Final Exam

- Very good performance overall
- Essays were particularly good
- Mean - 88.5%
- Standard deviation - 5.7%

Homework

- HW#8
  - Mean = 96.1
  - Standard Deviation = 7.4
- HW#9
  - Mean = 94.9
  - Standard Deviation = 5.5

The Remainder of the Course

- Primary mission -- Complete your term projects
- Secondary mission -- Cover topics of interest
- 70% of your grades are set (term project = 30%)
- Class sessions (half new topics / half consultation)
  - Tolerance Design / Projects
  - Mahalanobis Taguchi System / Projects
  - Conceptual Robust Design / Projects
  - Final Project Presentations

Expectations on Final Project

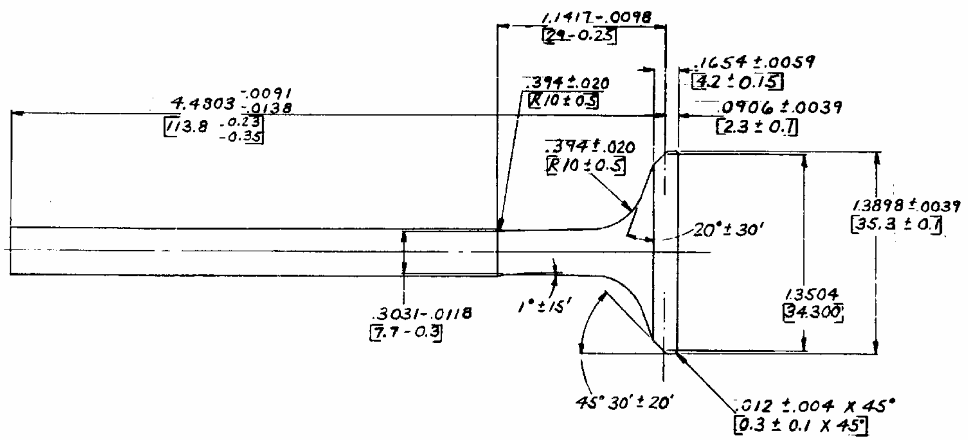
- Should represent ~30 hours of effort
- Options
  - Full robust design effort
  - Planning phase only
  - Post mortem analysis of a previous effort
  - Study of an advanced topic in robust design
  - Other possibilities with permission

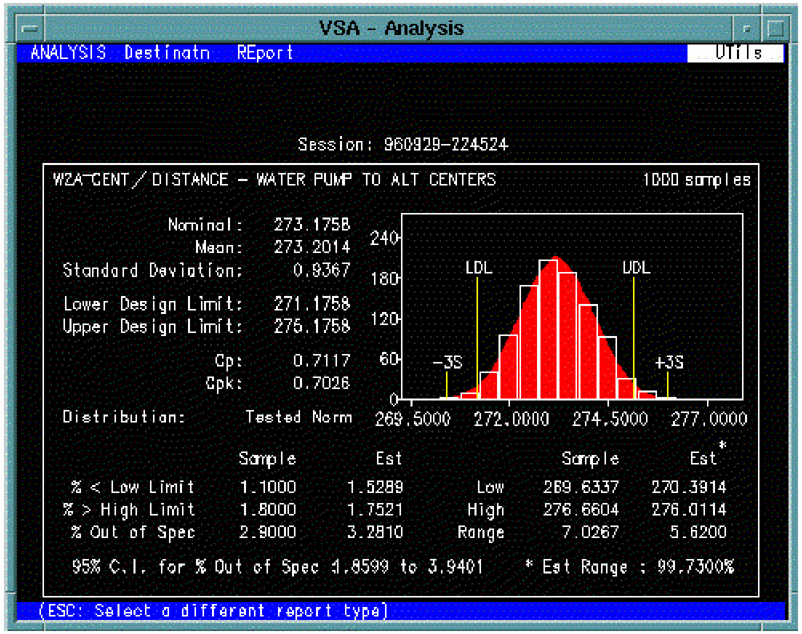
Grading of the Final Project

- 75% Written report
- 25% Oral presentation
- Grading criteria include
  - Impact and significance of the results
  - Quality of the planning and analysis
  - Clarity of technical exposition

Tolerance Design

The Interface Between Design and Manufacture





Outline

- History of tolerances
- Tolerancing standards
- Tolerance analysis
- Tolerance design
- Taguchi’s approach
- Case study

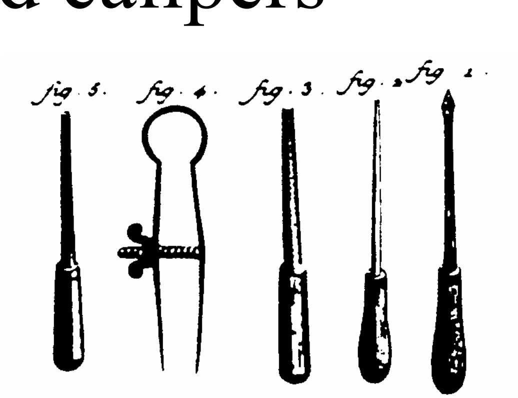
History of Tolerances

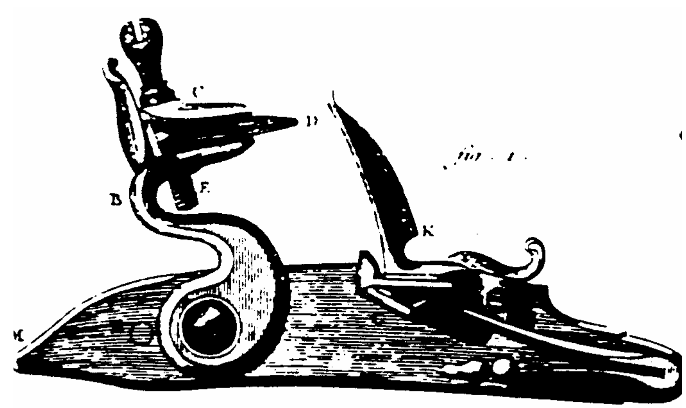
- pre 1800 -- Craft production systems
- 1800 -- Invention of machine tools & the English System of manufacture
- 1850 -- Interchangeability of components & the American system of manufacture

Jaikumar, Ramachandran. *From Filing and Fitting to Flexible Manufacture,* 1988.

