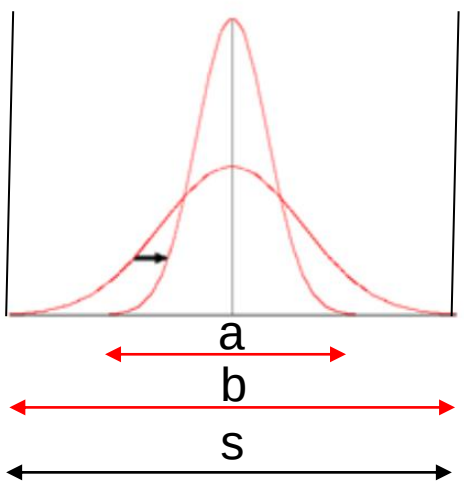


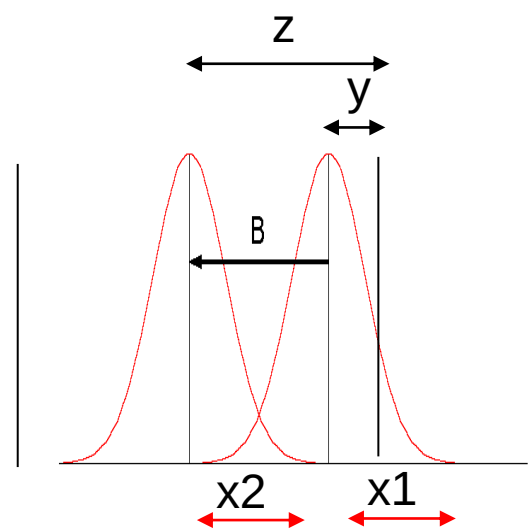
The standard deviation has changed

Summary

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



s/a =
Cp 2
s/b =
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

Measure – Variation - Exercise

A company have a feature of a shoulder on a machined part. The specification of this shoulder is 22.00mm – 23.50mm. They want to understand their process capability. Work out control limits and Cp and Cpk. Sizes are as follows: –

22.42
22.68
22.46
22.76
22.29
22.34
22.38
22.54
22.37
22.64
22.67
22.27
22.23
22.45
22.39
22.37
22.37
22.50
22.66
22.41
22.64
22.53
22.74
22.39
22.72

Tips:-

1. Find average of the data
2. Take each individual measurements from the average
3. Square each result (to remove negatives)
4. Find average of these values (the variance)
5. Square root variance to find Std Deviation
6. Find control limits (3*std dev +/- ave)
7. Find Cp (upper spec-lower spec)/6*std dev
8. Find Cpu (upper spec limit – ave)/3*std dev
9. Find Cpl (ave-lower spec limit)/3*std dev
10. Cpk is the lower value of 8 and 9 above
11. You can use spreadsheet sent separately

Measure – Variation - Exercise

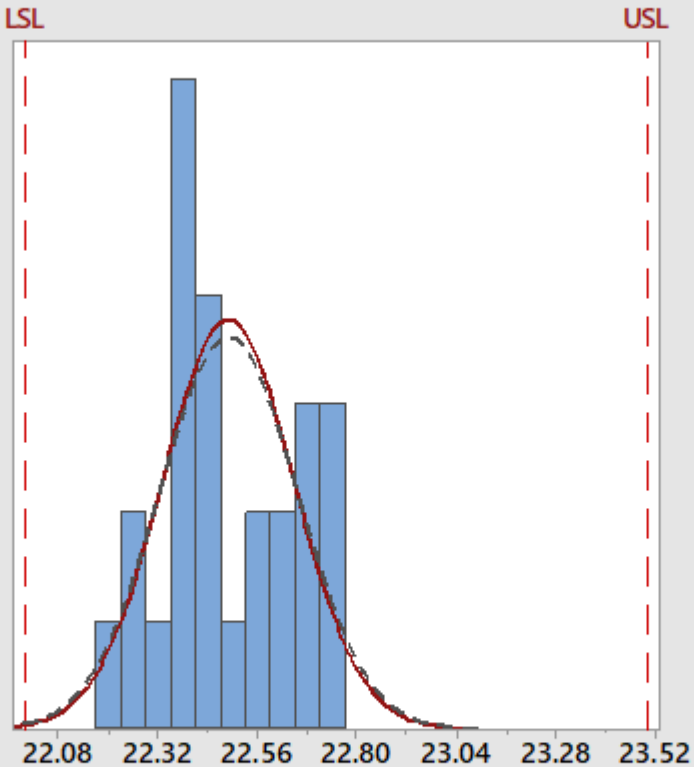
measurements		average	diff	sq diff	
22.42		22.49	-0.07	0.005	
22.68		22.49	0.19	0.038	
22.46		22.49	-0.03	0.001	
22.76		22.49	0.27	0.074	
22.29		22.49	-0.20	0.040	
22.34		22.49	-0.14	0.021	
22.38		22.49	-0.11	0.012	
22.54		22.49	0.05	0.003	
22.37		22.49	-0.12	0.013	
22.64		22.49	0.15	0.022	
22.67		22.49	0.18	0.034	
22.27		22.49	-0.22	0.049	
22.23		22.49	-0.26	0.068	
22.45		22.49	-0.04	0.001	
22.39		22.49	-0.10	0.009	
22.37		22.49	-0.12	0.015	
22.37		22.49	-0.12	0.014	
22.50		22.49	0.01	0.000	
22.66		22.49	0.17	0.029	
22.41		22.49	-0.08	0.006	
22.64		22.49	0.15	0.023	
22.53		22.49	0.04	0.002	
22.74		22.49	0.25	0.062	
22.39		22.49	-0.10	0.010	
22.72		22.49	0.23	0.053	
22.49	ave			0.025	variance
				0.158	std dev

