manufacturing processes - overview

Part 1:mechanisms of geometry formation
Part 2:performance (cost, variation, energy, rate)

2.810

T. Gutowski

Components of Cost

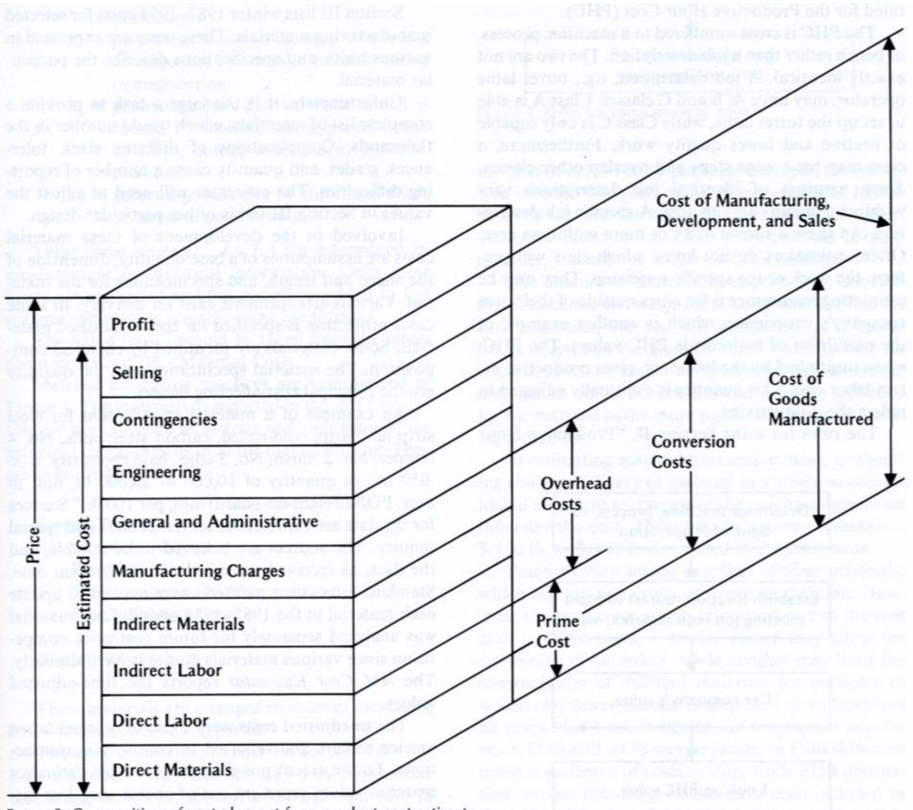


FIGURE 2 Composition of cost element for a product cost estimate.

Ostwald

Indirect costs: common activities that support many products

Direct costs: "touch" labor, direct materials & tooling

We will focus on ΔCost:

Direct Recurring Costs (Variable C = VN):

- Material
- Labor
- Equipment (rental)

Direct Non-recurring costs (Fixed C = F):

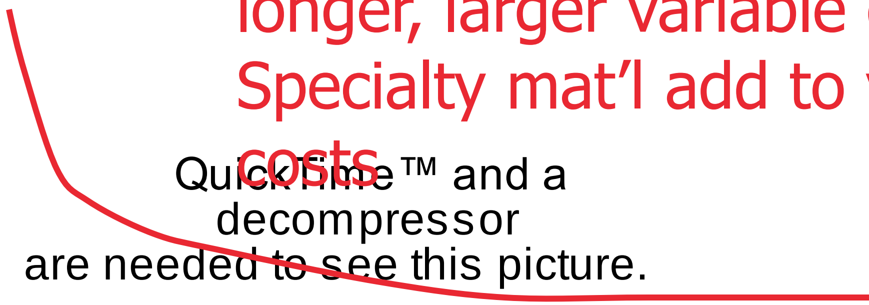
- Tooling, special equipment..

Indirect Costs

- Plant level costs including indirect labor
- Sales, general and administrative expenses
- Profit

Unit cost: C/N =F/N + V

Serial processes take longer, larger variable costs
Specialty mat'l add to variable costs

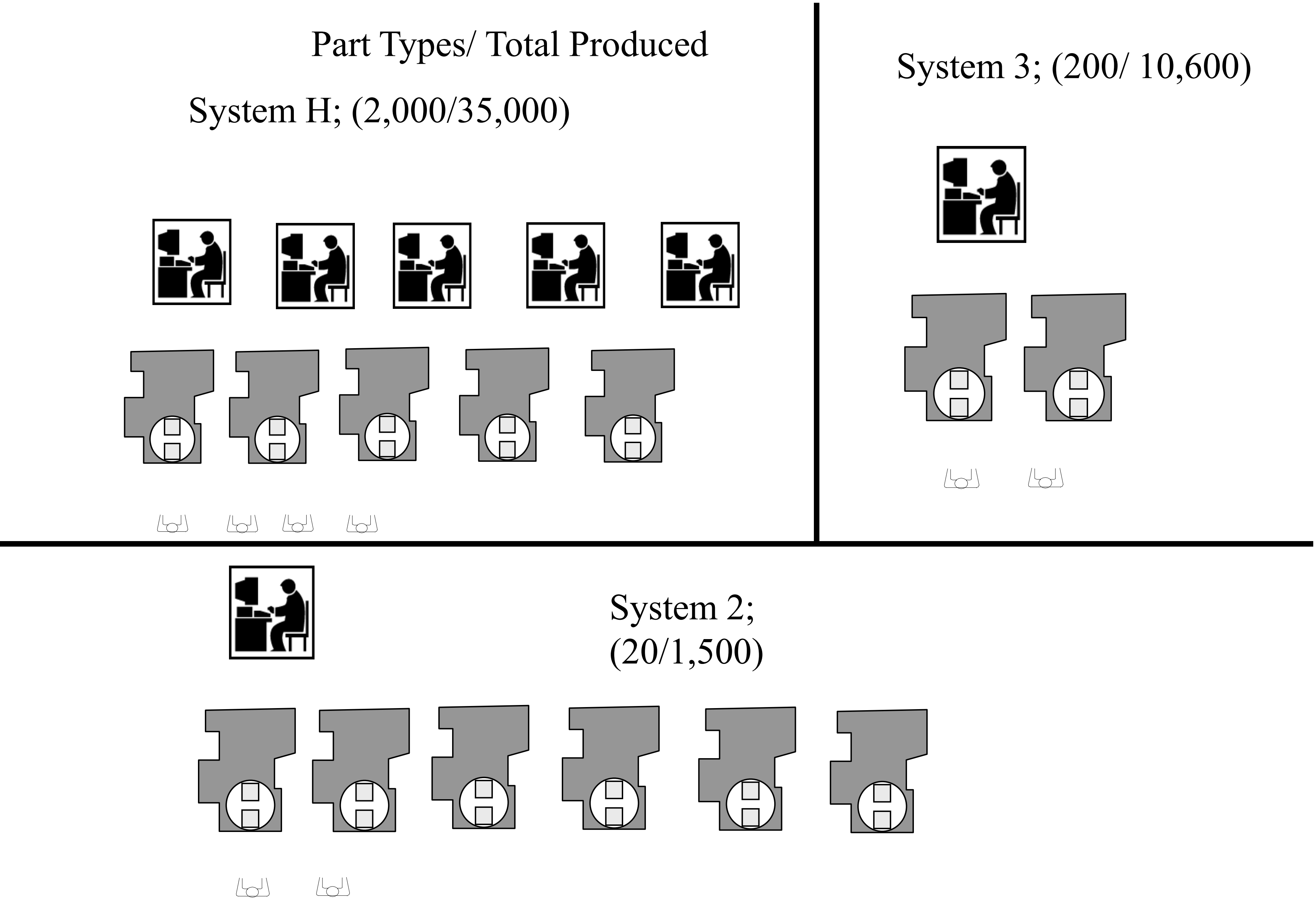


QuickTime™ and a decompressor are needed to see this picture.

Parallel processes require tooling, larger fixed costs, but short cycle time

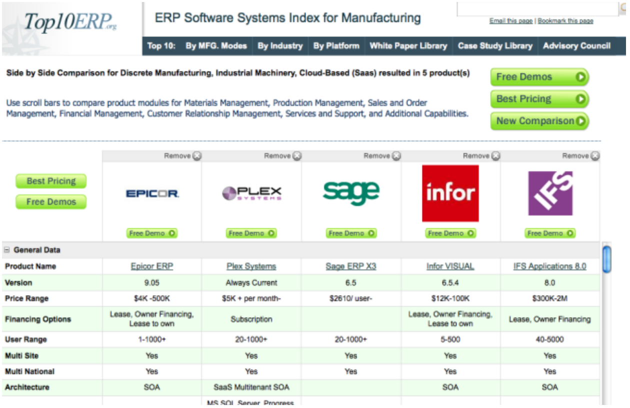
But, Indirect costs..

- Become more important for higher levels of automation,
- Become more difficult to allocate as the number of products and variation grows.
- Use “Activity Based Costing” and other tools


Part Types/ Total Produced
System H; (2,000/35,000)
System 3; (200/ 10,600)
System 2;
(20/1,500)

Parametric models

- DFM and DFA: Boothroyd, Dewhurst & Knight
- Software -



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Side by Side Comparison for Discrete Manufacturing, Industrial Machinery, Cloud-Based (Saas) resulted in 5 product(s)

Free Demos | Best Pricing | New Comparison

Use scroll bars to compare product modules for Materials Management, Production Management, Sales and Order Management, Financial Management, Customer Relationship Management, Services and Support, and Additional Capabilities.

Best Pricing / Free Demos	EPICOR (Free Demo)	PLEX SYSTEMS (Free Demo)	sage (Free Demo)	infor (Free Demo)	IFS (Free Demo)
General Data					
Product Name	Epicor ERP	Plex Systems	Sage ERP X3	Infor VISUAL	IFS Applications 8.0
Version	9.05	Always Current	6.5	6.5.4	8.0
Price Range	$4K -500K	$5K + per month-	$2610/ user-	$12K-100K	$300K-2M
Financing Options	Lease, Owner Financing, Lease to own	Subscription		Lease, Owner Financing, Lease to own	Lease, Owner Financing
User Range	1-1000+	20-1000+	20-1000+	5-500	40-5000
Multi Site	Yes	Yes	Yes	Yes	Yes
Multi National	Yes	Yes	Yes	Yes	Yes
Architecture	SOA	SaaS Multitenant SOA		SOA	SOA

- On-line
  - http://www.custompartnet.com/wu/die-casting
- Quotes-
- Parametric Models; Ostwald, Polgar

Energy &
Environmental Science

RSC Publishing

ANALYSIS

View Article Online
View Journal

Assessing the drivers of regional trends in solar photovoltaic manufacturing†

Cite this: DOI: 10.1039/c3ee40701b

Alan C. Goodrich,*[a] Douglas M. Powell,*[b] Ted L. James,[a] Michael Woodhouse[a] and Tonio Buonassisi*[b]

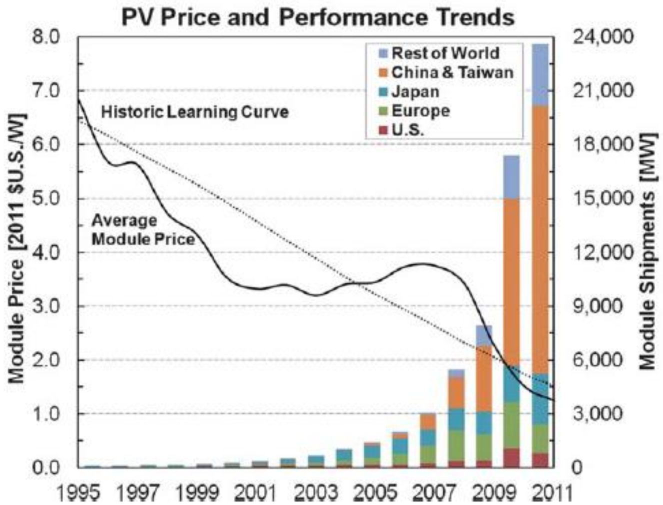


Fig. 1 From 2008 to 2011, reductions in the average global prices of c-Si PV modules have been in line with experience, but the rise of module manufacturing in China and Taiwan has been striking.[6]

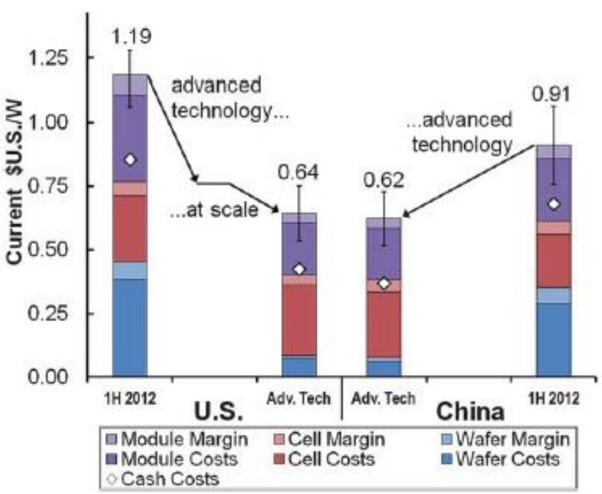
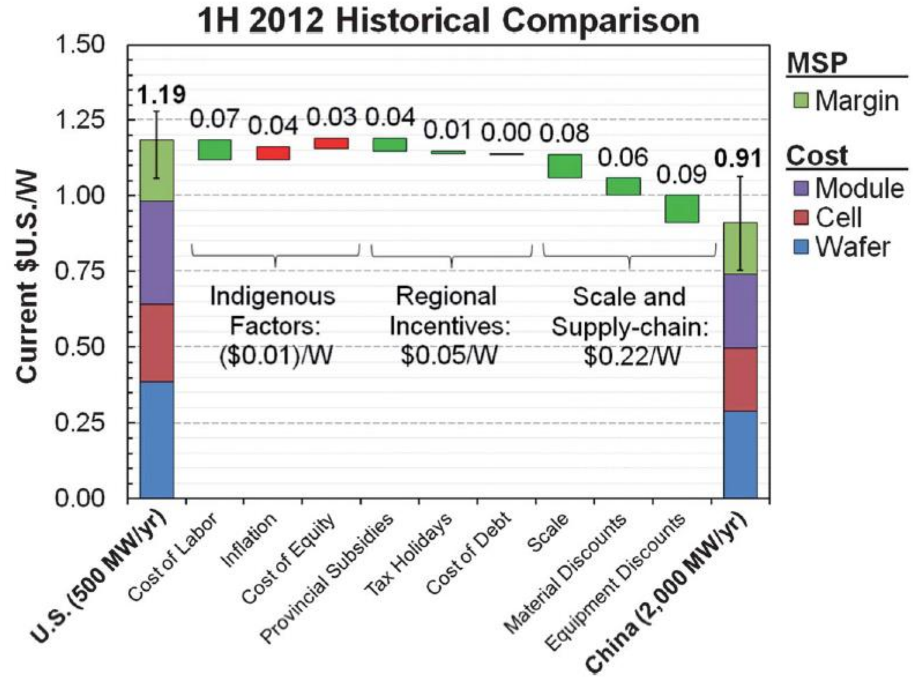
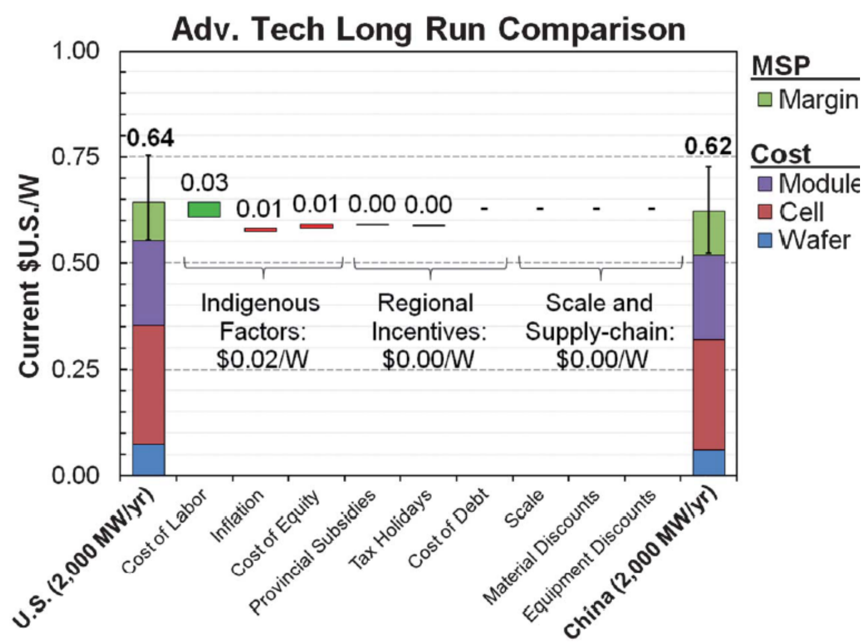


