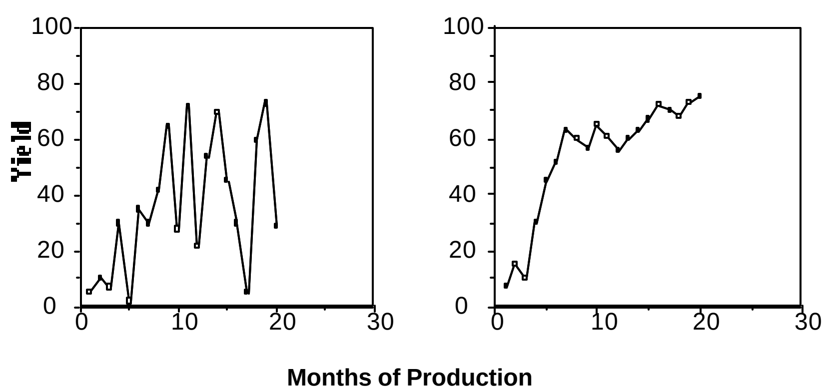
Control Charts for Attributes

The p (fraction non-conforming),
c (number of defects) and the
u (non-conformities per unit) charts.
The rest of the magnificent seven.

Yield Control



The fraction non-conforming

The most inexpensive statistic is the yield of the production line.

Yield is related to the ratio of defective vs. non-defective, conforming vs. non-conforming or functional vs. non-functional.

We often measure:

• Fraction non-conforming (p)

• Number of defects on product (c)

• Average number of non-conformities per unit area (u)

The p-Chart

The p chart is based on the binomial distribution:

$$P\{D = X\} = \binom{n}{x} p^x (1-p)^{n-x} \quad x = 0,1,\ldots,n$$

$$\text{mean } np$$

$$\text{variance } np(1-p)$$

$$\text{the sample fraction } \hat{p} = \frac{D}{n}$$

$$\text{mean } p$$

$$\text{variance } \frac{p(1-p)}{n}$$

The p-chart (cont.)

p must be estimated. Limits are set at +/- 3 sigma.

$$\bar{p} = \frac{\sum_{i=1}^{m} \hat{p}_i}{m}$$

mean p

variance $\frac{p(1-p)}{nm}$

(in this and the following discussion, "n" *is the number of samples in each group and* "m" *is the number of groups that we use in order to determine the control limits)*

Designing the p-Chart

In general, the control limits of a chart are:

UCL= $\mu + k\sigma$

LCL= $\mu - k\sigma$

where k is typically set to 3.

These formulas give us the limits for the p-Chart (using the binomial distribution of the variable):

$$UCL = \bar{p} + 3\sqrt{\frac{\bar{p}(1-\bar{p})}{n}}$$

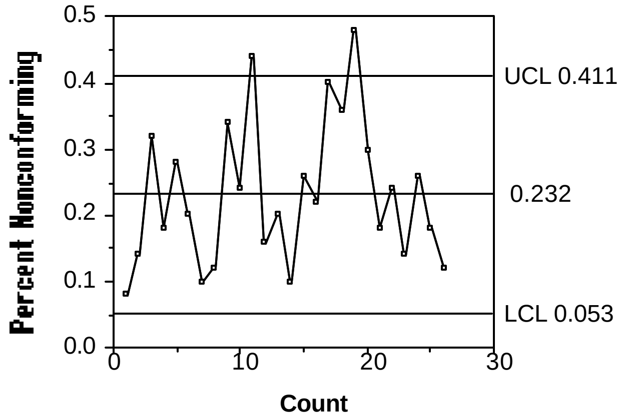
$$LCL = \bar{p} - 3\sqrt{\frac{\bar{p}(1-\bar{p})}{n}}$$

p can be estimated:

$$\hat{p}_i = \frac{D_i}{n} \quad i = 1,...,m \ (m = 20 \sim 25)$$

$$\bar{p} = \frac{\sum_{i=1}^{m} \hat{p}_i}{m}$$

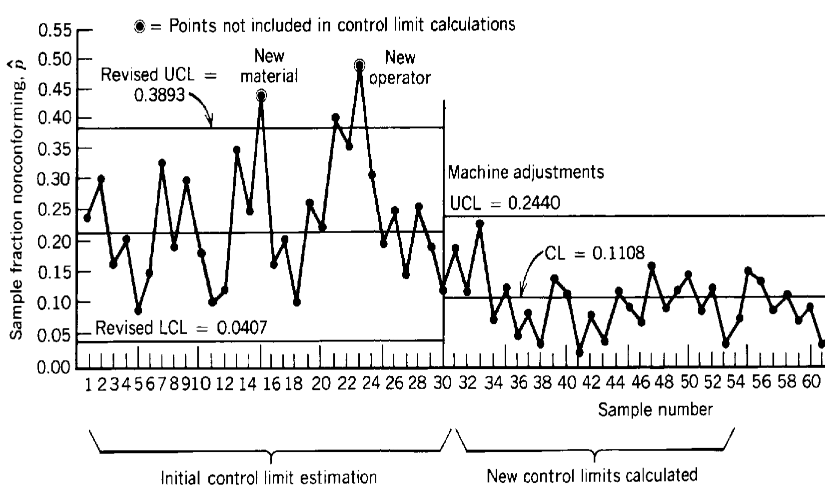
Example: Defectives (1.0 minus yield) Chart



"Out of control points" must be explained and eliminated before we recalculate the control limits. This means that *setting the control limits is an iterative process!* Special patterns must also be explained.

Example (cont.)

After the original problems have been corrected, the limits must be evaluated again.



Operating Characteristic of p-Chart

In order to calculate type I and II errors of the p chart we need a convenient statistic.

Normal approximation to the binomial (DeMoivre-Laplace).

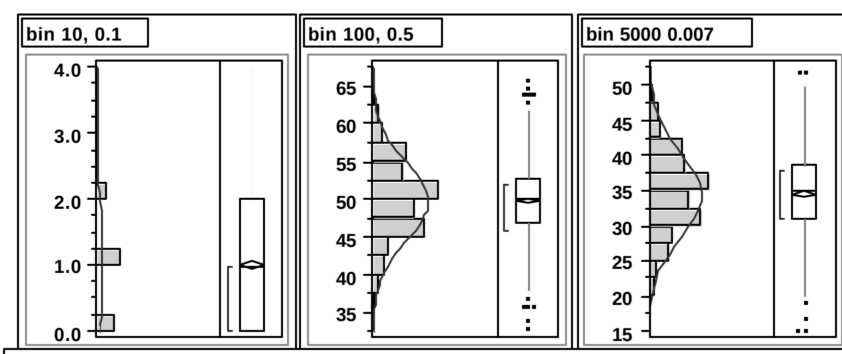
if n large and np(1-p) >> 1, then

$$P\{D = x\} = \binom{n}{x} p^{x}(1-p)^{(n-x)} \sim \frac{1}{\sqrt{2\pi np(1-p)}} e^{-\frac{(x-np)^2}{2np(1-p)}}$$

In other words, the fraction nonconforming can be treated as having a nice normal distribution! (with μ and σ as given).

This can be used to set frequency, sample size and control limits. Also to calculate the OC.

Binomial distribution and the Normal



Designing the p-Chart

Assuming that the discrete distribution of x can be approximated by a continuous normal distribution as shown, then we must:

- choose n so that we get at least one defective with 0.95 probability.
- choose n so that a given shift is detected with 0.50 probability.

or

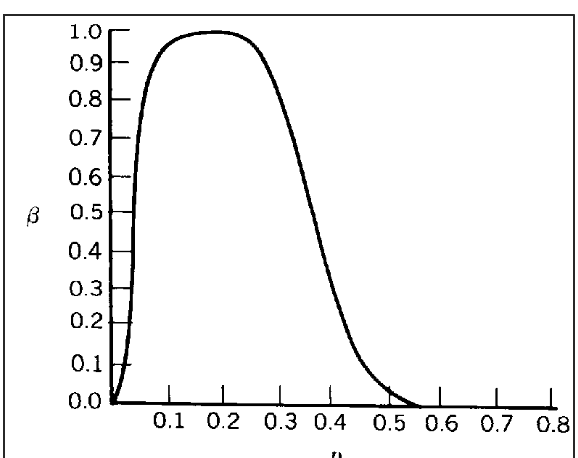
- choose n so that we get a positive LCL.