22.96	UCL		lower		specification			
		22.00	spec		tol		spread	
22.01	LCL	23.50	upper spec		1.50		0.950928	1.58 Cp
								2.13 CpU
								1.03 CpL

Measure – Variation - Exercise

Process Capability Report for measurements

Process Data	
LSL	22
Target	*
USL	23.5
Sample Mean	22.4885
Sample N	25
StDev(Overall)	0.158488
StDev(Within)	0.165638



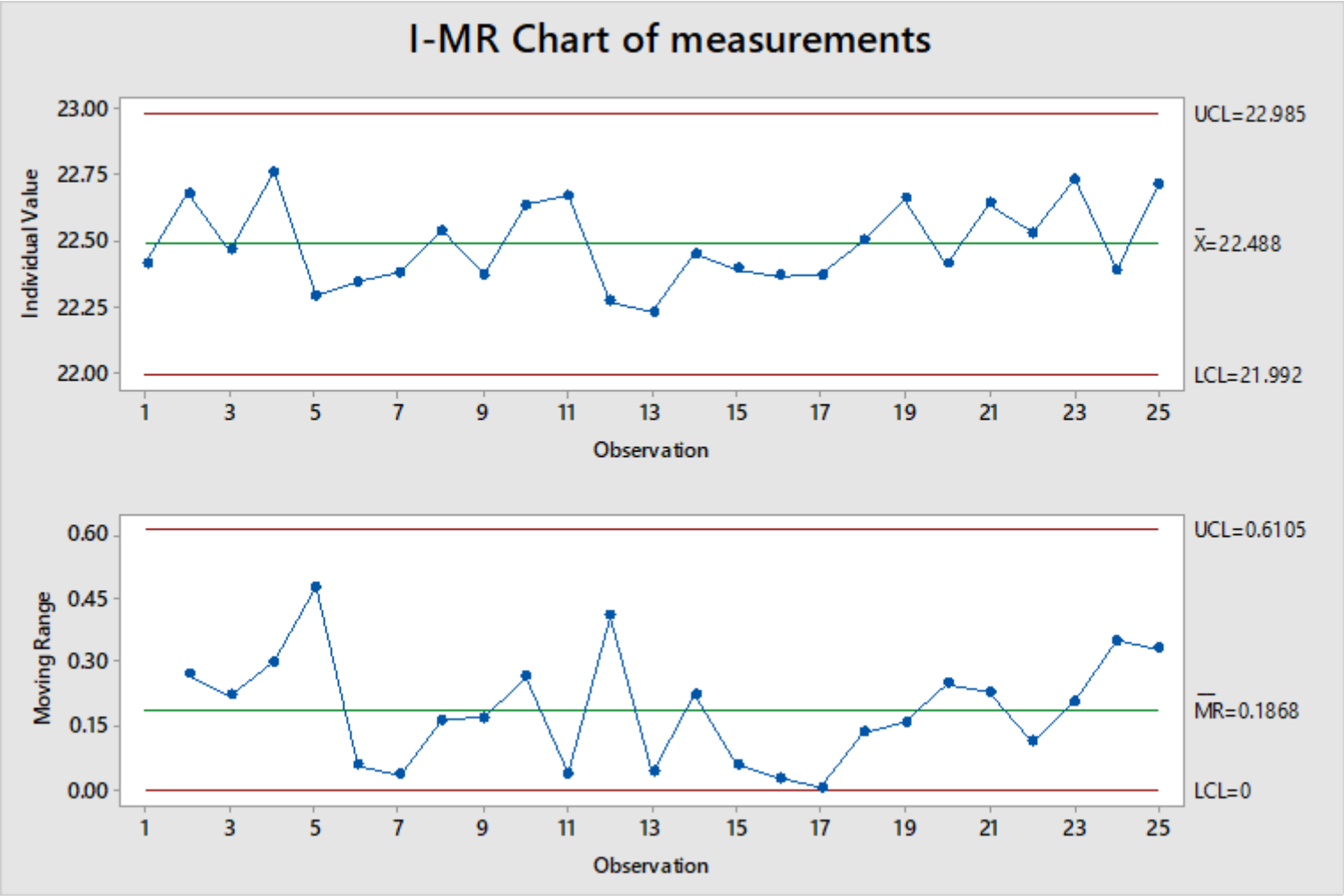
Overall
Within

Overall Capability	
Pp	1.58
PPL	1.03
PPU	2.13
Ppk	1.03
Cpm	*

Potential (Within) Capability	
Cp	1.51
CPL	0.98
CPU	2.04
Cpk	0.98

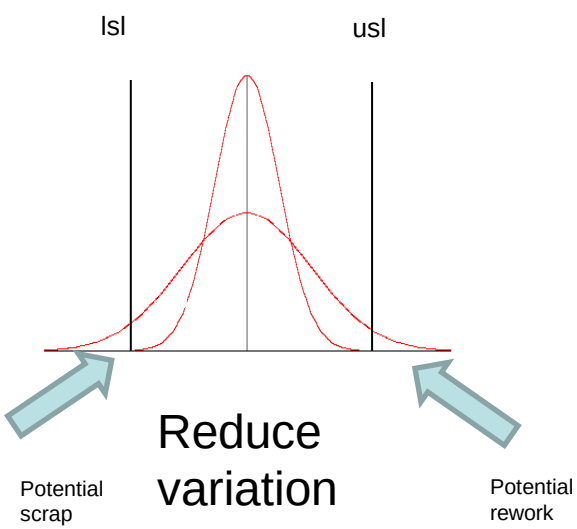
Performance	Observed	Expected Overall	Expected Within
PPM < LSL	0.00	1027.65	1593.66
PPM > USL	0.00	0.00	0.00
PPM Total	0.00	1027.65	1593.66

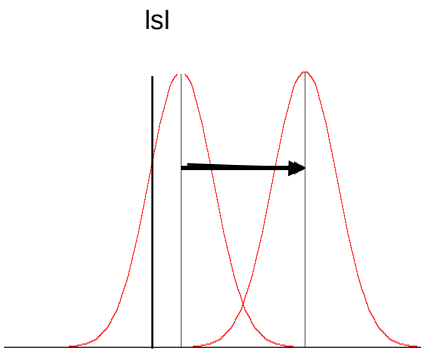
Measure – Variation - Exercise

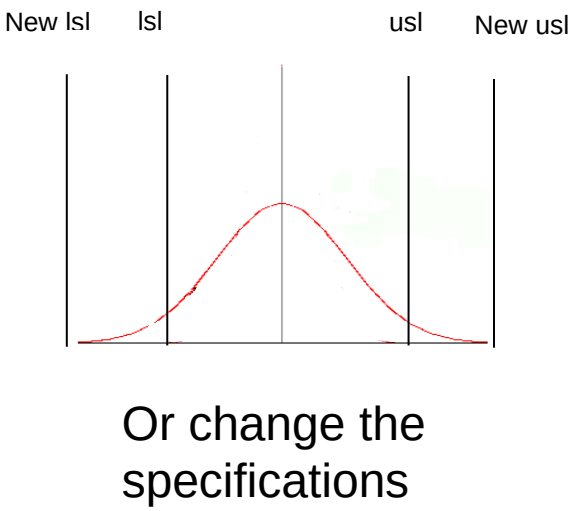


Interpreting charts

- When we have a degree of statistical control the only way to tackle non-conforming product is to bring ‘the voices’ into alignment

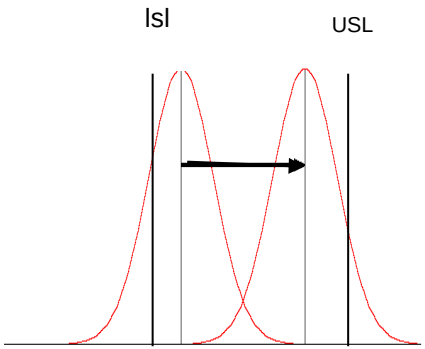






Interpreting charts

- If you only shift the aim, the scrap reduces but you potentially have re-work to consider



Shift the Aim

Measure – Variation – Exercise 2

A company have lorries which are loaded with aggregates. The weights of the lorries should be between 20 and 23t. They want to understand their process capability. Work out control limits and Cp and Cpk. Sizes are as follows: –

20589
21256
20577
21547
21384
21400
21839
21098
20763
21441
21551
20413
20722
21247
21609
21345
21347
20424
20560
21389
20983
20652
21375
21584
21497
21188
21786
21220
21345
21581

Tips:-

1. Find average of the data
2. Take each individual measurements from the average
3. Square each result (to remove negatives)
4. Find average of these values (the variance)
5. Square root variance to find Std Deviation
6. Find control limits (3*std dev +/- ave)
7. Find Cp (upper spec-lower spec)/6*std dev
8. Find Cpu (upper spec limit – ave)/3*std dev
9. Find Cpl (ave-lower spec limit)/3*std dev
10. Cpk is the lower value of 8 and 9 above
11. You can use spreadsheet sent separately