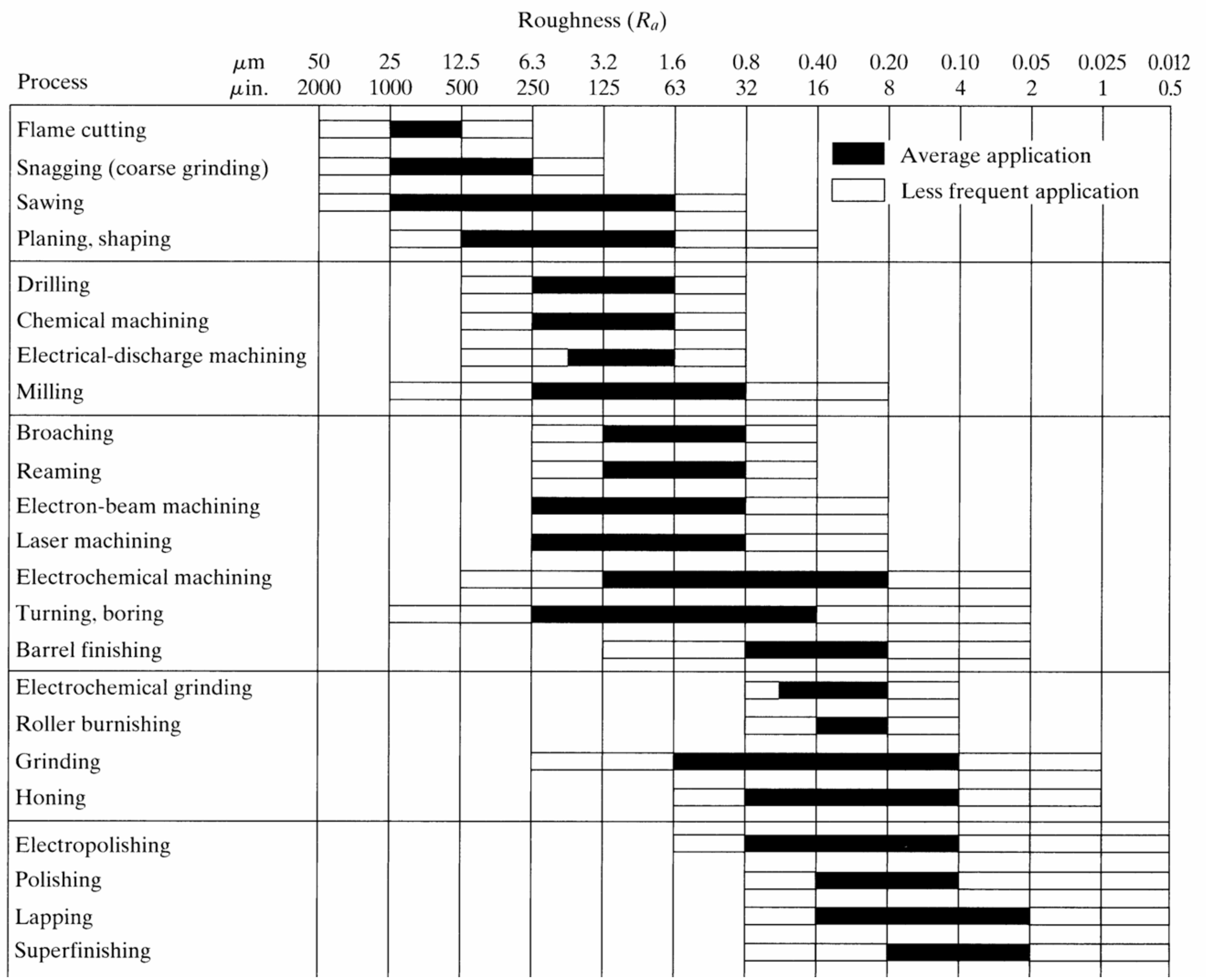
Fig. 4 Innovation and scale can lead to regional PV module manufacturing price parity.





Process Variation: Empirical

FIGURE 22.14 The range of surface roughnesses obtained in various machining processes. Note the wide range within each group, especially in turning and boring. See also Fig. 26.4.



Kalpakjian & Schmid

Process Variation: Empirical

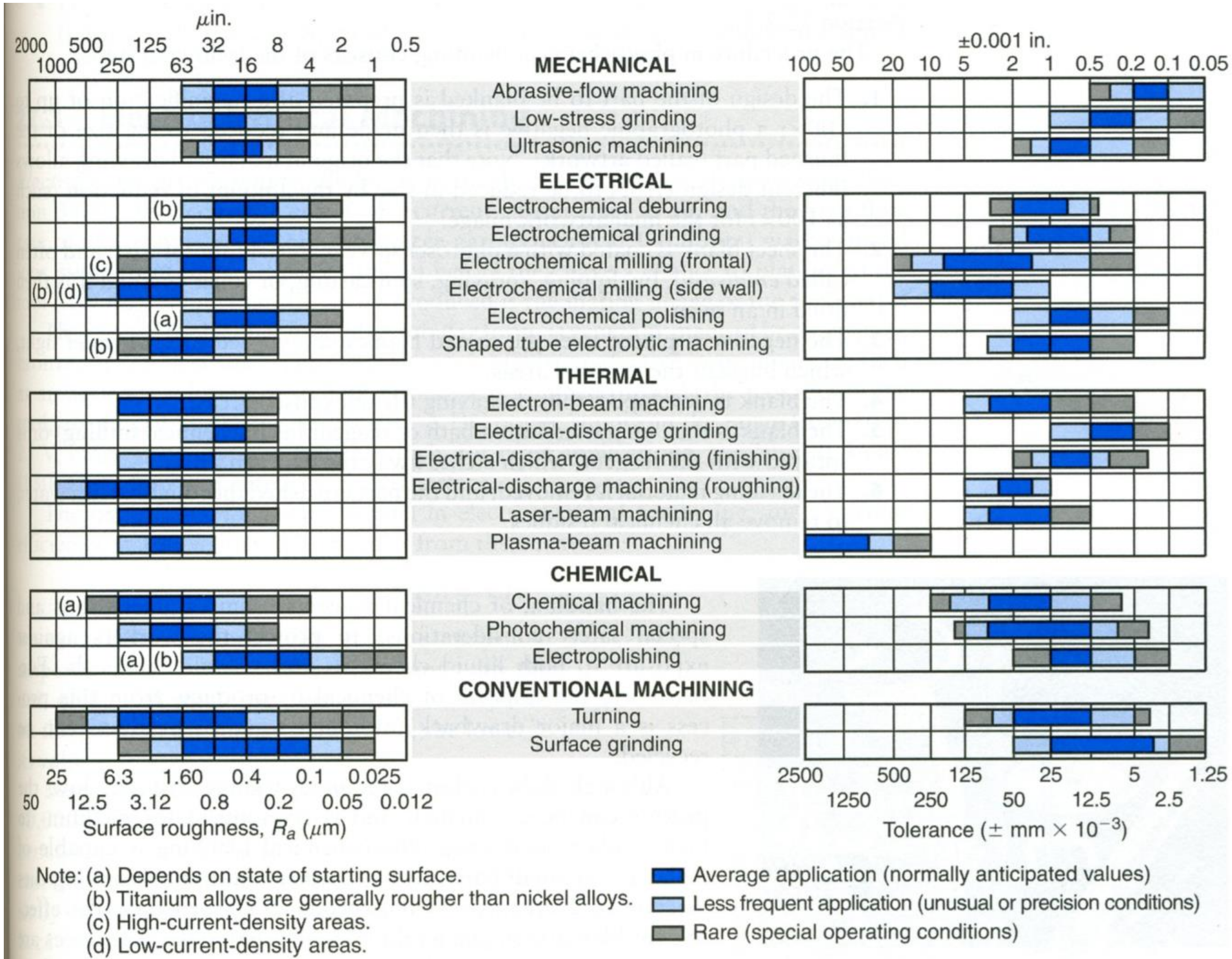
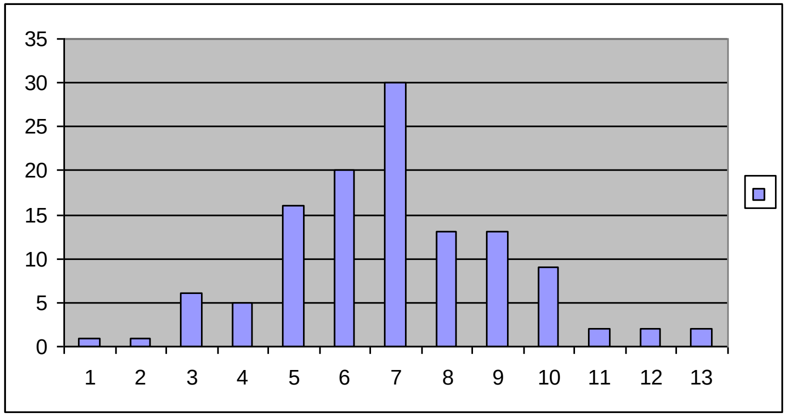


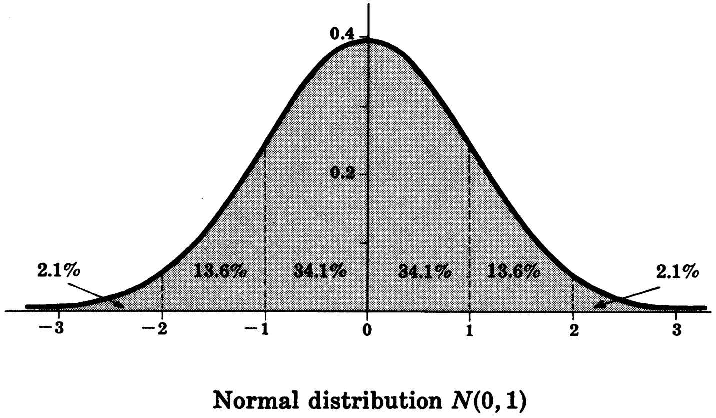
FIGURE 27.4 Surface roughness and tolerances obtained in various machining processes; note the wide range within each process (see also Fig. 23.13). *Source:* Based on data from *Machining Data Handbook*, 3rd ed. Copyright 1980.

Kalpakjian and Schmid 7th ed

What is Process Variation?

Process measurement reveals a distribution in output values.





Discrete probability distribution based upon measurements

Continuous "Normal" distribution

In general if the randomness is due to many different factors, the distribution of the means will tend toward a "normal" distribution. (Central Limit Theorem)

If the dimension "X" is a random variable, the mean is given by

$$\mu = E(X) \quad (1)$$

and the variation is given by

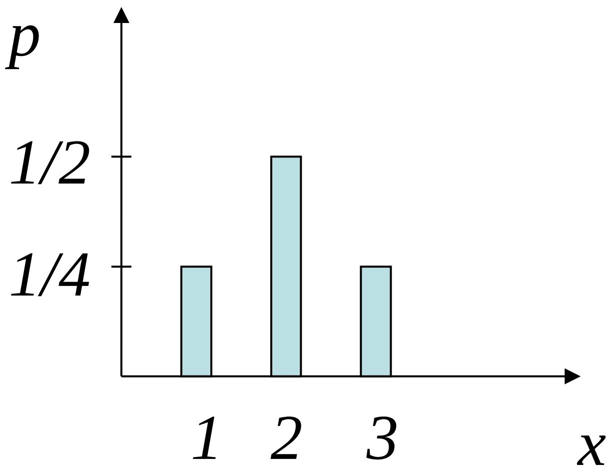
$$\text{Var}(x) = E[(x - \mu)^2] = \sigma^2 \quad (2)$$

both of these can be obtained from the probability density function p(x).

For a discrete pdf, the expectation operation is:

$$E(X) = \sum_i x_i p(x_i) \quad (3)$$

Sample calculation of $E(x) = \mu$, and $Var(x) = \sigma^2$



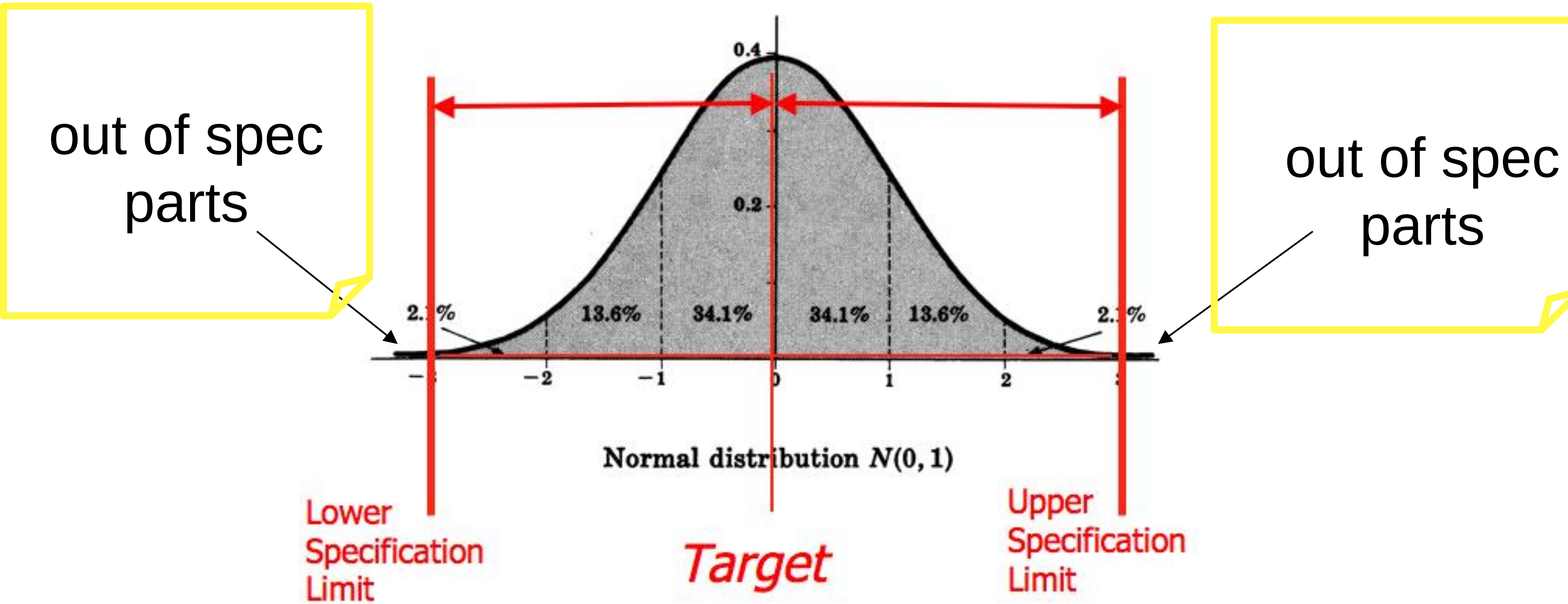
$$\sum p_i = \frac{1}{4} + \frac{1}{2} + \frac{1}{4} = 1$$

$$\mu = \sum x_i p = 1 \times \frac{1}{4} + 2 \times \frac{1}{2} + 3 \times \frac{1}{4} = 2$$

$$Var = \sum (x_i - \mu)^2 p_i = \frac{1}{4} + 0 + \frac{1}{4} = \frac{1}{2}$$

$$\sigma = \frac{1}{\sqrt{2}}$$

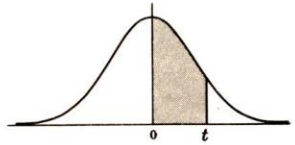
Comparing the variation with the specifications