Then, the operating characteristic can be drawn from:

$$\beta = P\{ D < n\ UCL / p \} - P\{ D < n\ LCL / p \}$$

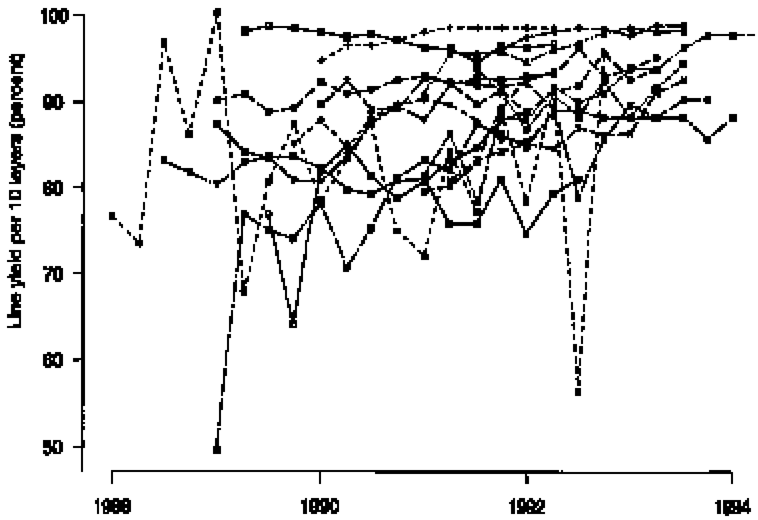
The Operating Characteristic Curve (cont.)

The OCC can be calculated two distributions are equivalent and $np=\lambda$).



p = 0.20,
LCL=0.0303,
UCL=0.3697

In reality, p changes over time



(data from the Berkeley Competitive Semiconductor Manufacturing Study)

EE290H F03 Spanos & Poolla

The c-Chart

Sometimes we want to actually *count* the number of defects. This gives us more information about the process.

The basic assumption is that defects "arrive" according to a Poisson model:

$$p(x) = \frac{e^{-c}\, c^{x}}{x!} \quad x = 0,1,2,...$$

$$\mu = c, \quad \sigma^2 = c$$

This assumes that defects are independent and that they arrive uniformly over time and space. Under these assumptions:

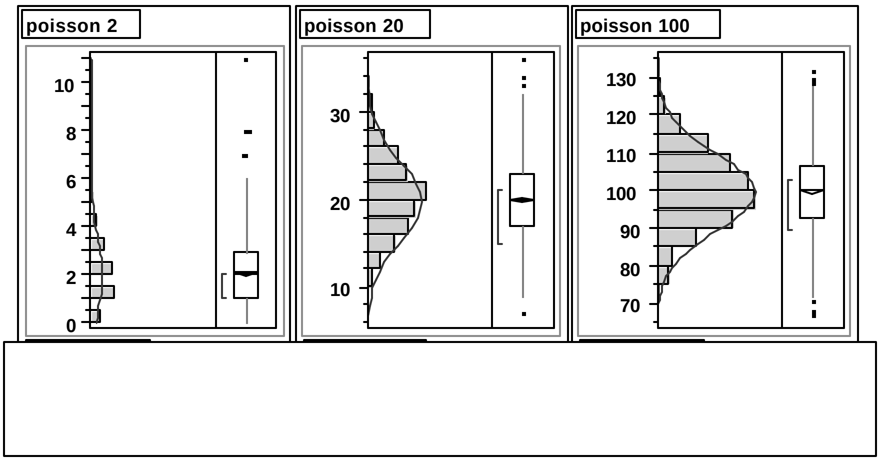
$$UCL = c + 3\sqrt{c}$$

$$\text{center at } c$$

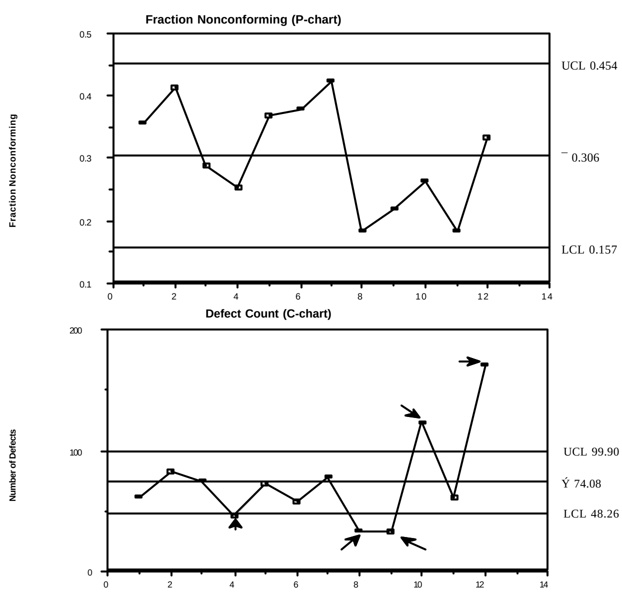
$$LCL = c - 3\sqrt{c}$$

and c can be estimated from measurements.