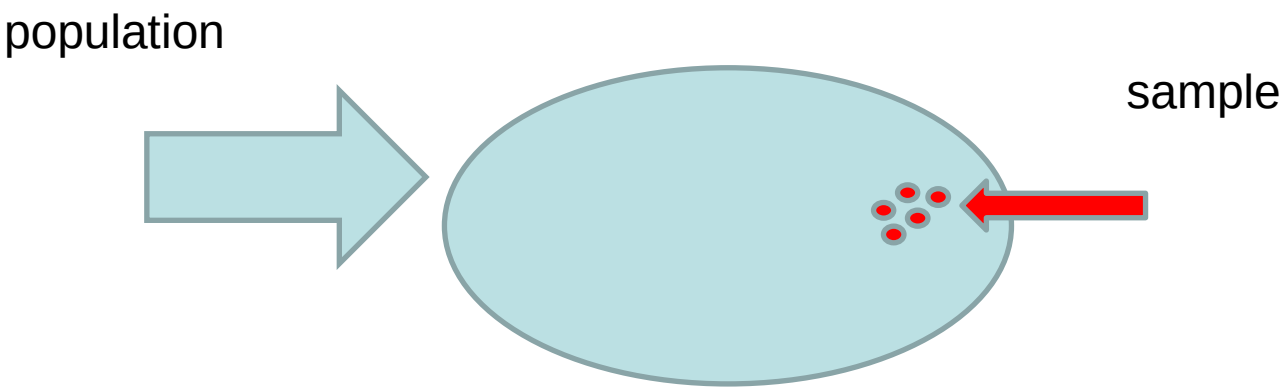
Measure – Variation - Exercise

measurements		average	diff	sq diff	
20589		21190.4	-601.4	361682	
21256		21190.4	65.6	4303.36	
20577		21190.4	-613.4	376259.6	
21547		21190.4	356.6	127163.6	
21384		21190.4	193.6	37480.96	
21400		21190.4	209.6	43932.16	
21839		21190.4	648.6	420682	
21098		21190.4	-92.4	8537.76	
20763		21190.4	-427.4	182670.8	
21441		21190.4	250.6	62800.36	
21551		21190.4	360.6	130032.4	
20413		21190.4	-777.4	604350.8	
20722		21190.4	-468.4	219398.6	
21247		21190.4	56.6	3203.56	
21609		21190.4	418.6	175226	
21345		21190.4	154.6	23901.16	
21347		21190.4	156.6	24523.56	
20424		21190.4	-766.4	587369	
20560		21190.4	-630.4	397404.2	
21389		21190.4	198.6	39441.96	
20983		21190.4	-207.4	43014.76	
20652		21190.4	-538.4	289874.6	
21375		21190.4	184.6	34077.16	
21584		21190.4	393.6	154921	
21497		21190.4	306.6	94003.56	
21188		21190.4	-2.4	5.76	
21786		21190.4	595.6	354739.4	
21220		21190.4	29.6	876.16	
21345		21190.4	154.6	23901.16	
21581		21190.4	390.6	152568.4	
21190.4	ave			171667.1	variance
				414.3273	std dev

	lower		specificati				
20000	spec		on tol	spread			
			300				
23000	upper spec		0.00	2485.964			
						1.21	Cp
						1.46	CpU
						0.96	CpL

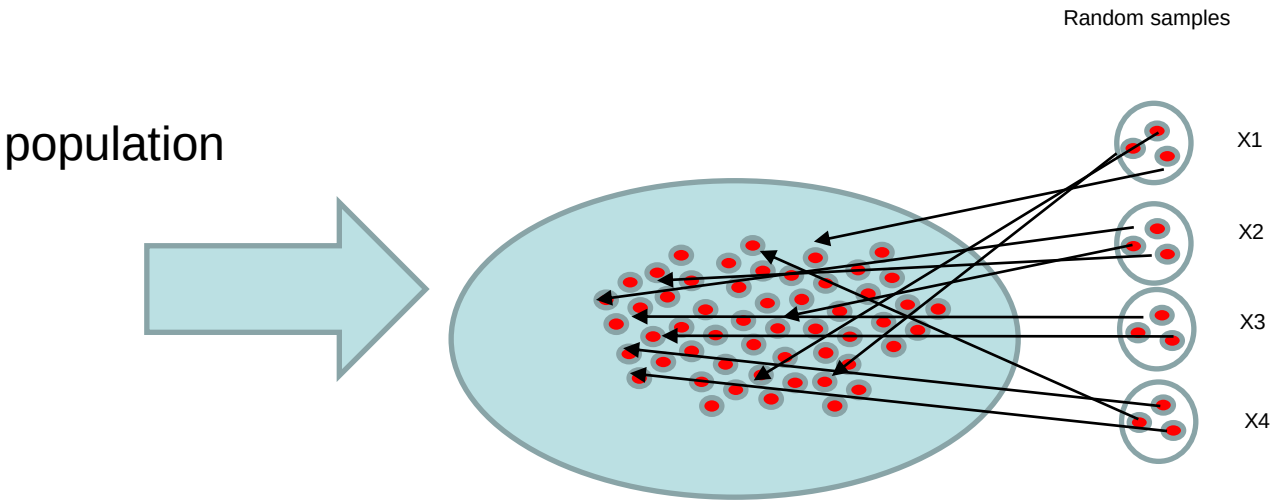
Sampling Strategies

What is a sample?