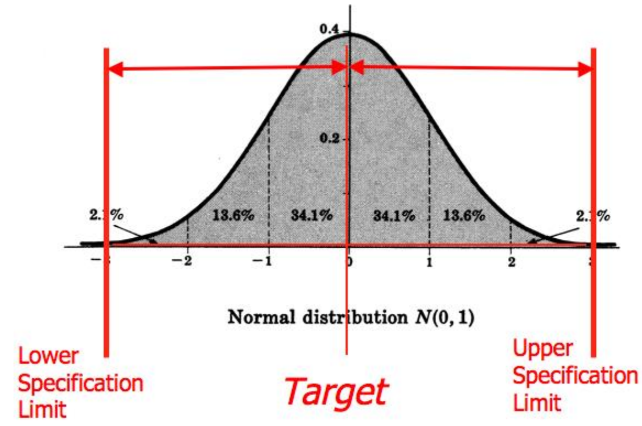
Goals: 6σ < (USL-LSL)
and mean centered

STANDARD NORMAL CURVE AREAS

This table gives areas under the standard normal distribution ϕ between 0 and $t \geq 0$ in steps of 0.01.



t	0	1	2	3	4	5	6	7	8	9
0.0	.0000	.0040	.0080	.0120	.0160	.0199	.0239	.0279	.0319	.0359
0.1	.0398	.0438	.0478	.0517	.0557	.0596	.0636	.0675	.0714	.0754
0.2	.0793	.0832	.0871	.0910	.0948	.0987	.1026	.1064	.1103	.1141
0.3	.1179	.1217	.1255	.1293	.1331	.1368	.1406	.1443	.1480	.1517
0.4	.1554	.1591	.1628	.1664	.1700	.1736	.1772	.1808	.1844	.1879
0.5	.1915	.1950	.1985	.2019	.2054	.2088	.2123	.2157	.2190	.2224
0.6	.2258	.2291	.2324	.2357	.2389	.2422	.2454	.2486	.2518	.2549
0.7	.2580	.2612	.2642	.2673	.2704	.2734	.2764	.2794	.2823	.2852
0.8	.2881	.2910	.2939	.2967	.2996	.3023	.3051	.3078	.3106	.3133
0.9	.3159	.3186	.3212	.3238	.3264	.3289	.3315	.3340	.3365	.3389
1.0	.3413	.3438	.3461	.3485	.3508	.3531	.3554	.3577	.3599	.3621
1.1	.3643	.3665	.3686	.3708	.3729	.3749	.3770	.3790	.3810	.3830
1.2	.3849	.3869	.3888	.3907	.3925	.3944	.3962	.3980	.3997	.4015
1.3	.4032	.4049	.4066	.4082	.4099	.4115	.4131	.4147	.4162	.4177
1.4	.4192	.4207	.4222	.4236	.4251	.4265	.4279	.4292	.4306	.4319
1.5	.4332	.4345	.4357	.4370	.4382	.4394	.4406	.4418	.4429	.4441
1.6	.4452	.4463	.4474	.4484	.4495	.4505	.4515	.4525	.4535	.4545
1.7	.4554	.4564	.4573	.4582	.4591	.4599	.4608	.4616	.4625	.4633
1.8	.4641	.4649	.4656	.4664	.4671	.4678	.4686	.4693	.4699	.4706
1.9	.4713	.4719	.4726	.4732	.4738	.4744	.4750	.4756	.4761	.4767
2.0	.4772	.4778	.4783	.4788	.4793	.4798	.4803	.4808	.4812	.4817
2.1	.4821	.4826	.4830	.4834	.4838	.4842	.4846	.4850	.4854	.4857
2.2	.4861	.4864	.4868	.4871	.4875	.4878	.4881	.4884	.4887	.4890
2.3	.4893	.4896	.4898	.4901	.4904	.4906	.4909	.4911	.4913	.4916
2.4	.4918	.4920	.4922	.4925	.4927	.4929	.4931	.4932	.4934	.4936
2.5	.4938	.4940	.4941	.4943	.4945	.4946	.4948	.4949	.4951	.4952
2.6	.4953	.4955	.4956	.4957	.4959	.4960	.4961	.4962	.4963	.4964
2.7	.4965	.4966	.4967	.4968	.4969	.4970	.4971	.4972	.4973	.4974
2.8	.4974	.4975	.4976	.4977	.4977	.4978	.4979	.4979	.4980	.4981
2.9	.4981	.4982	.4982	.4983	.4984	.4984	.4985	.4985	.4986	.4986
3.0	.4987	.4987	.4987	.4988	.4988	.4989	.4989	.4989	.4990	.4990
3.1	.4990	.4991	.4991	.4991	.4992	.4992	.4992	.4992	.4993	.4993
3.2	.4993	.4993	.4994	.4994	.4994	.4994	.4994	.4995	.4995	.4995
3.3	.4995	.4995	.4995	.4996	.4996	.4996	.4996	.4996	.4996	.4997
3.4	.4997	.4997	.4997	.4997	.4997	.4997	.4997	.4997	.4997	.4998
3.5	.4998	.4998	.4998	.4998	.4998	.4998	.4998	.4998	.4998	.4998
3.6	.4998	.4998	.4999	.4999	.4999	.4999	.4999	.4999	.4999	.4999
3.7	.4999	.4999	.4999	.4999	.4999	.4999	.4999	.4999	.4999	.4999
3.8	.4999	.4999	.4999	.4999	.4999	.4999	.4999	.4999	.4999	.4999
3.9	.5000	.5000	.5000	.5000	.5000	.5000	.5000	.5000	.5000	.5000

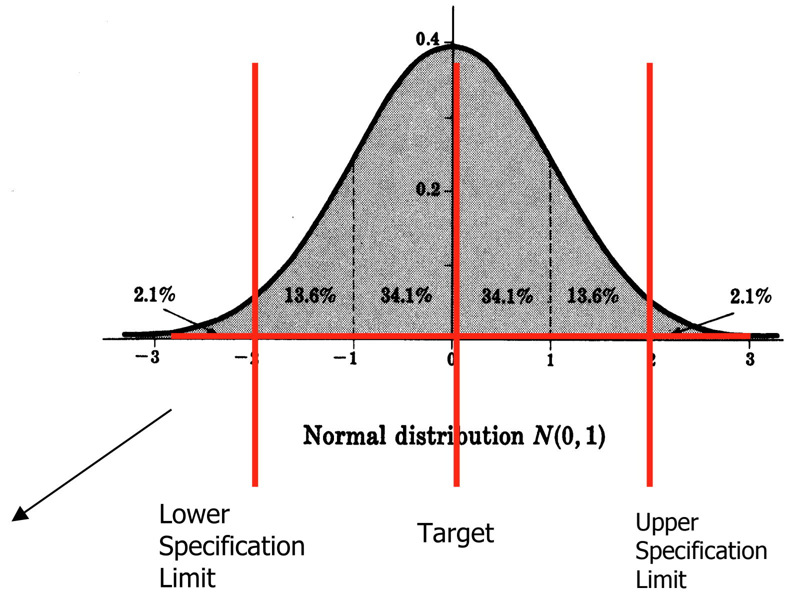


If UCL-LCL = 6σ
and the process mean
is in the center, then
The out of compliance
parts are given by
$2(0.500-\phi(3\sigma))$ =
2(0.500-0.4987) =
0.0026 or 0.26% or 2600ppm

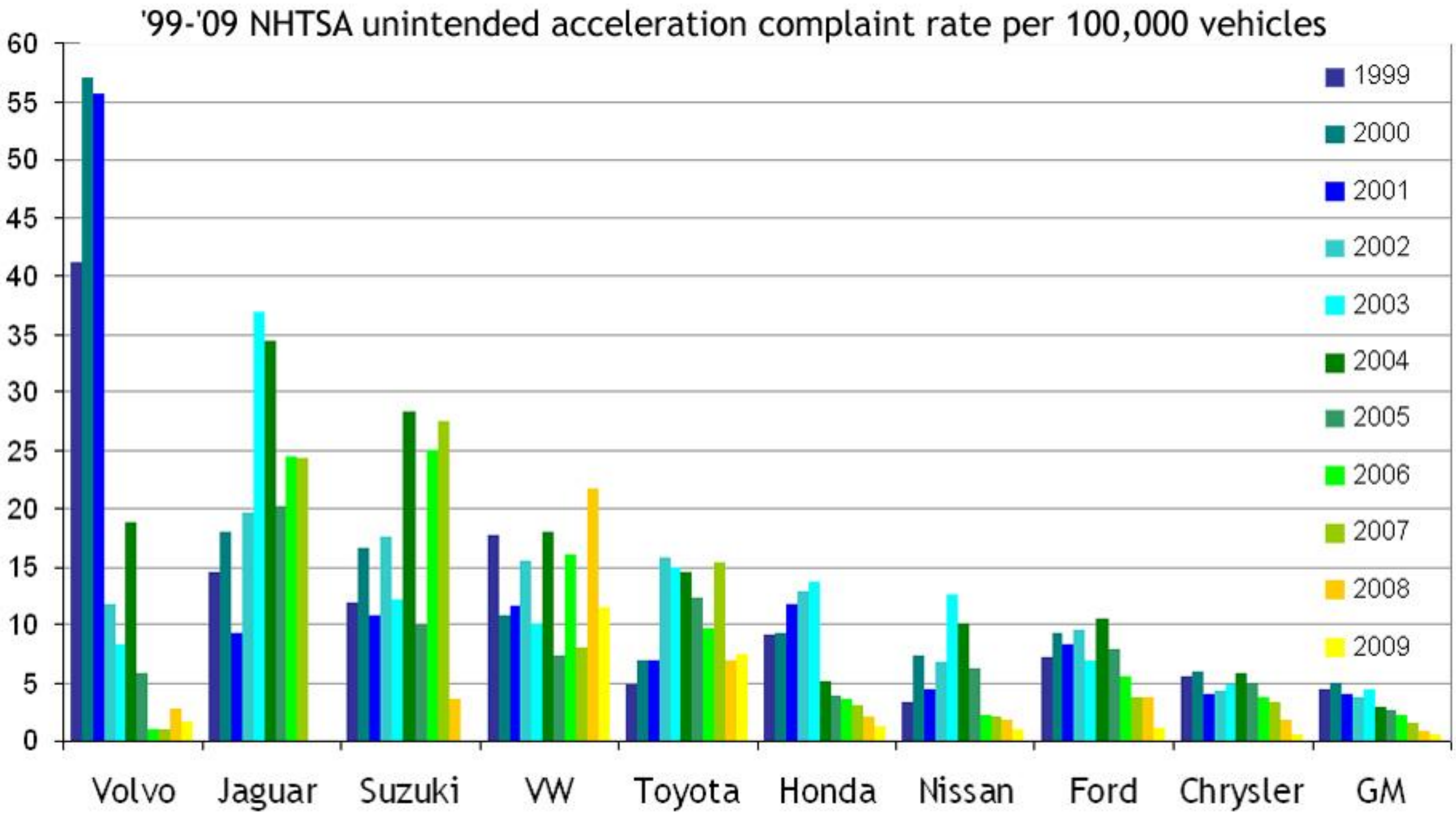
Some propose a process capability index C_p that compares the tolerance interval USL-LSL vs the process variation 6σ.

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

C_p	% out	ppm
⅔	4.55	45,500
1	0.26	2600
1 ⅓	.0063	63

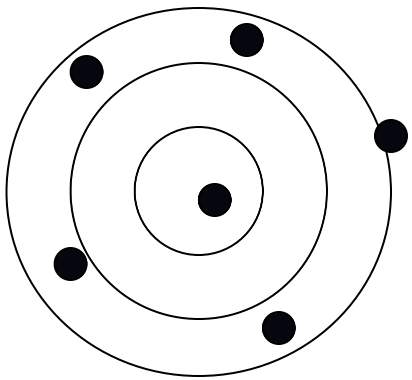


How big is 2600ppm?

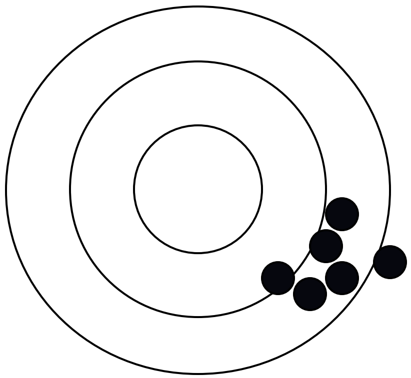


10/100,000 = 100 ppm

Mean drift



Mean on target, but large variation due to many random effects



Mean drift has assignable cause, tight grouping means small variation

Examples of mean drift in processing

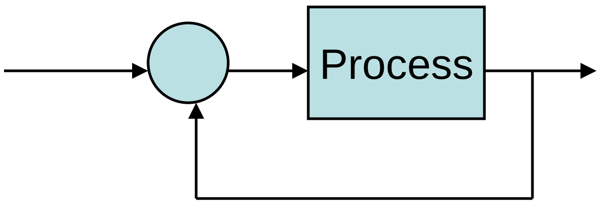
- Cutting tool wears gradually
- Temperature in the room (and the work piece) changes gradually
- Machine adjusts as it is warming up
- New batch of materials have slightly different properties