Poisson and the Normal



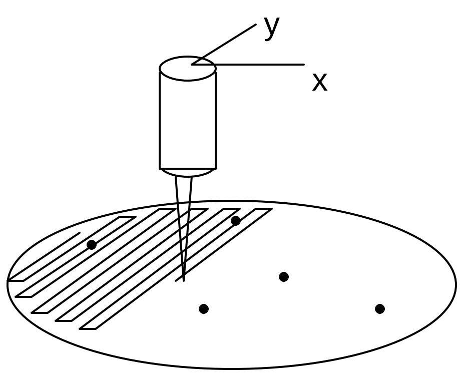
Example: "Filter" wafers used in yield model



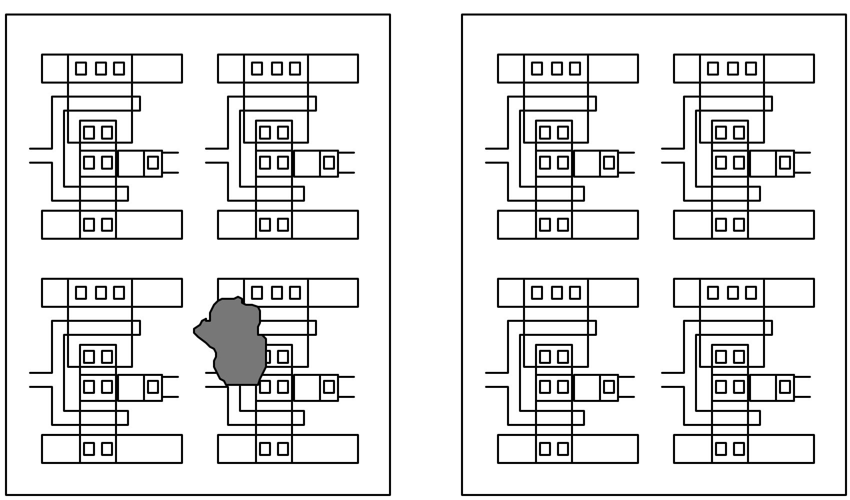
Counting particles

Scanning a “blanket” monitor wafer.

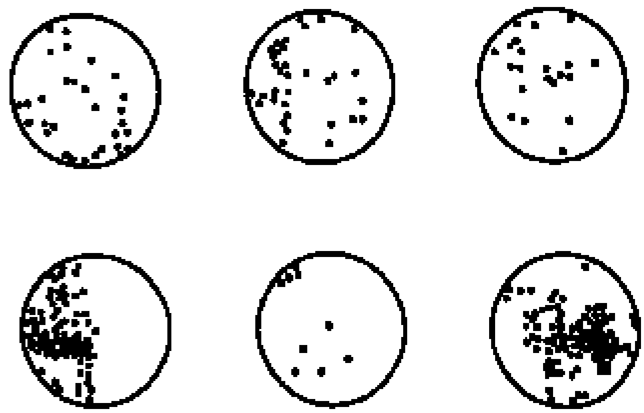
Detects position and approximate size of particle.



Scanning a product wafer

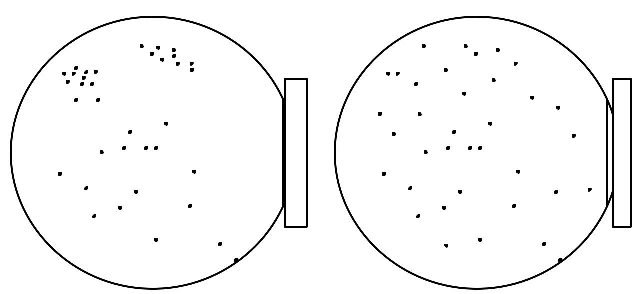


Typical Spatial Distributions



The Problem with Wafer Maps

Wafer maps contain information that is very difficult to enumerate



A simple particle count cannot convey what is happening.