- A sample is a sub-set of all possible values
- As the sample does not contain all possible values there is some uncertainty about the population
- Any statistics are just estimates of the true population parameters

Sampling Strategies



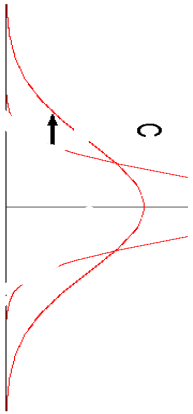
Mean of <u>all</u> samples (population) $= \frac{x1+x2+x3+x4}{4}$

Mean of random samples $= \frac{x1+x2+x3+x4}{4-1}$

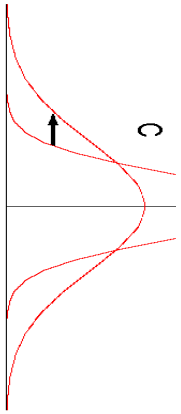
.

Sampling Strategies

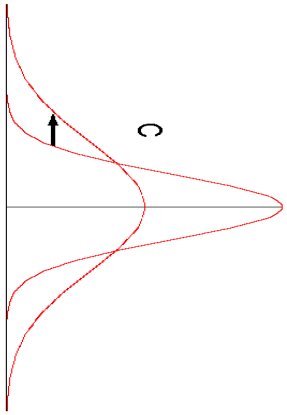
Sample 1 – short term



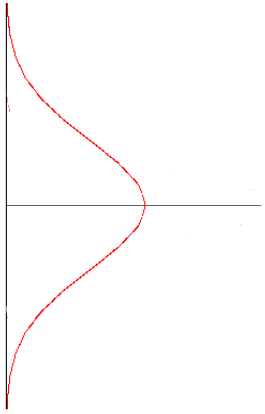
Sample 2 – short term



Sample 3 –

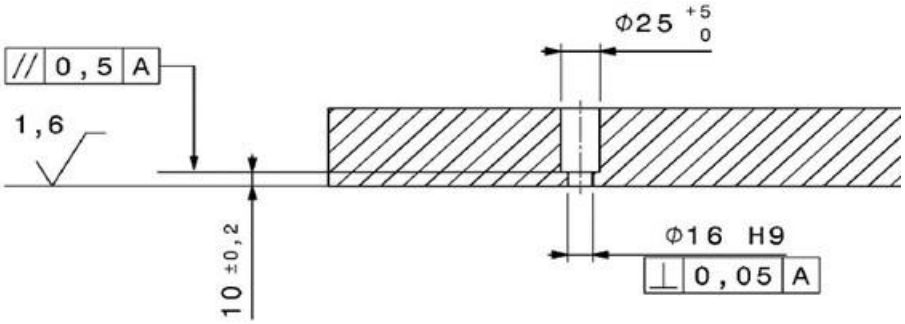


Population – long term



- Short term variation expressed as Cp and Cpk (within sub-groups)
- Long term variation expressed as Pp and Ppk (overall)
- Be warned many companies calculate long term capability and express as Cp and Cpk

Example



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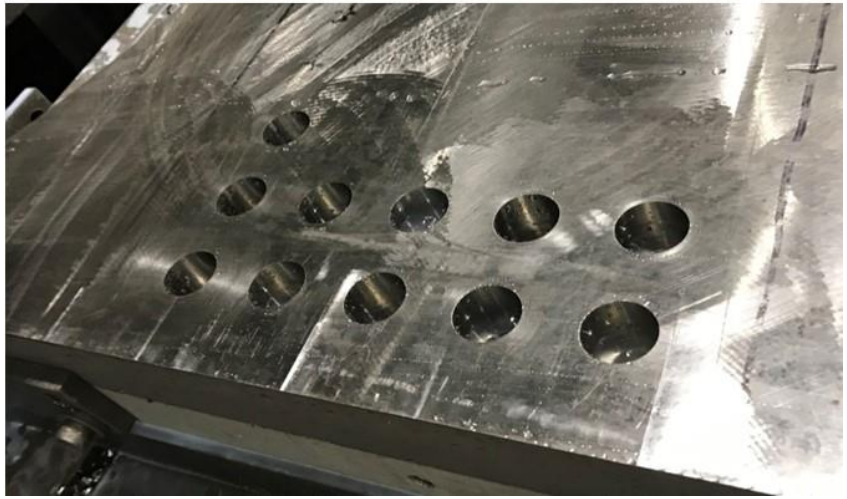
Example