But each of these can be controlled…

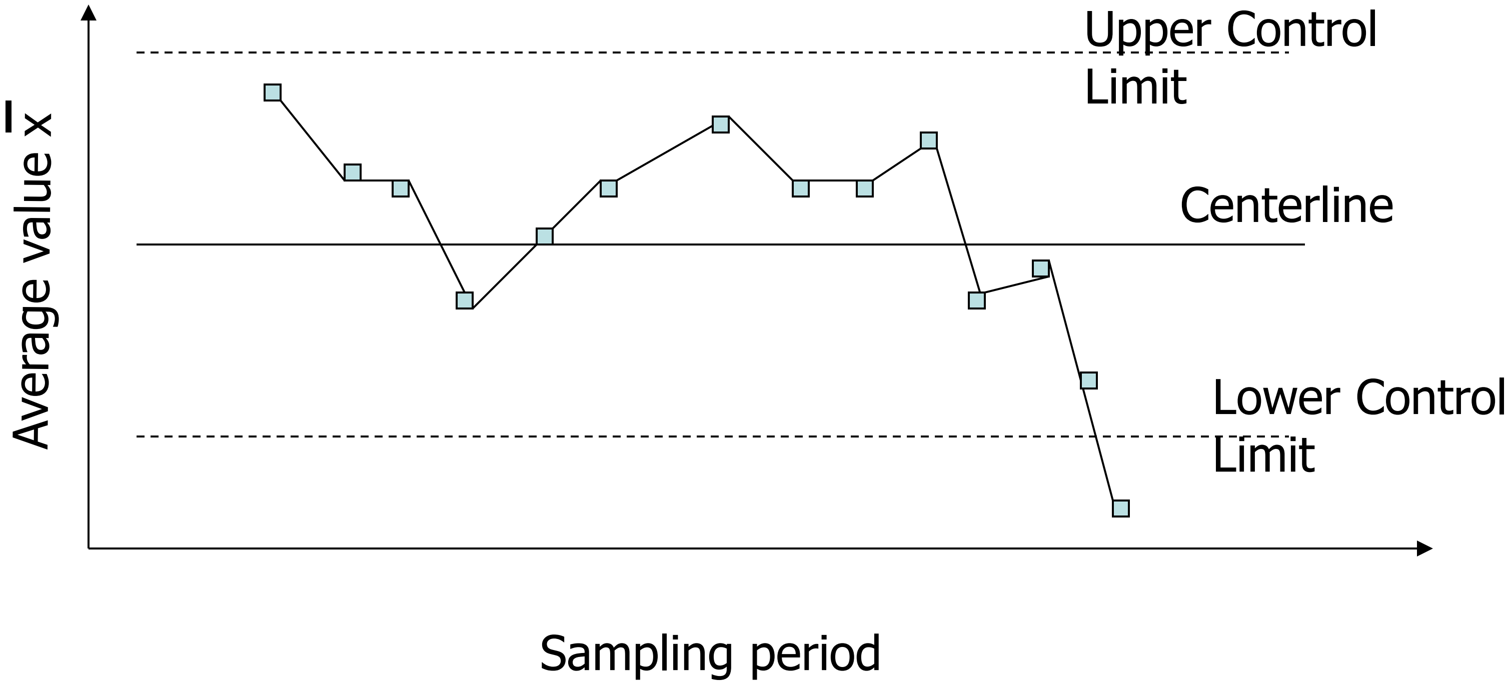
Observing changes in the mean and variance

- Use Statistical Process Control and Process Control Charts
- Kalpakjian & Schmid: section 36.8
- Handout by Hogg, and Ledolter

Measurement

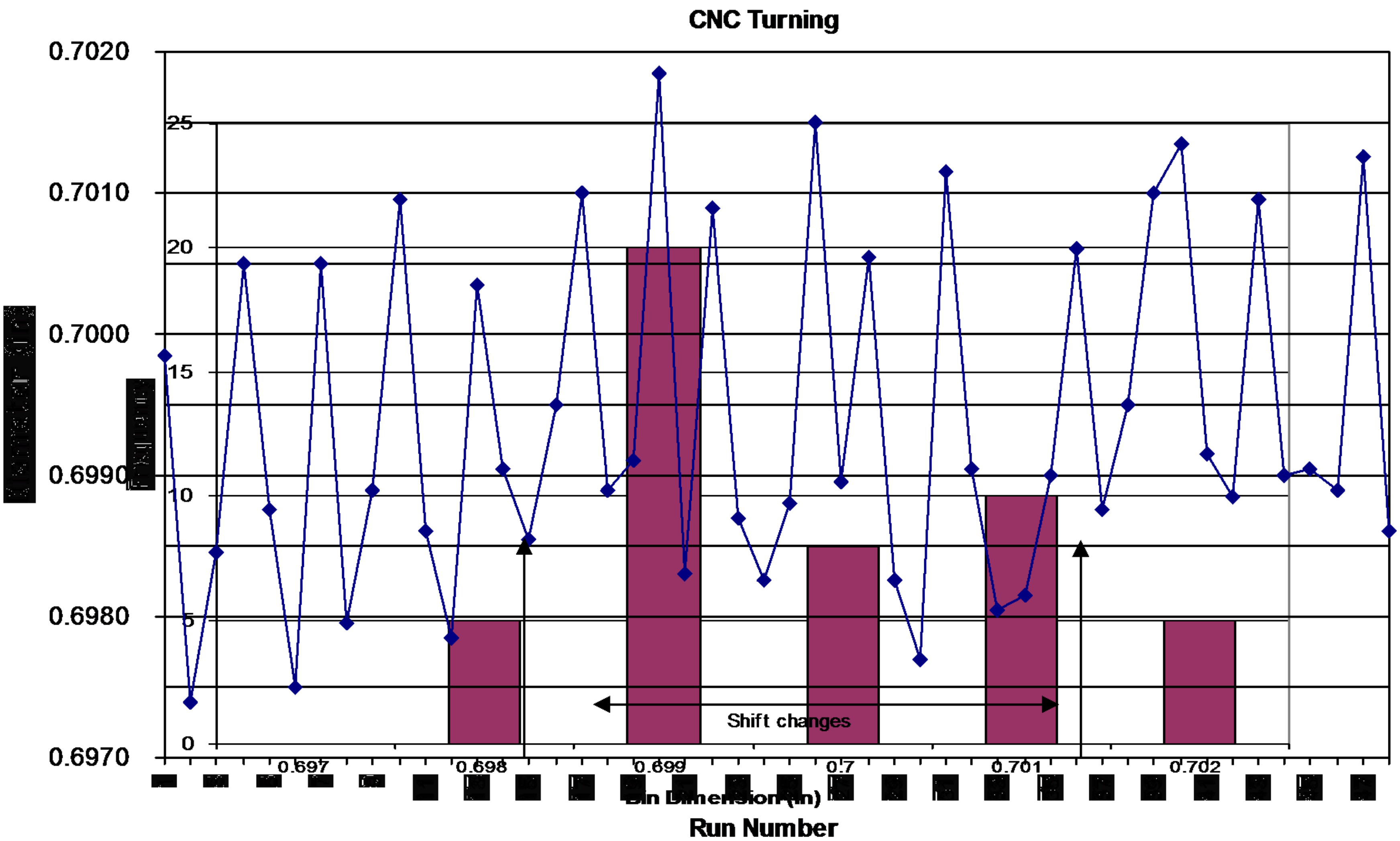


- Statistical Process Control

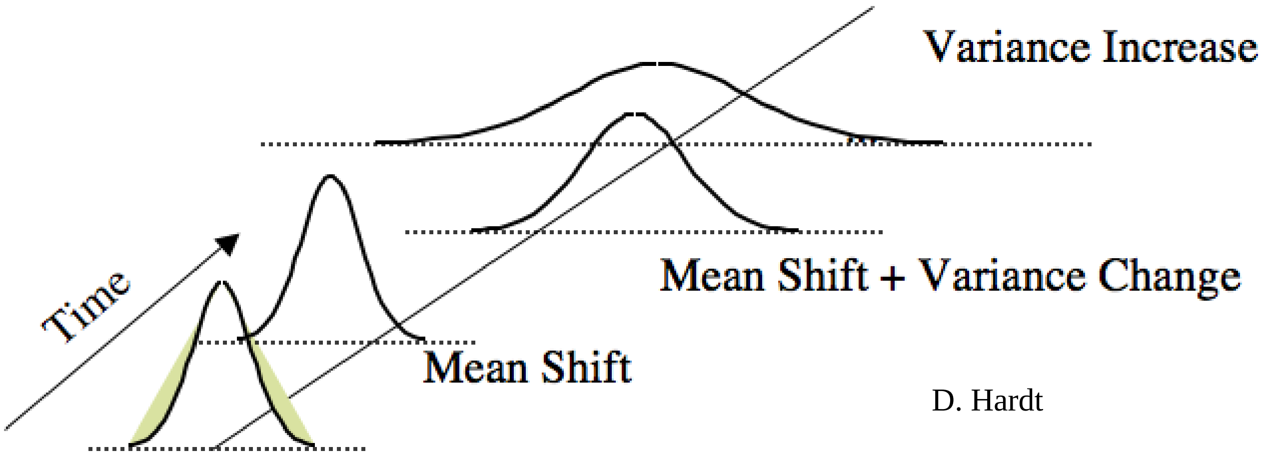


"Shewhart Control Charts"

Histogram for CNC Turning



From Dave Hardt



D. Hardt

Better to label as
UCL instead of USL

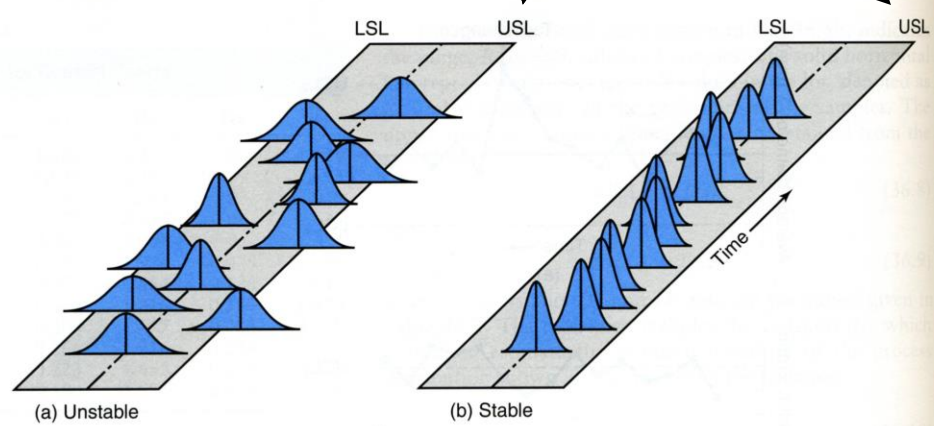


FIGURE 36.7 Illustration of processes that are (a) unstable or out of control and (b) stable or in control. Note in part (b) that all distributions have standard deviations that are lower than those of the distributions shown in part (a) and have means that are closer to the desired value. *Source:* Based on K. Crow.

Schematic representation
of how the distribution
of a measurement may
change with time

Kalpakjian & Schmid

Statistical Control Methods

Strategy:

1. Determine ***Centerline***, ***UCL***, and ***LCL*** (from past data sampling when process is under control)
2. Monitor stability of process
3. Data outside of UCL/LCL indicates mean shift
4. Investigate and eliminate causes of shift

Statistical Control Methods

Factors that determine the appropriate sampling frequency:

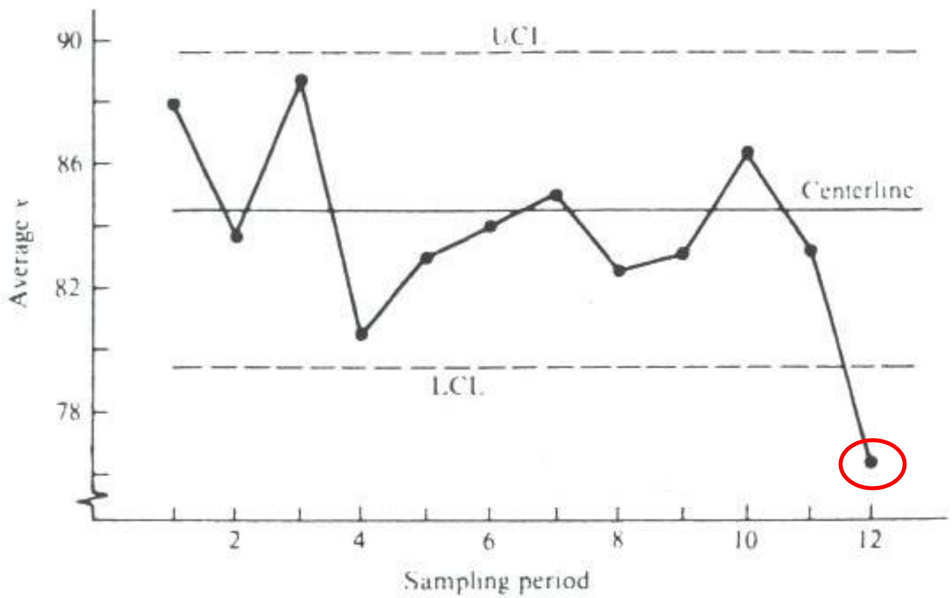
– Stability of process

– Potential loss

– Cost of sampling inspection

“x-bar charts”

Mean of the means



$\bar{x}$-chart for the sample means

$$\bar{x} = \sum_{i=1}^{n} x_i / n$$

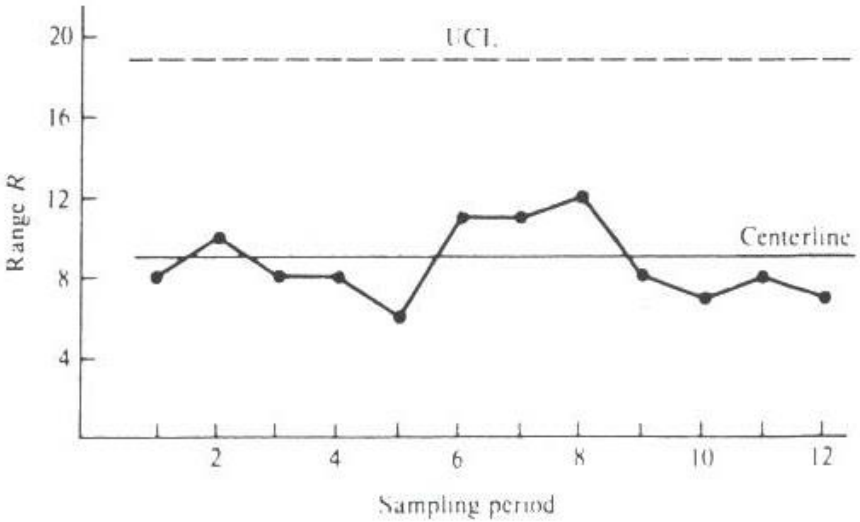
$$\bar{\bar{x}} = \frac{1}{k} \sum_{j=1}^{k} \bar{x}_j$$

$$UCL, LCL = \bar{\bar{x}} \pm A_2 \bar{R}$$

Where,
- n = sample size
- k = number of samples
- A_2 = constant from Table C.1
- R = defined next slide

“R-charts” Range = high - low

- Standard Deviation can be estimated from R



R-chart for the sample ranges

$$R = \max(x_1, \ldots, x_n) - \min(x_1, \ldots, x_n)$$

$$\overline{R} = \frac{1}{k}\sum_{j=1}^{k} R_j$$

$$LCL = D_3\overline{R}$$
$$UCL = D_4\overline{R}$$

Where, n = sample size
k = number of samples
D_3 , D_4 = constants from Table C.1

Estimate of standard deviation from range
ref. P. Lyonnet

estimate for m, and if W is the range or spread of values in the sample, i.e. the difference between the greatest and least values, an estimate for σ is W/d_n, where n is the number of items in the sample and d_n is a known function (Table 3.3 gives values of d_n).

Table 3.3 Estimation of σ from range $W : \hat{\sigma} = W/\mathrm{d_n}$

Size of each sample	$1/d_n$	d_n
2	0.886	1.128
3	0.591	1.693
4	0.486	2.059
5	0.430	2.326
6	0.395	2.534
7	0.370	2.704
8	0.351	2.847
9	0.337	2.970
10	0.325	3.078
11	0.315	3.173
12	0.307	3.258

Table C.1 Factors for Determining the 3σ Control Limits in $\bar{x}$-Charts and R-Charts.