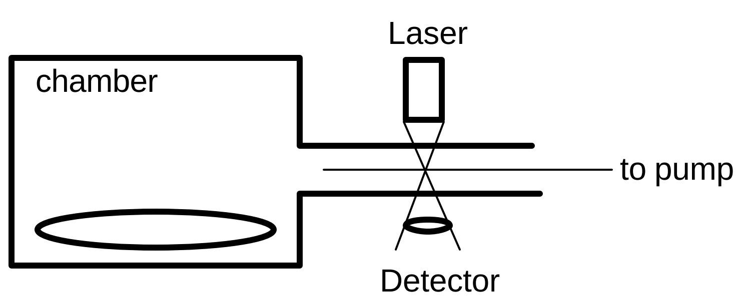
Special Wafer Scan Statistics for SPC applications

- Particle Count
- Particle Count by Size (histogram)
- Particle Density
- Particle Density variation by sub area (clustering)
- Cluster Count
- Cluster Classification
- Background Count

Whatever we use (and we might have to use more than one), must follow a known, usable distribution.

In Situ Particle Monitoring Technology

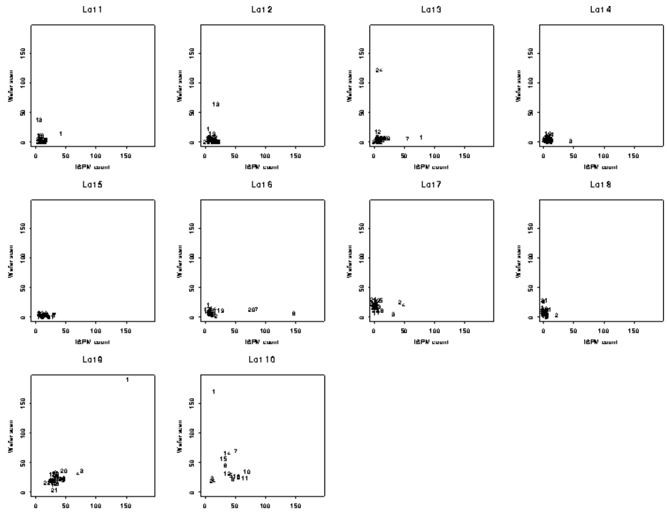
Laser light scattering system for detecting particles in exhaust flow. Sensor placed down stream from valves to prevent corrosion.



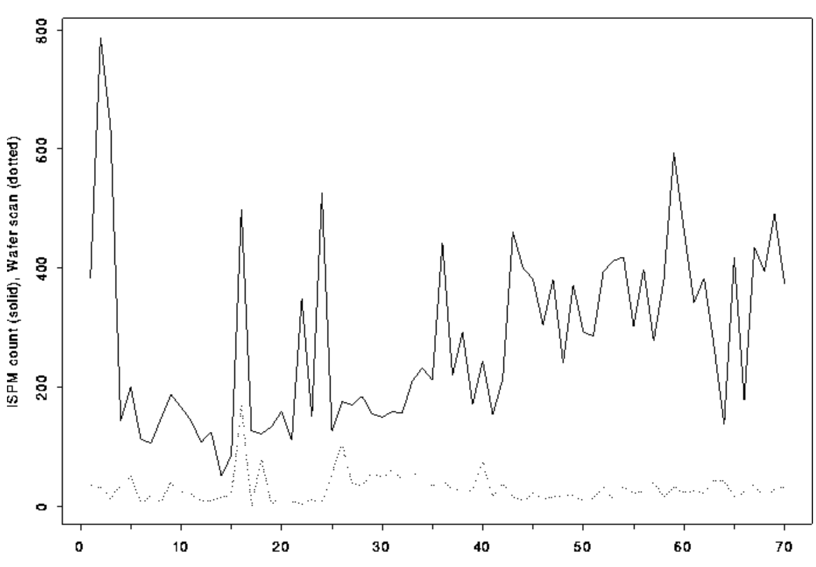
Assumed to measure the particle concentration in vacuum

Progression of scatter plots over time

The endpoint detector failed during the ninth lot, and was detected during the tenth lot.



Time series of ISPM counts vs. Wafer Scans



The u-Chart

We could condense the information and avoid outliers by using the "average" defect density u = $\Sigma c/n$. It can be shown that u obeys a Poisson "type" distribution with:

$$\mu_u = \bar{u}, \ \sigma_u^2 = \frac{\bar{u}}{n}$$

so

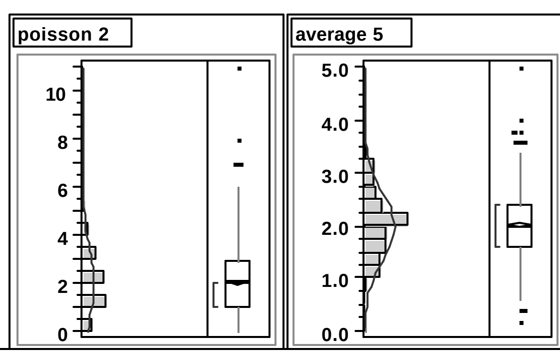
$$UCL = \bar{u} + 3\sqrt{\frac{\bar{u}}{n}}$$