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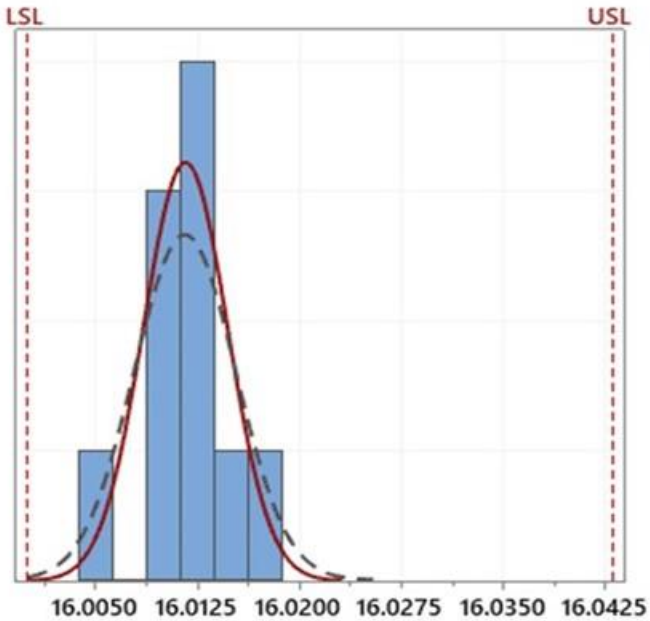
Example

rocess Capability Report for 16mm dia hole using 15.7 reamer hea

Process Data	
LSL	16
Target	*
USL	16.043
Sample Mean	16.0116
Sample N	10
StDev(Overall)	0.00309839
StDev(Within)	0.0037431



Overall
Within

Overall Capability	
Pp	2.31
PPL	1.25
PPU	3.38
Ppk	1.25
Cpm	*

Potential (Within) Capability	
Cp	1.91
CPL	1.03
CPU	2.80
Cpk	1.03

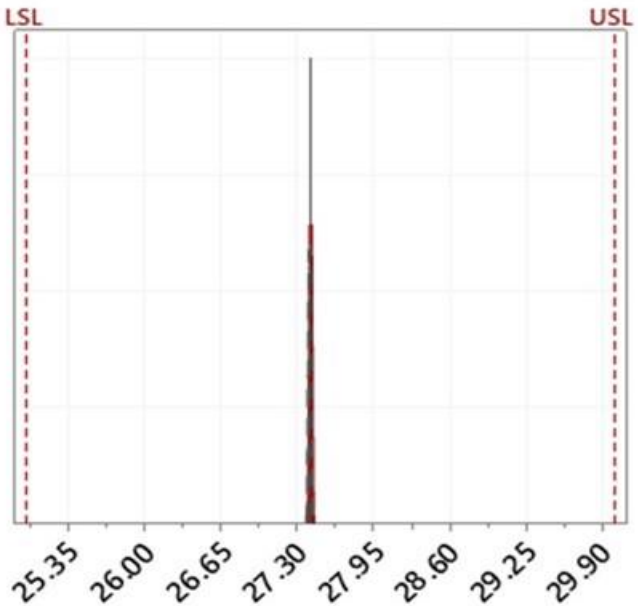
Performance	Observed	Expected Overall	Expected Within
PPM < LSL	0.00	90.60	970.77
PPM > USL	0.00	0.00	0.00
PPM Total	0.00	90.60	970.77

The actual process spread is represented by 6 sigma.

Example

Process Capability Report for 25mm dia

Process Data	
LSL	25
Target	*
USL	30
Sample Mean	27.4175
Sample N	10
StDev(Overall)	0.00773843
StDev(Within)	0.00843184



Overall
Within

Overall Capability	
Pp	107.69
PPL	104.13
PPU	111.24
Ppk	104.13
Cpm	*

Potential (Within) Capability	
Cp	98.83
CPL	95.57
CPU	102.09
Cpk	95.57

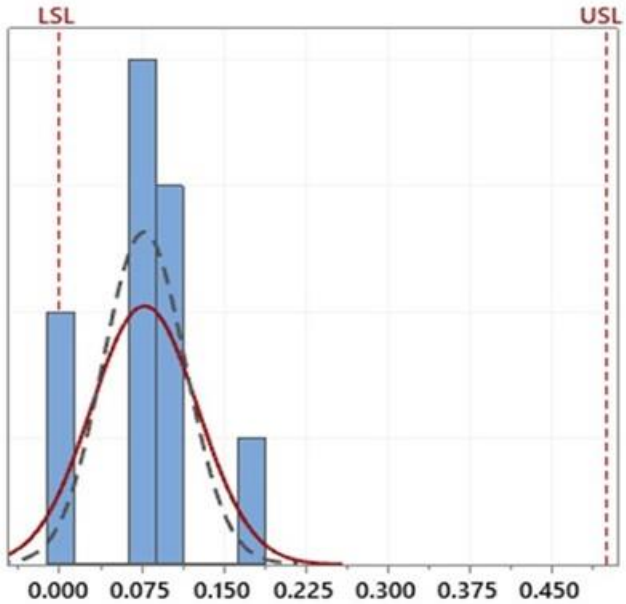
	Performance		
	Observed	Expected Overall	Expected Within
PPM < LSL	0.00	0.00	0.00
PPM > USL	0.00	0.00	0.00
PPM Total	0.00	0.00	0.00

The actual process spread is represented by 6 sigma.