Number of Observations in Sample, n	Factors for $\bar{x}$-Charts		Factors for R-Chart	
	Using $\bar{s}$ A_3	Using $\bar{R}$ A_2	D_3	D_4
2	2.66	1.88	0	3.27
3	1.95	1.02	0	2.57
4	1.63	0.73	0	2.28
5	1.43	0.58	0	2.11
6	1.29	0.48	0	2.00
7	1.18	0.42	0.08	1.92
8	1.10	0.37	0.14	1.86
9	1.03	0.34	0.18	1.82
10	0.98	0.31	0.22	1.78
11	0.93	0.29	0.26	1.74
12	0.89	0.27	0.28	1.72
13	0.85	0.25	0.31	1.69
14	0.82	0.24	0.33	1.67
15	0.79	0.22	0.35	1.65
16	0.76	0.21	0.36	1.64
17	0.74	0.20	0.38	1.62
18	0.72	0.19	0.39	1.61
19	0.70	0.19	0.40	1.60
20	0.68	0.18	0.41	1.59

Source: Reproduced with permission from E. L. Grant, *Statistical Quality Control*, 2nd ed. (New York: McGraw-Hill, 1952), pp. 513 and 514.

What causes variation in dimensions?

- Machine variation
  - e.g. bearing compression, thermal expansion, tool wear..
- Material variation
  - e.g.from supplier, during process
- Operator variation
  - Jim instead of Joe, or Alice instead of Mary
- Method variation
  - Mary always does it this way…

Process variation/tolerance

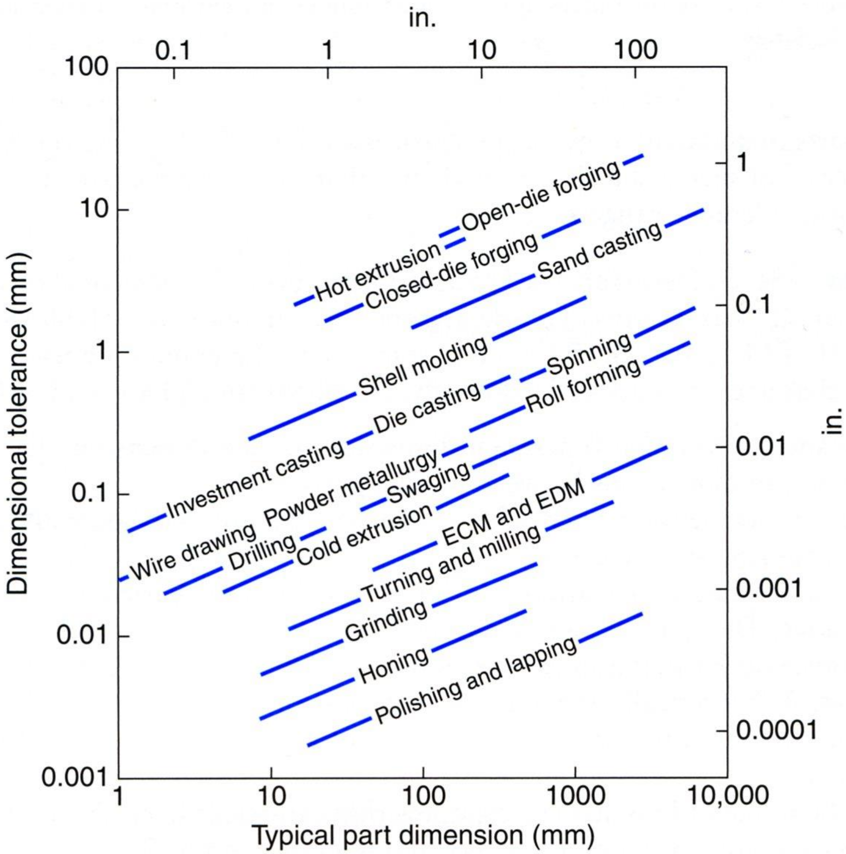


FIGURE 35.20 Dimensional tolerances as a function of part size for various manufacturing processes; note that because many factors are involved, there is a broad range for tolerances.

What are the most important variables?

Process variation/tolerance

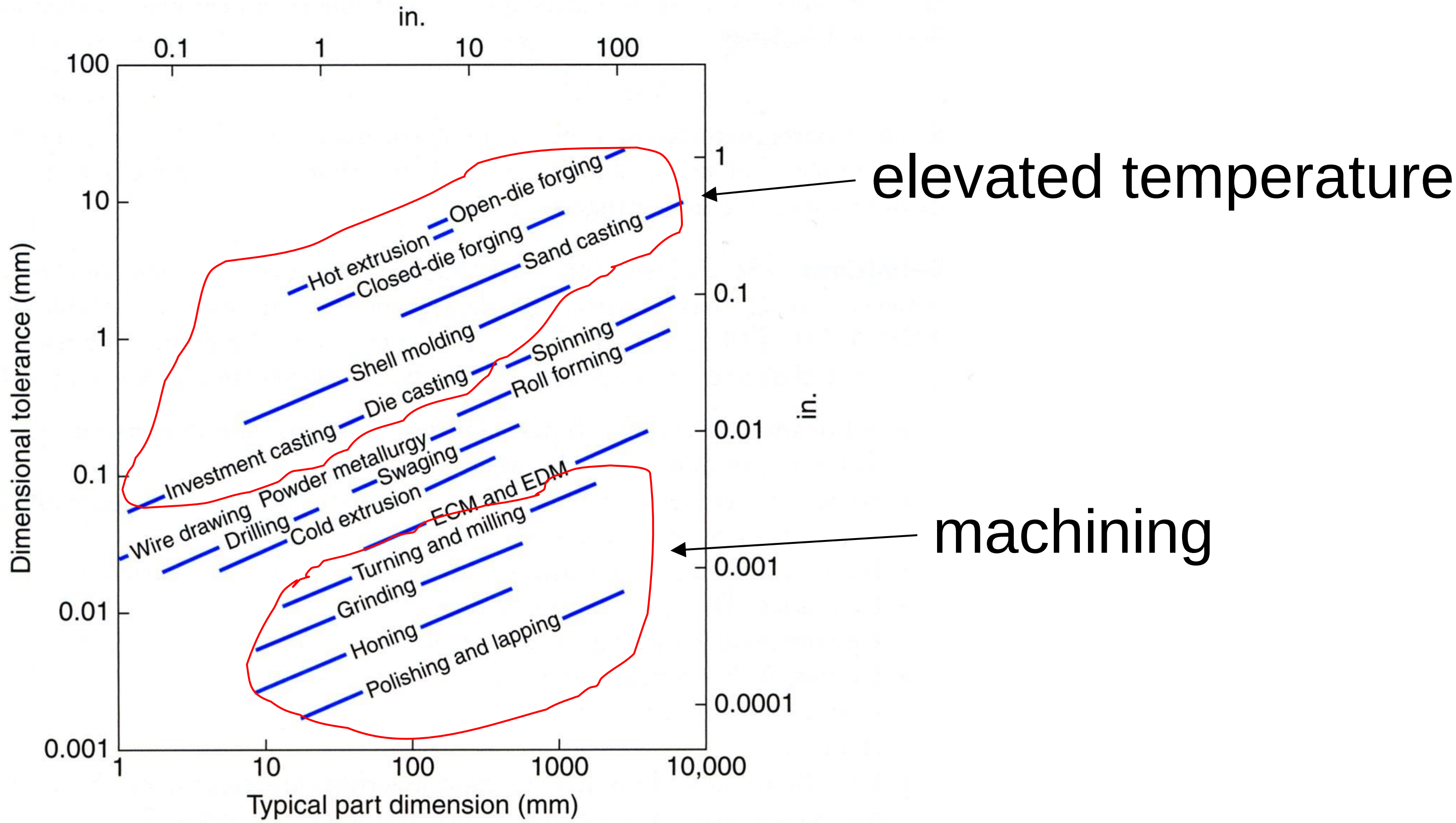


FIGURE 35.20 Dimensional tolerances as a function of part size for various manufacturing processes; note that because many factors are involved, there is a broad range for tolerances.

Process variation

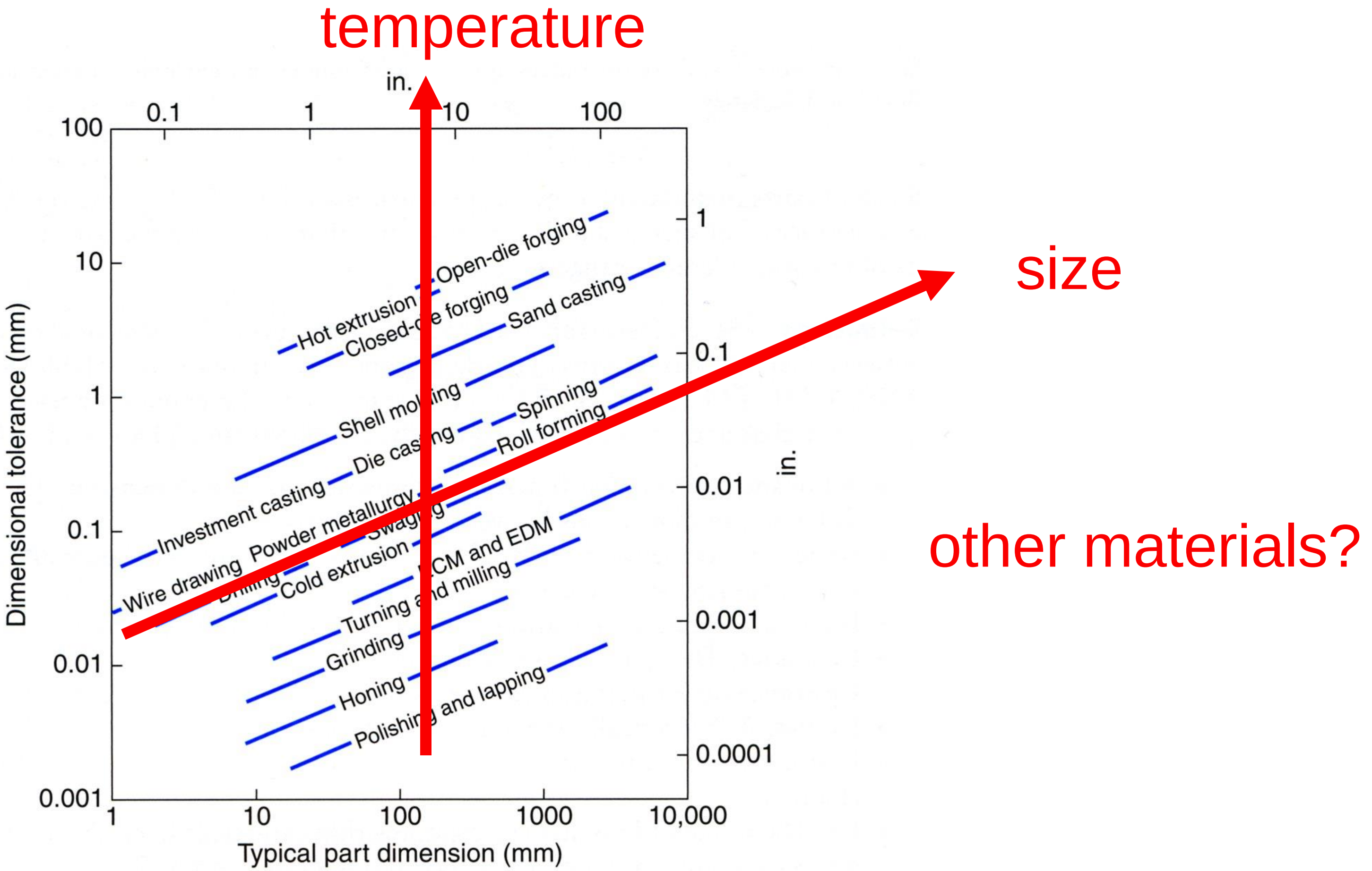


FIGURE 35.20 Dimensional tolerances as a function of part size for various manufacturing processes; note that because many factors are involved, there is a broad range for tolerances.

e.g.Thermal expansion

$$\delta = \alpha L \Delta T$$

change in dimension

coef. of thermal expansion

length of sample

change in temperature

Random variables

If the variables are independent:

$$E(\delta) = E(\alpha)E(L)E(\Delta T)$$

..and the variation is small:

$$\left(\frac{\sigma_\delta}{\bar{\delta}}\right)^2 = \left(\frac{\sigma_L}{\bar{L}}\right)^2 + \left(\frac{\sigma_\alpha}{\bar{\alpha}}\right)^2 + \left(\frac{\sigma_{\Delta T}}{\overline{\Delta}\,\bar{T}}\right)^2$$

Ref: Lipschutz

Properties of the Expectation

1. If $Y = aX + b$;

   where Y, X are random variables; a, b are constants,

   $$E(Y) = aE(X) + b \tag{4}$$

2. If $X_1, \ldots X_n$ are random variables,

   $$E(X_1 + \ldots + X_n) = E(X_1) + \ldots + E(X_n) \tag{5}$$

Properties of the Variance

1. For a and b constants,

$$\text{Var}(aX + b) = a^2\text{Var}(X) \qquad (6)$$

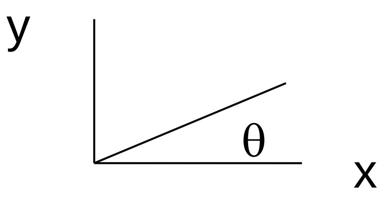
2. If $X_1, \ldots, X_n$ are <u>independent</u> random variables

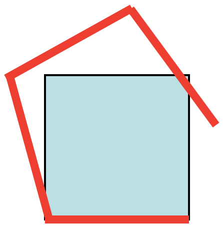
$$\text{Var}(X_1 + \ldots + X_n) = \text{Var}(X_1) + \text{Var}(X_2) + \quad + \text{Var}(X_n)$$

(7)

Propagation of errors approach

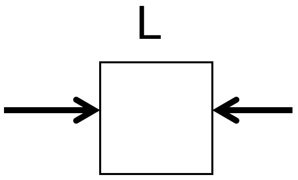
- examples





  - Abbe error: $y \approx \theta\, x$

  - thermal expansion: $\delta L = L\, \alpha\, \Delta T$



  - Mean $E(y) = E(\theta)\, E(x)$, if <u>independent</u>, but
  - Var $(y) = ?$
  - Linearize for small values of δx, $\delta\theta$

Propagation of errors $y = \theta \cdot x$

$$y = \bar{y} + \delta y = (\bar{\theta} + \delta\theta)(\bar{x} + \delta x)$$

$$\delta y \cong \bar{\theta}\,\delta x + \bar{x}\,\delta\theta$$

$$Var(y) = E[(\delta y)^2]$$

$$\delta y^2 \cong (\bar{\theta}\,\delta x)^2 + 2\bar{\theta}\,\delta x \cdot \bar{x}\,\delta\theta + (\bar{x}\,\delta\theta)^2$$

recall $\quad E(x) = \sum x_i\, p(x_i)$

$$Var(y) \cong \bar{\theta}^2 Var(x) + \bar{x}^2 Var(\theta)$$

This gives…

- this result is called “quadrature”,

  in general, if $y = \theta x$, with θ, x independent random variables with small variation, then

  with Var (x) = σ_x^2

$$\left(\frac{\sigma_y}{\bar{y}}\right)^2 = \left(\frac{\sigma_\theta}{\bar{\theta}}\right)^2 + \left(\frac{\sigma_x}{\bar{x}}\right)^2$$

A more general results is…

- for any relationship like $y=z^{\alpha}x^{\beta}$, with z, x independent random variables with small variation, then

$$\left(\frac{\sigma_y}{\bar{y}}\right)^2 = \alpha^2\left(\frac{\sigma_z}{\bar{z}}\right)^2 + \beta^2\left(\frac{\sigma_x}{\bar{x}}\right)^2$$

Hence for Thermal Expansion…

If the variables are independent:

$$E(\delta) = E(\alpha)E(L)E(\Delta T)$$

..and the variation is small:

$$\left(\frac{\sigma_\delta}{\bar{\delta}}\right)^2 = \left(\frac{\sigma_L}{\bar{L}}\right)^2 + \left(\frac{\sigma_\alpha}{\bar{\alpha}}\right)^2 + \left(\frac{\sigma_{\Delta T}}{\overline{\Delta T}}\right)^2$$