$$LCL = \bar{u} - 3\sqrt{\frac{\bar{u}}{n}}$$

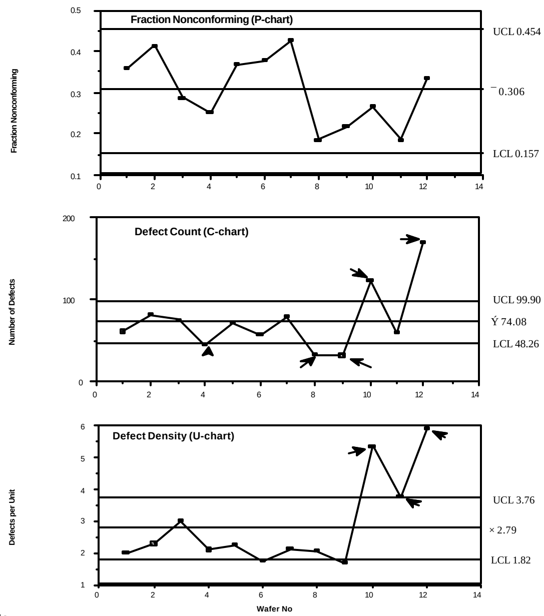
where $\bar{u}$ is the estimated value of the unknownn of u.

The sample size n may vary. This can easily be accommodated.

The Averaging Effect of the u-chart

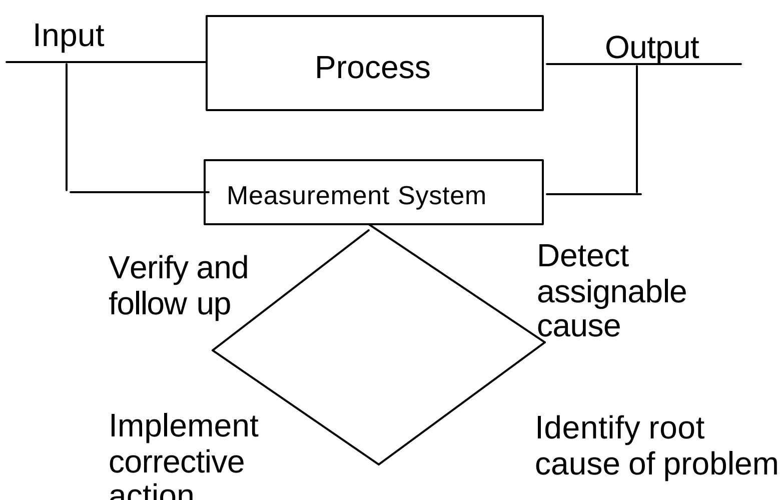


Filter wafer data for yield models (CMOS-1):



The Use of the Control Chart

The control chart is in general a part of the feedback loop for process improvement and control.



Choosing a control chart...

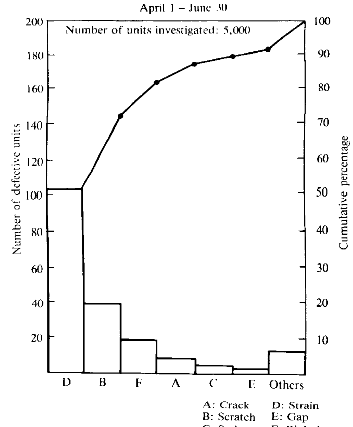
...depends very much on the analysis that we are pursuing. In general, the control chart is only a small part of a procedure that involves a number of statistical and engineering tools, such as:

- experimental design
- trial and error
- pareto diagrams
- influence diagrams
- charting of critical parameters

The Pareto Diagram in Defect Analysis

Typically, a small number of defect types is responsible for the largest part of yield loss.

The most cost effective way to improve the yield is to identify these defect types.