Example

Process Capability Report for parallelism

Process Data	
LSL	0
Target	*
USL	0.5
Sample Mean	0.07746
Sample N	10
StDev(Overall)	0.0487655
StDev(Within)	0.037894



Overall
Within

Overall Capability	
Pp	1.71
PPL	0.53
PPU	2.89
Ppk	0.53
Cpm	*

Potential (Within) Capability	
Cp	2.20
CPL	0.68
CPU	3.72
Cpk	0.68

Performance	Observed	Expected Overall	Expected Within
PPM < LSL	0.00	56095.83	20470.72
PPM > USL	0.00	0.00	0.00
PPM Total	0.00	56095.83	20470.72

The actual process spread is represented by 6 sigma.

Level 5 – Continuous Improvement with Industry 4.0

Measure 4 – **Overall Equipment Effectiveness (OEE)**

MANUFACTURE ADVANCED DESIGN ENGINEERING

Prifysgol Cymru
Y Drindod Dewi Sant
University of Wales
Trinity Saint David

Cronfa Gymdeithasol Ewrop
European Social Fund

Overall Equipment Effectiveness (OEE)

Availability

Performance

Quality

= Overall Equipment Effectiveness (OEE)

Overall Equipment Effectiveness (OEE)

Focuses on the ‘six big losses’ experienced within manufacturing environments:-

Availability

- Equipment failure
- Set up and changeovers

Performance

- Machinery idling
- Reduced speed

Quality

- Yield, re-work and scrap
- Start up losses

Overall Equipment Effectiveness (OEE)

Availability - Equipment failure

- Sporadic breakdowns – these are generally obvious and easily repaired
- Chronic breakdowns – these are accepted by the organization as repeated repairs fail and are ‘part of the job’

Overall Equipment Effectiveness (OEE)

Availability – Set-up and changeovers

- Losses occur due to excessive set-up times

- Changeovers are not repeatable and unforeseen occurrences happen

Overall Equipment Effectiveness (OEE)

Performance – Machinery idling

- Idling between products and temporary malfunctions

- Exactly the same effect as a breakdown stopping a machine to work but can be more frequent and is often overlooked

Overall Equipment Effectiveness (OEE)

Performance – Reduced speed

- Difference between designed speed and actual speed achieved
- Can happen when quality issues occur, or machinery develops faults

Overall Equipment Effectiveness (OEE)

Quality – Yield, re-work and scrap

- Component does not achieve specification (VoC) so has to travel around the process again

- Component does not achieve specification, cannot be re-worked and is scrapped – control charts could help in identifying potential issues before they happen!

Quality – Start up losses

- Losses occur during start up or until the process becomes stable

Availability

- Availability considers all events that stop planned production long enough where it makes sense to track a reason for being down (typically several minutes.)

Availability = Run Time / Planned Production Time

- Run time is Planned Production Time less Stop Time, where Stop Time is defined as all the time where the manufacturing process was intended to be running but was not due to unplanned stops (breakdowns) or planned stops (changeovers.)

Run Time = Planned Production Time - Stop Time (Planned & Unplanned)

Performance

- Performance takes into account anything that causes the manufacturing process to run at less than the maximum possible speed when it is running (including both slow cycles and small stops)

Performance = Total Count / (Run Time x Ideal Run Rate)

Ideal Cycle Time is the fastest cycle time that your process can achieve in optimal circumstances.

(**Run time** is Planned Production Time less Stop Time)

✍ *Performance should never be greater than 100%. If it is, that usually indicates that the Ideal Cycle Time is set incorrectly!*

Quality

- Quality considers manufactured parts that do not meet quality standards, including parts that need rework.

✍ Remember; OEE Quality is like **First Past Yield** (or **First Time Through** - FTT) in that it defines **Good Parts** as parts that successfully pass through the manufacturing process first time without needing any rework.

Quality = Good Count / Total Count

OEE

- OEE considers all losses, resulting in a measure of truly productive manufacturing time.

- OEE scores provide a very valuable oversight – an accurate picture on how effectively your manufacturing process is running.
- Easy to track improvements over time.

OEE = Availability * Performance * Quality

- What your OEE score doesn't provide is any insights as to the underlying causes of lost productivity. That is visible through the individual elements; **Availability, Performance and Quality.**

- In the preferred calculation you get the best of both worlds. A single number that captures how well you are doing (**OEE**) and three numbers that capture the fundamental nature of your losses (**Availability, Performance, and Quality**).

Listen to your process

- What are your thoughts on some date you've just seen from your production area for last week?