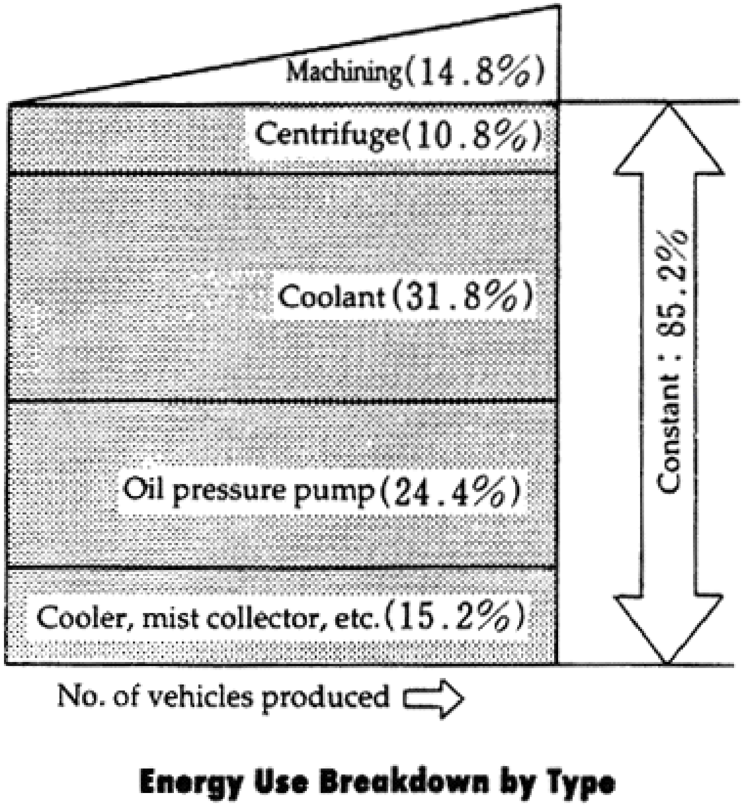
Energy intensity of Mfg Processes

1. Machining
2. Grinding
3. Casting
4. Injection Molding
5. Abrasive Waterjet
6. EDM
7. Laser DMD
8. CVD
9. Sputtering
10. Thermal Oxidation

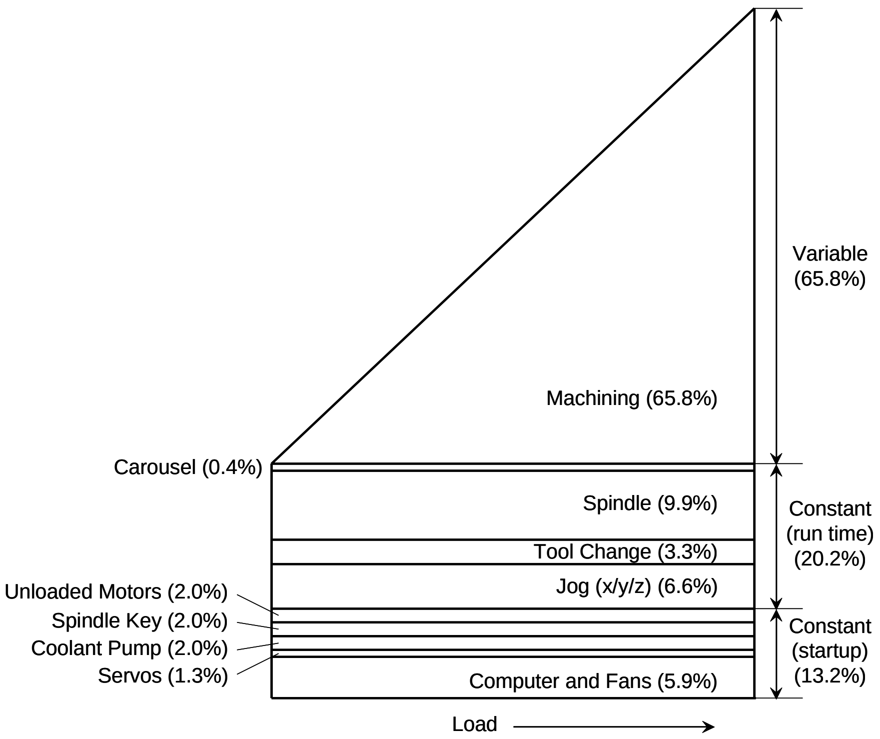
Electricity requirements for manufacturing processes

$MJ_{electricity}/kg_{processed}$

Energy Requirements at the Machine Tool



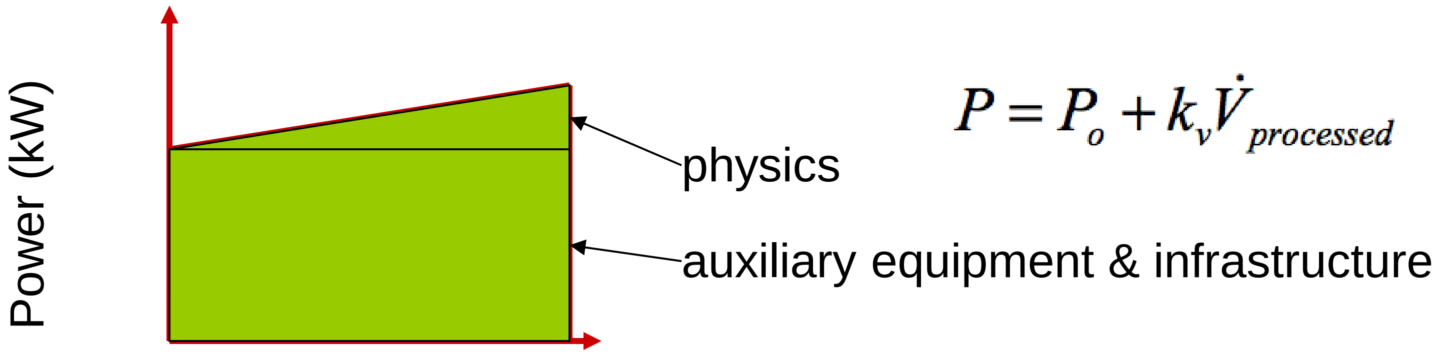
Production Machining Center



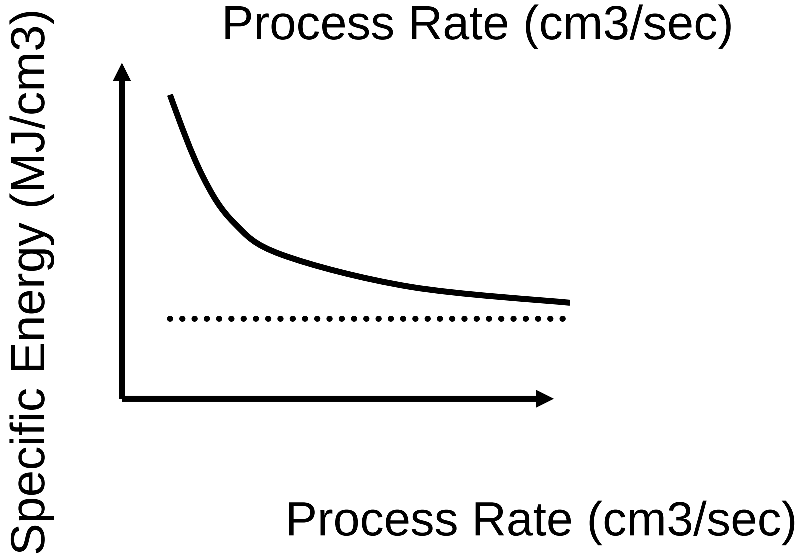
Automated Milling Machine

From Toyota 1999, and Kordonowy 2002.

Electric Energy Intensity for Manufacturing Processes

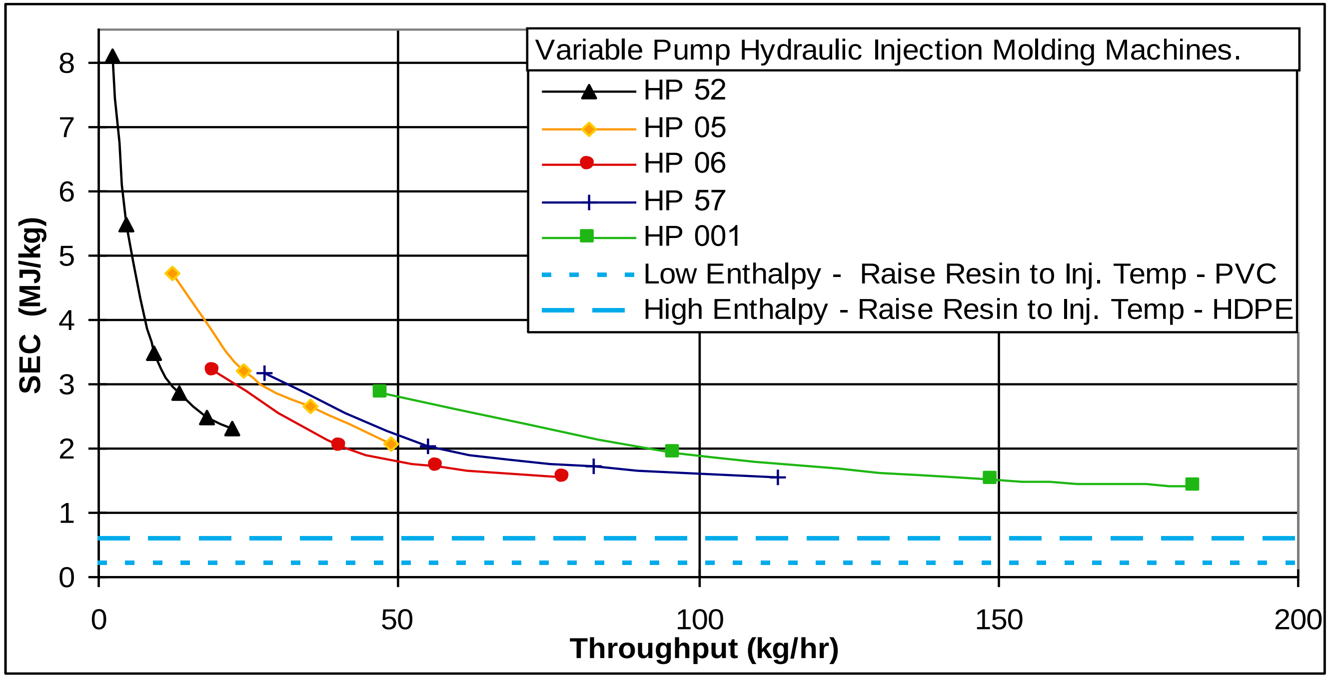


$$P = P_o + k_v \dot{V}_{processed}$$



$$\frac{P}{\dot{V}} = \frac{P_o}{\dot{V}} + k_v = \frac{E}{V}$$

Injection Molding Machines



Source: [Thiriez '06]

$$\frac{P}{\dot{m}} = \frac{P_o}{\dot{m}} + k_m = \frac{E}{m}$$

Does not account for the electric grid.

Thermal Oxidation, SiO_2

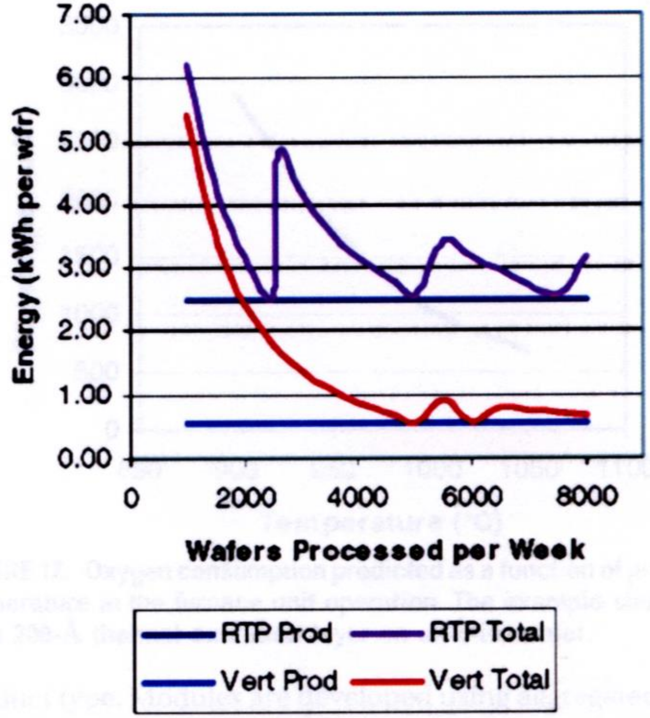


FIGURE 9. Energy consumption for growth of a 25-Å oxide layer as a function of equipment type (RTP vs vertical furnace), number of wafers processed per week, and total run time (production plus idle). The example shown is for 8-in. wafers.

Ref: Murphy et al es&t 2003

Power Requirements

TABLE 2. Average Number of Functions, Throughputs, and Power Requirements for a Hypothetical 0.13-μM Microprocessor Wafer Fab

unit operation	no. of functions 8-layer metal	6-layer metal	wafers/ run	wafers/ h	power (kW) process	idle
implant	16	16	25	20	27	15
CVD	13	11	10	15	16	14
wafer clean	35	31	50	150	8	7.5
furnace	21	17	150	35	21	16
furnace (RTP)	7	7	1	10	48	45
photo (stepper)	27	23	1	60	115	48
photo (coater)	27	23	1	60	90	37
etch (pattern)	24	20	1	35	135	30
etch (ash)	27	23	1	20	1	0.8
metallization	11	9	1	25	150	83
CMP	18	14	1	25	29	8

Ref: Murphy et al es&t 2003

Process Name	Power Required			Process Rate				Electricity Required			References
	kW			cm^3/s				J/cm^3			
Injection Molding	10.76	-	71.40	3.76	-	50.45	of polymer processed	1.75E+03	-	3.41E+03	[Thiriez 2006]
Machining	2.80	-	194.80	0.35	-	20.00	of material removed	3.50E+03	-	1.87E+05	[Dahmus 2004], [Morrow, Qi & Skerlos 2004] & [Time Estimation Booklet 1996]
Finish Machining	9.59			2.05E-03			of material removed	4.68E+06			[Morrow, Qi & Skerlos 2004] & [Time Estimation Booklet 1996]
CVD	14.78	-	25.00	6.54E-05	-	3.24E-03	of material deposited on wafer area	4.63E+06	-	2.44E+08	[Murphy et al. 2003], [Wolf & Tauber 1986, p.170], [Novellus Concept One 1995b] & [Krishnan Communication 2005]
Sputtering	5.04	-	19.50	1.05E-05	-	6.70E-04	of material deposited on wafer area	7.52E+06	-	6.45E+08	[Wolf & Tauber 1986] & [Holland Interview]
Grinding	7.50	-	0.03	1.66E-02	-	2.85E-02	of material removed	6.92E+04	-	3.08E+05	[Baniszewski 2005] & [Chryssolouris 1991]
Waterjet	8.16	-	16.00	5.15E-03	-	8.01E-02	of material removed	2.06E+05	-	3.66E+06	[Kurd 2004]
Wire EDM	6.60	-	14.25	2.23E-03	-	2.71E-03	of material removed	2.44E+06	-	6.39E+06	[Sodick], [Kalpakjian & Schmid 2001], & [AccuteX 2005]
Drill EDM	2.63			1.70E-07			of material removed	1.54E+10			[King Edm 2005] & [McGeough, J.A. 1988]
Laser DMD	80.00			1.28E-03			of material removed	6.24E+07			[Morrow, Qi & Skerlos 2004]
Thermal Oxidation	21.00	-	48.00	4.36E-07	-	8.18E-07	of material deposited on wafer area	2.57E+10	-	1.10E+11	[Murphy et al. 2003]