Pareto Diagrams (cont)

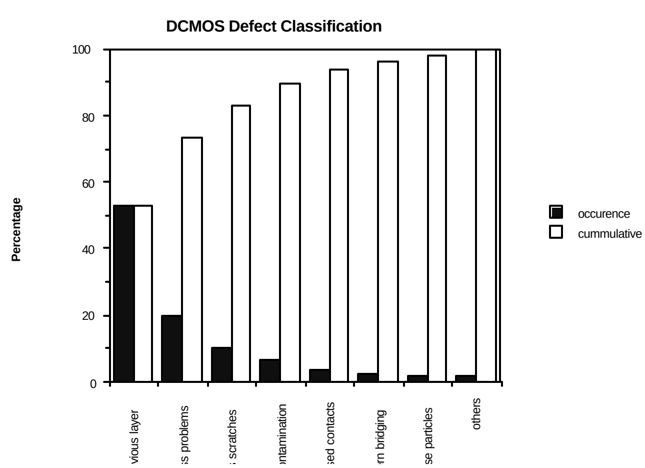
Diagrams by Phenomena

- defect types (pinholes, scratches, shorts,...)
- defect location (boat, lot and wafer maps...)
- test pattern (continuity etc.)

Diagrams by Causes

- operator (shift, group,...)
- machine (equipment, tools,...)
- raw material (wafer vendor, chemicals,...)
- processing method (conditions, recipes,...)

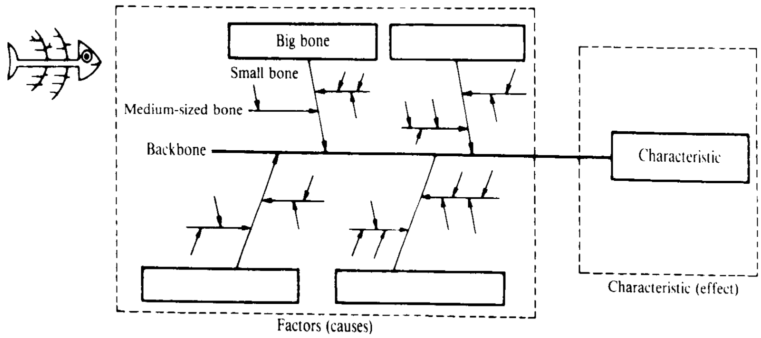
Example: Pareto Analysis of DCMOS Process



Though the defect classification by type is fairly easy, the classification by cause is not...

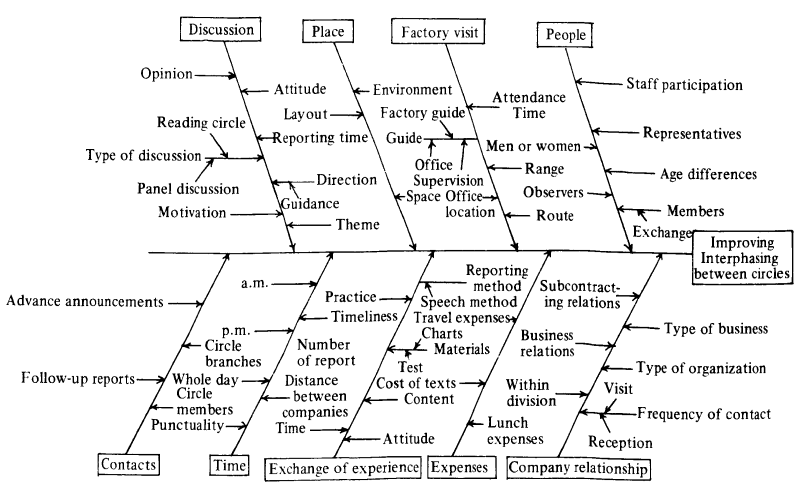
Cause and Effect Diagrams

(Also known as *Ishikawa,fish bone* or *influence*diagrams.)

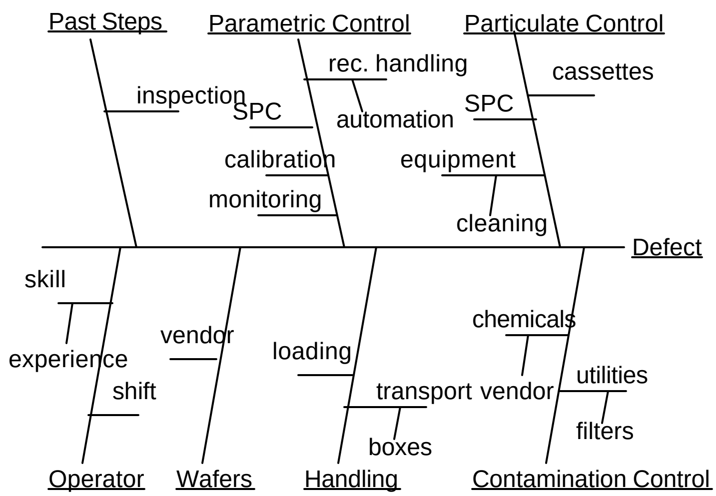


Creating such a diagram requires good understanding of the process.