OEE Factor	16-Nov-20	23-Nov-20
OEE	85.10%	85.70%
Availability	90.00%	95.00%
Performance	95.00%	95.00%
Quality	99.50%	95.00%

OEE Calculation

Item	Data
Shift Length	8 hours (480 minutes)
Breaks	(2) 15 minute and (1) 30 minute
Downtime	47 minutes
Ideal Cycle Time	1.0 seconds
Total Count	19,271 widgets
Reject Count	423 widgets

Planned Production Time = Shift Length – Breaks

Run Time = Planned Production Time - Stop Time

Good Count = Total Count – Reject Count

Availability = Run Time / Planned Production Time

Performance = (Total Count / Run Time) / Ideal Run Rate

Quality = Good Count / Total Count

OEE = Availability * Performance * Quality

OEE Calculation

Item	Data
Shift Length	8 hours (480 minutes)
Breaks	(2) 15 minute and (1) 30 minute
Downtime	47 minutes
Ideal Cycle Time	1.0 seconds
Total Count	19,271 widgets
Reject Count	423 widgets

Planned Production Time = Shift Length – Breaks = *480mins - 60mins* = ***420mins***

Run Time = Planned Production Time - Stop Time = *420mins – 47mins* = ***373mins***

Good Count = Total Count – Reject Count = *19,271 – 423* = ***18,848***

Availability = Run Time / Planned Production Time = *373mins / 420mins* = ***0.8881*** *(88.81%)*

Performance = (Total Count / Run Time x id. cycle time) = *(19,271 / 373minsx60)* = ***0.8611*** *(86.11%)*

Quality = Good Count / Total Count = *18,848 / 19,271* = ***0.9780*** *(97.80%)*

OEE = Availability * Performance * Quality = *0.881 * 0.8611 * 0.9780* = ***0.7479 (74.79%)***

OEE Calculation - Exercise

Inputs		
Shift Length	720	minutes
Breaks	45	minutes
Downtime	67	minutes
Ideal Cycle Time	1	minute
Total Count	567	Parts
Reject Count	23	Parts

OEE Calculation

Inputs		
Shift Length	720	minutes
Breaks	45	minutes
Downtime	67	minutes
Ideal Cycle Time	1	minute
Total Count	567	Parts
Reject Count	23	Parts

Planned Production Time = Shift Length – Breaks = *720mins - 45mins =*

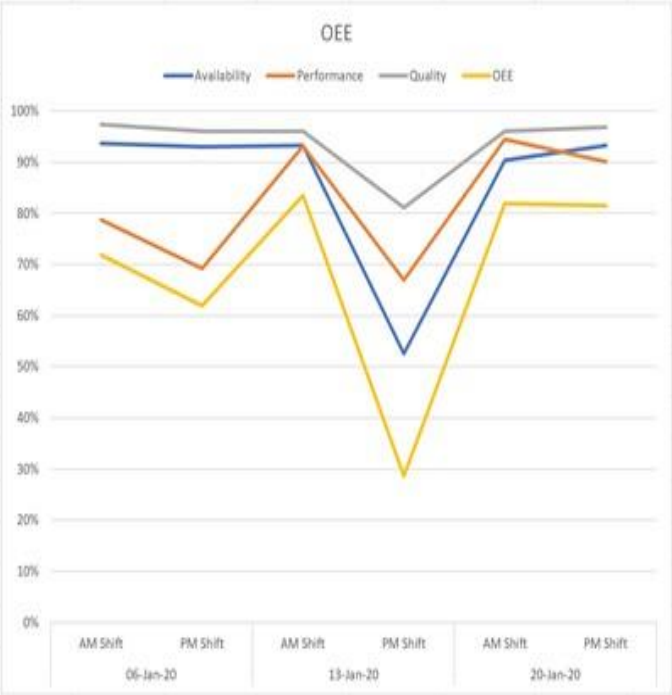
Run Time = Planned Production Time - Stop Time = *675mins – 67mins =*

Good Count = Total Count – Reject Count = *567 – 23 =*

Availability = Run Time / Planned Production Time = *608mins / 675mins =*

Performance = (parts made / Run Time x ideal cycle time) = *(567 / 608mins x 1)* = **Quality** = Good Count / Total Count = *544 / 567 =*

OEE = Availability * Performance * Quality =

OEE Calculation - Exercise

			06-Jan-20		13-Jan-20		20-Jan-20	
Inputs			AM Shift	PM Shift	AM Shift	PM Shift	AM Shift	PM Shift
Shift Length	720	minutes	720	720	720	720	720	720
Breaks	45	minutes	60	60	60	60	60	60
Downtime	67	minutes	43	47	45	320	65	45
Ideal Cycle Time	1	minutes	1	1	1	1	1	1
Total Count	567	Parts	498	435	587	238	576	568
Reject Count	23	Parts	13	17	23	45	23	18
Calculations								
Planned Production Time	675	minutes	675	675	675	675	675	675
Run Time	608	minutes	632	628	630	355	610	630
Good Count	544	Parts	485	418	564	193	553	550
Availability	90.07%		93.63%	93.04%	93.33%	52.59%	90.37%	93.33%
Performance	93.26%		78.80%	69.27%	93.17%	67.04%	94.43%	90.16%
Quality	95.94%		97.39%	96.09%	96.08%	81.09%	96.01%	96.83%
OEE	80.59%		71.83%	61.93%	83.56%	28.59%	81.93%	81.48%