In General, over many manufacturing processes,

Idle Power

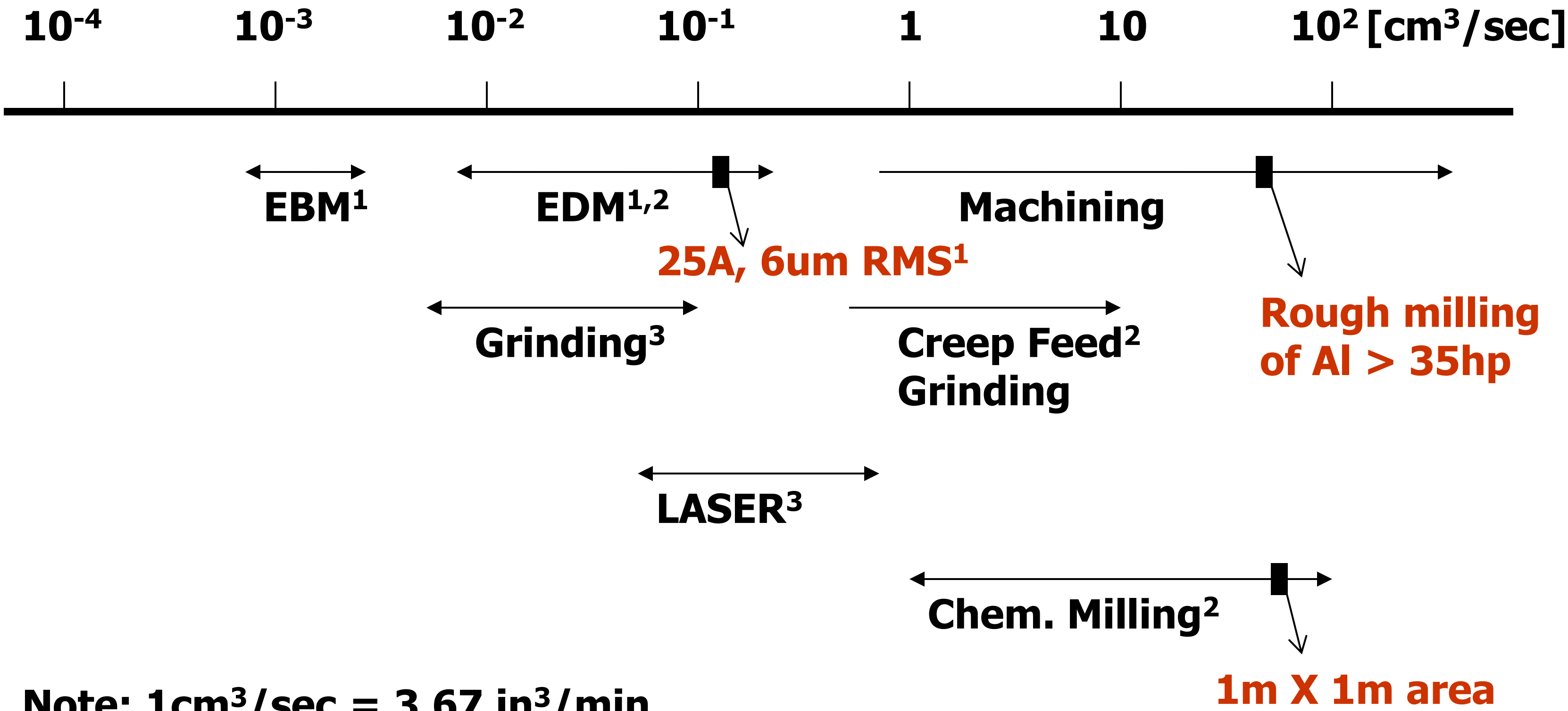
$$5kW \le P_o \le 50kW$$

and

Material Process Rates

$$10^{-7}\ \text{cm}^3/\text{sec} \le \dot{V} \le 1\ \text{cm}^3/\text{sec}$$

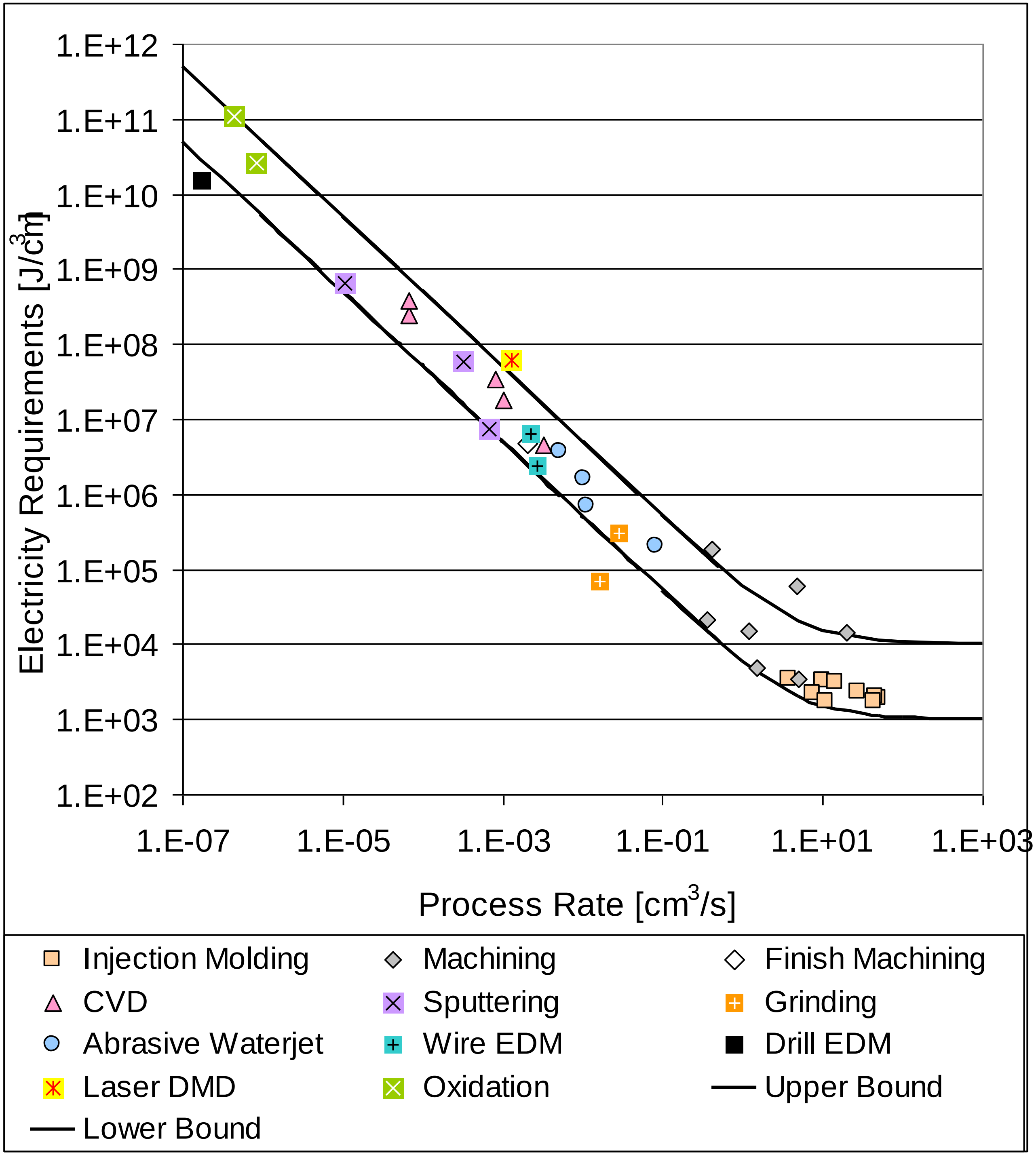
Typical Material Removal Rate



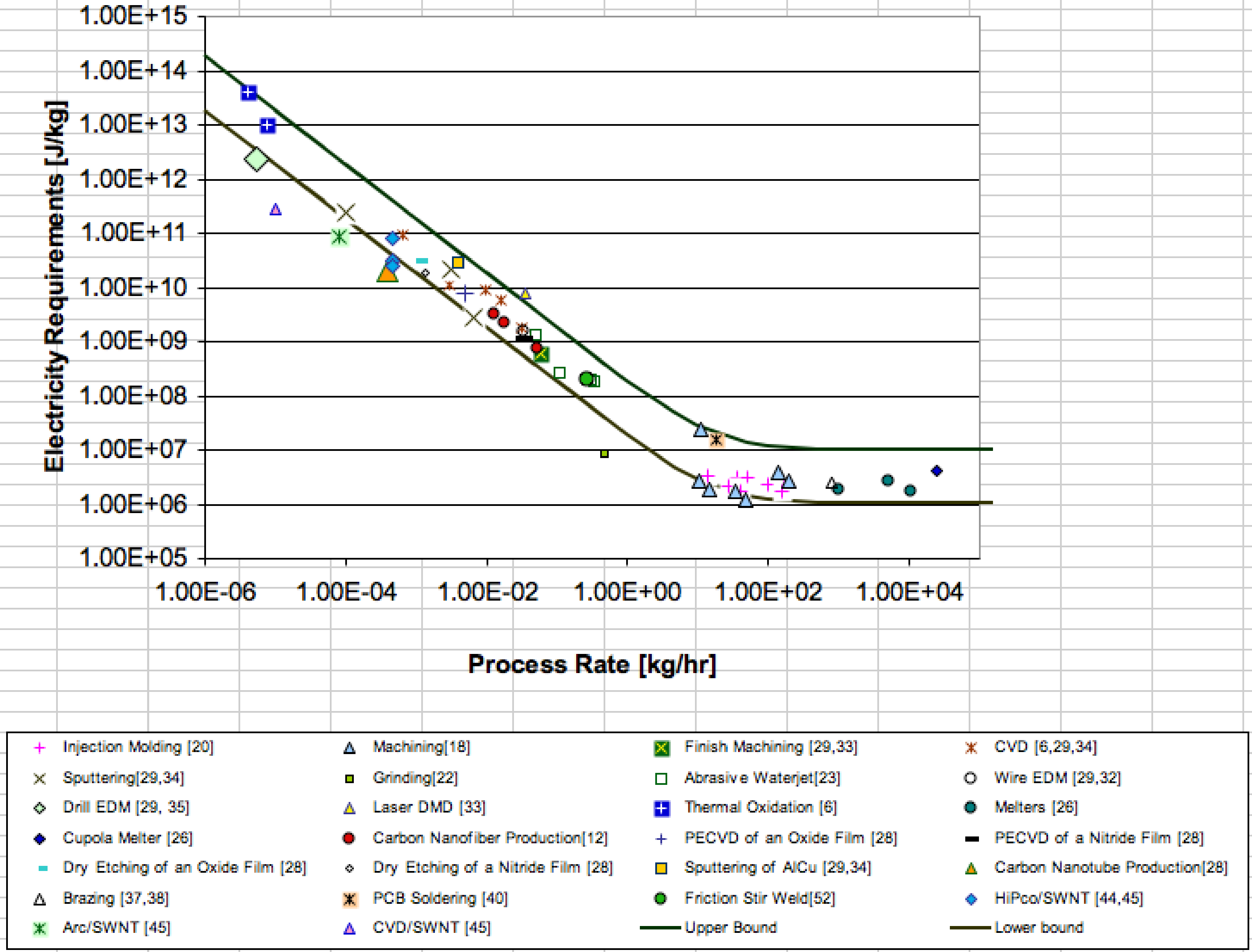
Note: 1cm^3/sec = 3.67 in^3/min

* References: 1. Advanced Methods of Machining, J.A.McGeough, Chapman and Hall, 1988
2. Manufacturing Engineering and Technology, S. Kalpakjian, Addison-Wesley, 1992
3. Laser Machining, G. Chryssolouris, Springer-Verlag, 1991

Specific Energy Requirements J/cm^3 for Various Mfg Processes



Gutowski et al
IEEE, ISEE 2007


1.00E+15
1.00E+14
1.00E+13
1.00E+12
1.00E+11
1.00E+10
1.00E+09
1.00E+08
1.00E+07
1.00E+06
1.00E+05
Electricity Requirements [J/kg]
1.00E-06
1.00E-04
1.00E-02
1.00E+00
1.00E+02
1.00E+04
Process Rate [kg/hr]
Injection Molding [20]
Machining[18]
Finish Machining [29,33]
CVD [6,29,34]
Sputtering[29,34]
Grinding[22]
Abrasive Waterjet[23]
Wire EDM [29,32]
Drill EDM [29, 35]
Laser DMD [33]
Thermal Oxidation [6]
Melters [26]
Cupola Melter [26]
Carbon Nanofiber Production[12]
PECVD of an Oxide Film [28]
PECVD of a Nitride Film [28]
Dry Etching of an Oxide Film [28]
Dry Etching of a Nitride Film [28]
Sputtering of AlCu [29,34]
Carbon Nanotube Production[28]
Brazing [37,38]
PCB Soldering [40]
Friction Stir Weld[52]
HiPco/SWNT [44,45]
Arc/SWNT [45]
CVD/SWNT [45]
Upper Bound
Lower bound

QuickTime™ and a
decompressor
are needed to see this picture.

Why the two different distributions at Sony?

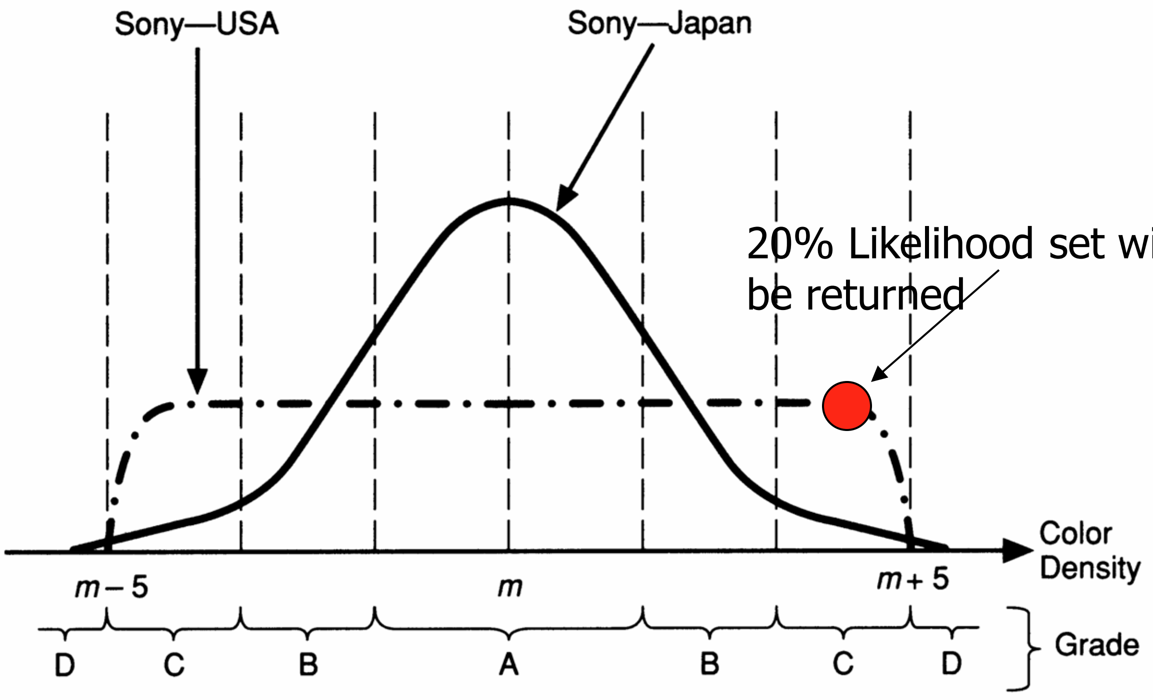


Figure 2.1 Distribution of color density in television sets. (Source: *The Asahi*, April 17, 1979).