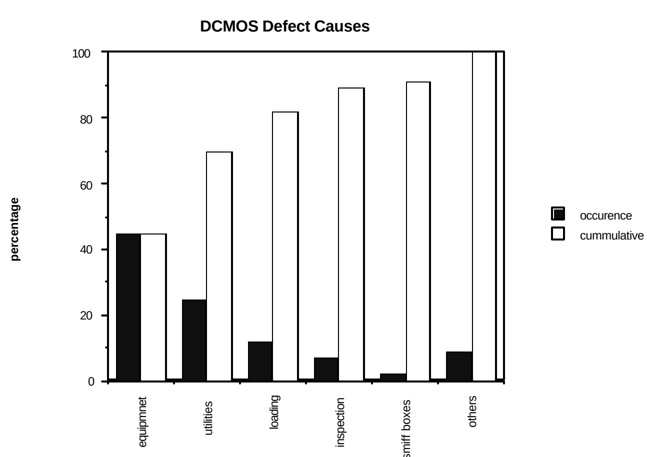
An Actual Example



Example: DCMOS Cause and Effect Diagram



Example: Pareto Analysis of DCMOS (cont)



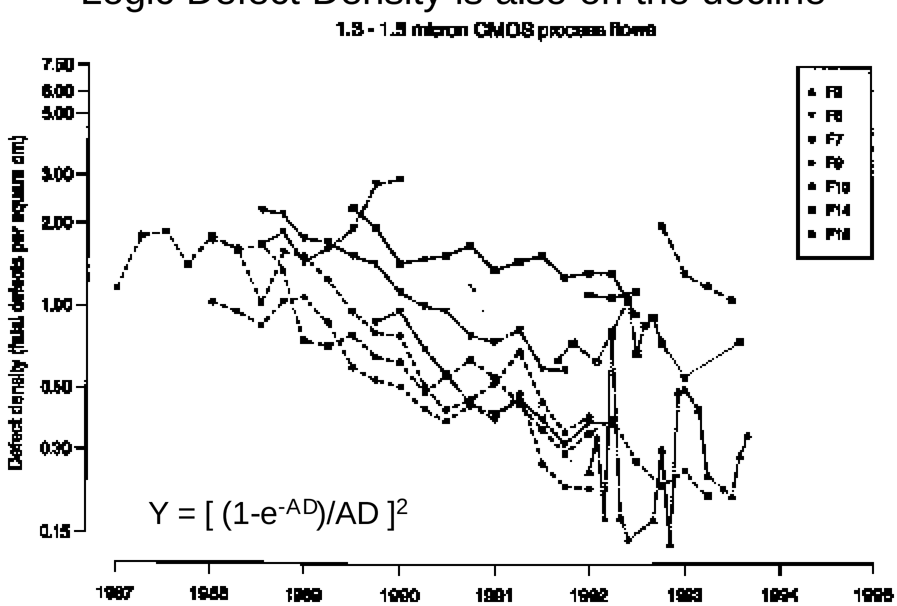
Once classification by cause has been completed, we can choose the first target for improvement.

Defect Control

In general, statistical tools like control charts must be combined with the rest of the "magnificent seven":

- Histograms
- Check Sheet
- Pareto Chart
- Cause and effect diagrams
- Defect Concentration Diagram
- Scatter Diagram
- Control Chart

Logic Defect Density is also on the decline



What Drives Yield Learning Speed?

RATING	SPC AUTOMATION		EXTENT OF SPC		
	Yes	No	High	Med	Low
High	2	0	0	2	0
Med	5	0	2	3	0
Low	2	3	1	1	3

RATING	PAPERLESS FAB		RECIPE DOWNLOAD		
	Yes	No	Full	Semi	None
High	0	2	0	2	0
Med	3	2	2	2	1
Low	1	4	1	0	4

RATING	YIELD MODEL		YIELD GR
	Home	Away	Yes
High	1	1	2
Med	1	4	3
Low	2	3	3

RATING	FAB REGION		
	U. S.	Asia	Europe
High	2	0	0
Med	2	2	1
Low	3	2	0