Extra slides

Cost of Energy in Machining

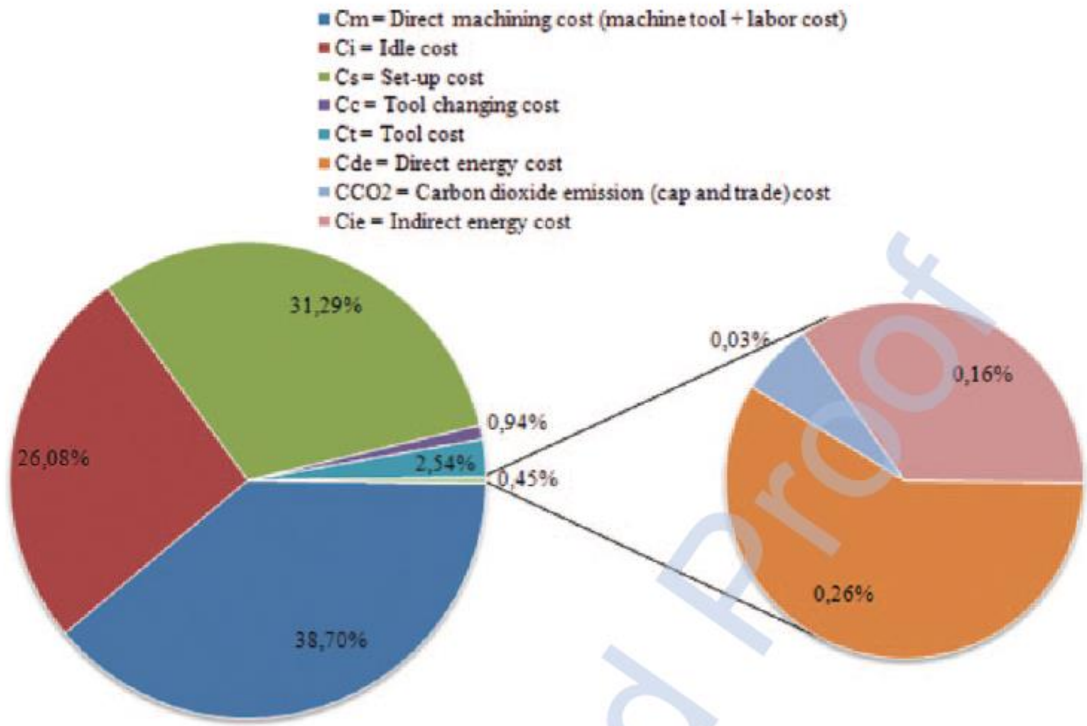
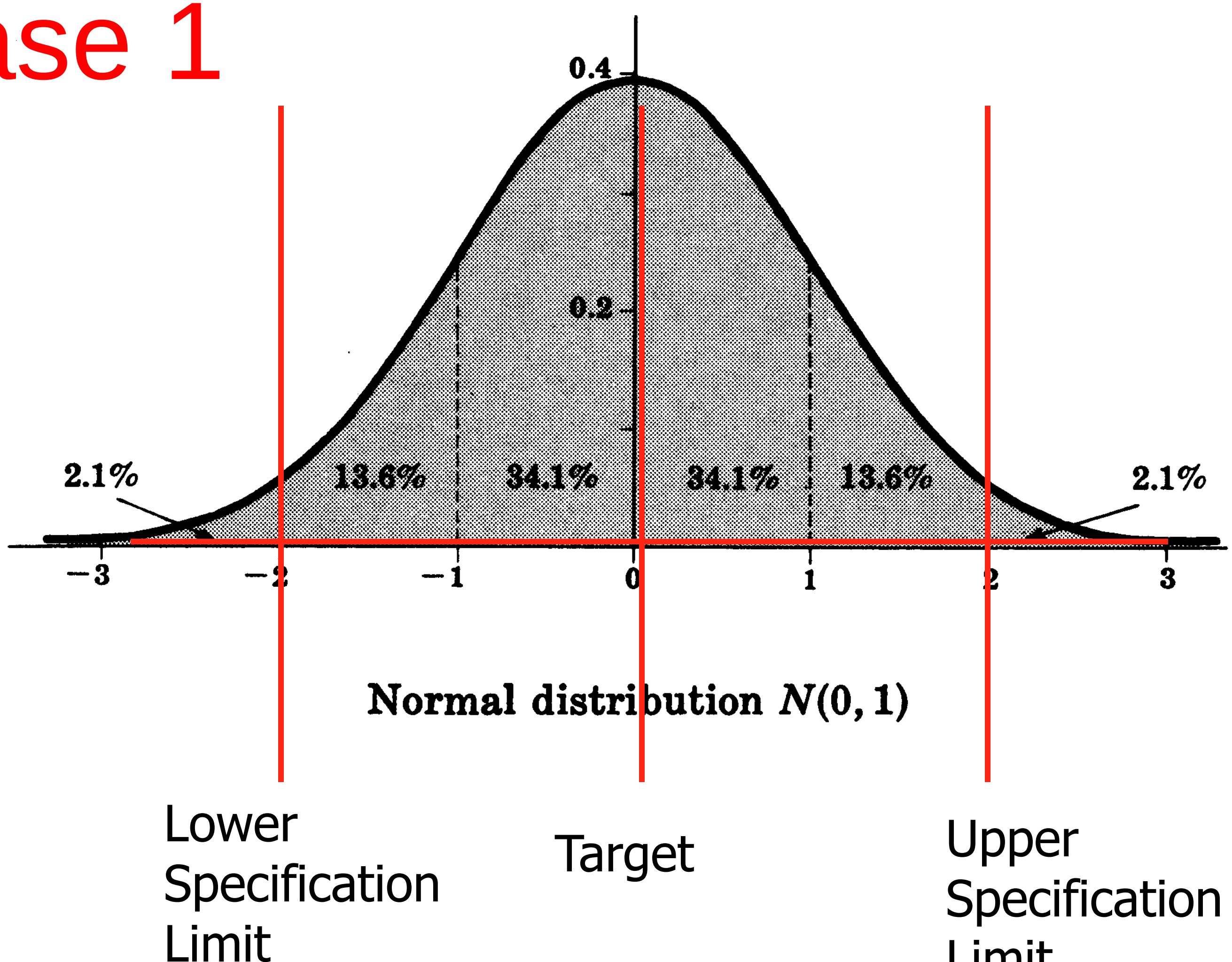


Fig. 2 Relative contribution of cost components. The right-hand panel shows the energy-related cost components for experiment E

Ref. Anderberg, Kara, Beno

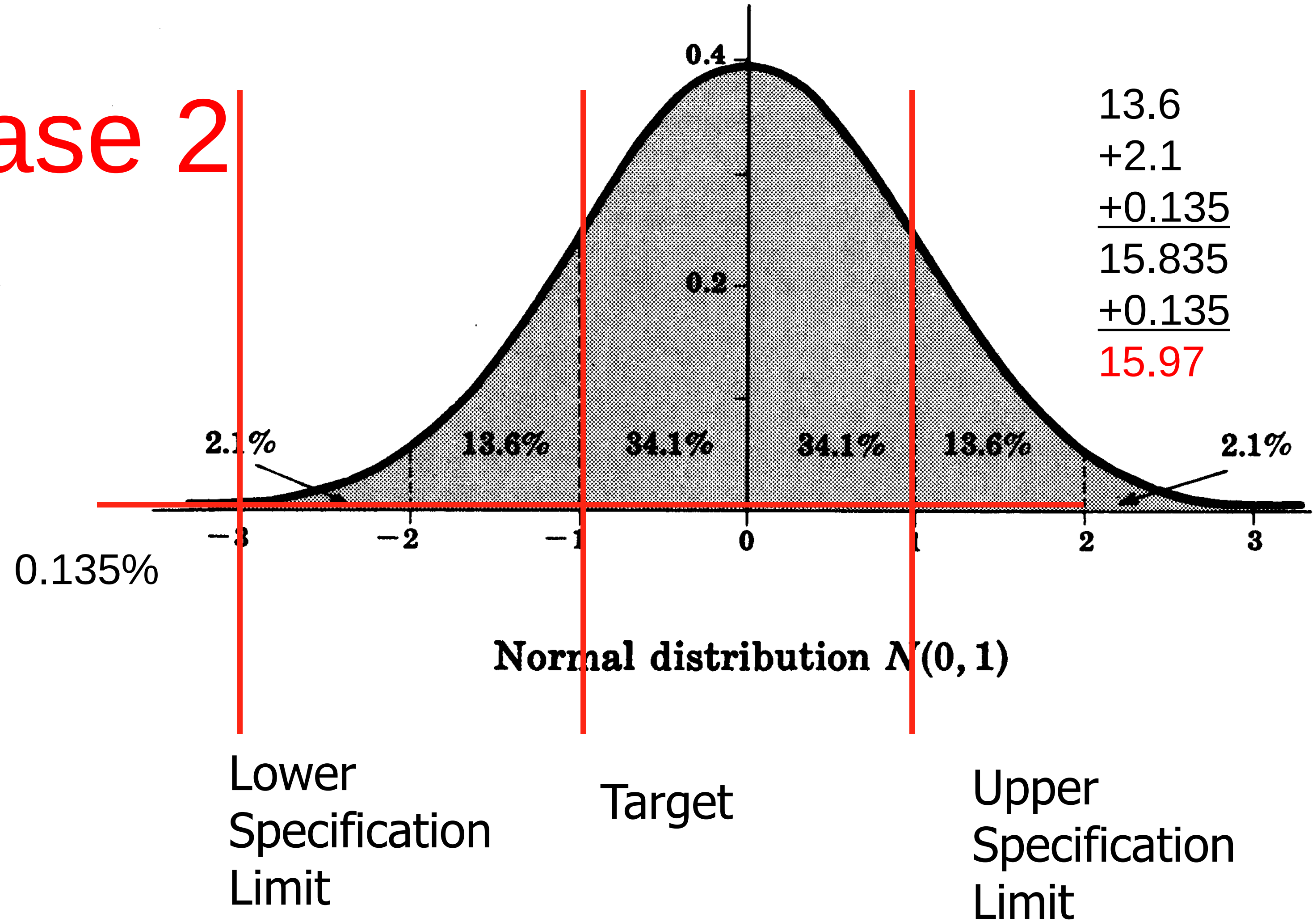
The out of specification parts are $2(0.5-\phi(2\sigma))$
$= 2(0.5 - 0.4772) = 0.0456$ or 4.56%

Case 1



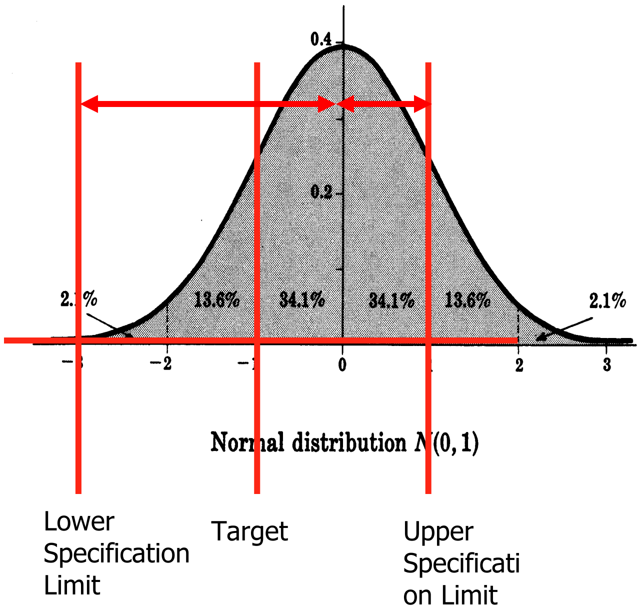
In general the mean and the target do not have to line up. In this case the C_p is misleading. A better question is, how many parts are out of

Case 2



13.6
+2.1
+0.135
15.835
+0.135
15.97

In this case an alternative process capability can be used called the C_{pk}



$$C_{pk} = \frac{\min(USL - \mu, \mu - LSL)}{3\sigma}$$

Comparison

Case 1 (μ on target)

$C_p = 4\sigma/6\sigma =$ 2/3

$C_{pk} =$

$\text{Min}(2\sigma/3\sigma, 2\sigma/3\sigma) =$ 2/3

Out of Spec = 4.55%

Case 2 (μ drift)

$C_p = 4\sigma/6\sigma =$ 2/3

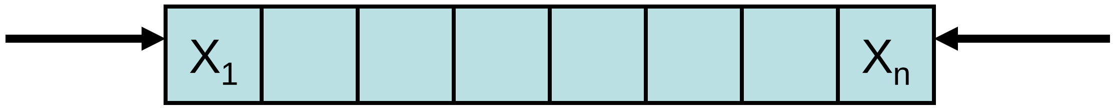
$C_{pk} =$

$\text{Min}(1\sigma/3\sigma, 3\sigma/3\sigma) =$ 1/3

Out of Spec =

15.835%

“Tolerance Stack up”, really about variance,



recall that

$$E(X_1 + \ldots + X_n) = E(X_1) + \ldots + E(X_n)$$

but how about

$$\mathrm{Var}(X_1 + \ldots + X_n) = ?$$

If X_1 and X_2 are random variables and not necessarily independent, then

$$\mathrm{Var}(X_1 + X_2) = \mathrm{Var}(X_1) + \mathrm{Var}(X_2) + 2\mathrm{Cov}(X_1 Y) \qquad (8)$$

this can be written using the standard deviation "σ", and the correlation "ρ" as

$$\sigma_L^2 = \sigma_1^2 + \sigma_2^2 + 2\sigma_1\sigma_2\rho \qquad (9)$$

where $L = X_1 + X_2$

If X_1 and X_2 are correlated ($\rho = 1$), then

$$\boxed{\sigma_L^2 = \sigma_1^2 + \sigma_2^2 + 2\sigma_1\sigma_2 = (\sigma_1 + \sigma_2)^2} \qquad (14)$$

for $X_1 = X_2 = X_0$

$$\sigma_L^2 = 4\sigma_0^2 \qquad (15)$$

for N $$\sigma_L^2 = N^2\sigma_0^2 \qquad (16)$$

or $$\boxed{\sigma_L = N\sigma_0} \qquad (17)$$

Now, if X_1 and X_2 are uncorrelated ($\rho = 0$) we get the result as in eq'n (7) or,

$$\boxed{\sigma_L^2 = \sigma_1^2 + \sigma_2^2} \qquad (10)$$

and for N

$$\sigma_L^2 = \sum_{i=1}^{N} \sigma_i^2 \qquad (11)$$

If X_1=X =X_o

$$\sigma_L^2 = N\sigma_0^2 \qquad (12)$$

Or

$$\boxed{\sigma_L = \sqrt{N}\sigma_0} \qquad (13)$$

"Tolerance Stack-up"

As the number of variables grow so does the variation in the system; but when normalized…

$$\frac{\sigma_L}{L} = \frac{N\sigma_0}{NL_0} = \frac{\sigma_0}{L_0}$$ ← correlated

$$\frac{\sigma_L}{L} = \frac{\sqrt{N}\sigma_0}{NL_0} = \frac{\sigma_0}{\sqrt{N}L_0}$$ ← uncorrelated

Where $L = NL_o$