Craft Production

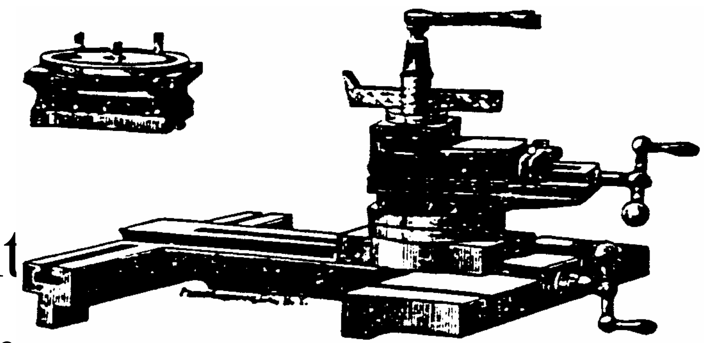
- Drawings communicated rough proportion and function
- Drawings carried no specifications or dimensions
- Production involved the master, the model, and calipers





The English System

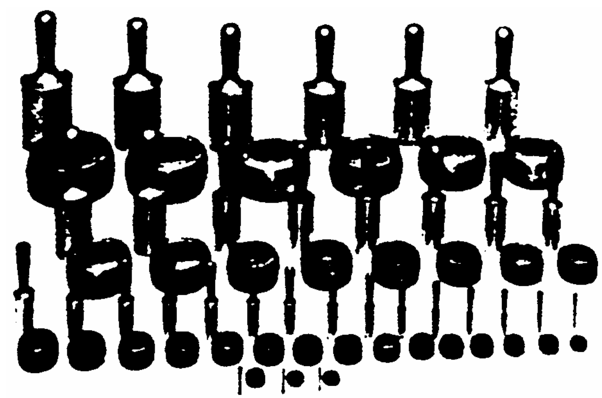
- Greater precision in machine tools
- General purpose machines
  - Maudslay invents the slide rest
- Accurate measuring instruments
  - Micrometers accurate to 0.001 inch
- Engineering drawings
  - Monge “La Geometrie Descriptive”
  - Orthographic views and dimensioning
- Parts made to fit to one another
  - Focus on perfection of fit



The American System

- Interchangeability required for field service of weapons
- Focus on management of clearances
- Go-no go gauges employed to ensure fit
- Allowed parts to be

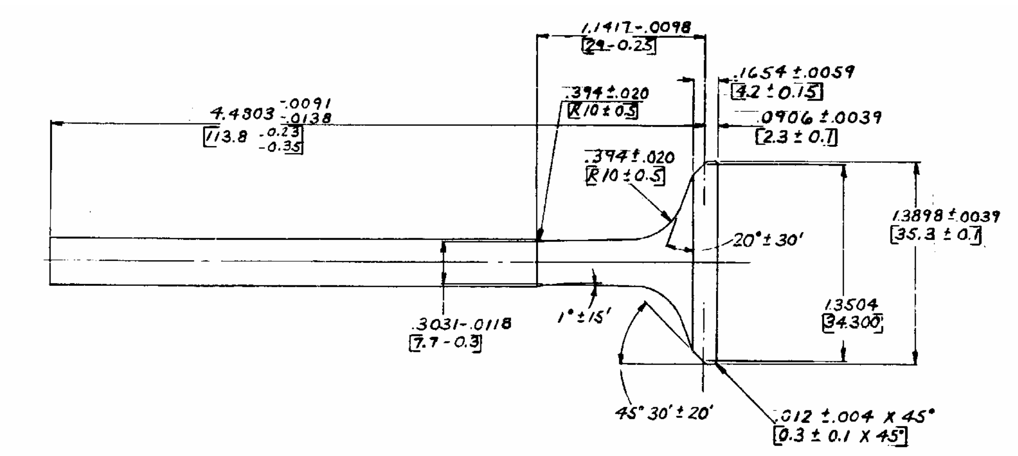
made in large lots



Go - no go gauges

Tolerances on Drawings

- Binary acceptance criteria
- Multiple quality characteristics
- *All* criteria must be met (dominance)



Basic Tolerancing Principles ref. ANSI Y14.5M

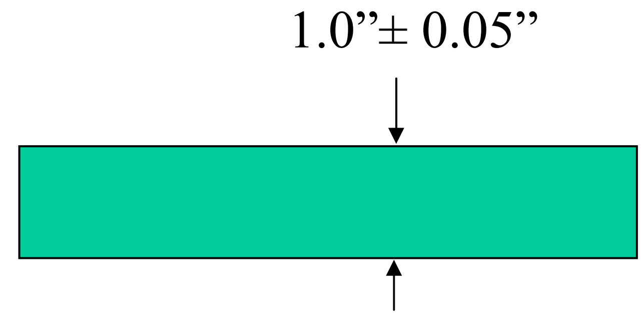
- Each dimension must have a tolerance
- Dimensions of size, form, and location must be complete
- No more dimensions than necessary shall be given
- Dimensions should not be subject to more than one interpretation
- Do not specify manufacturing method

Tolerance Analysis Probabilistic Approaches

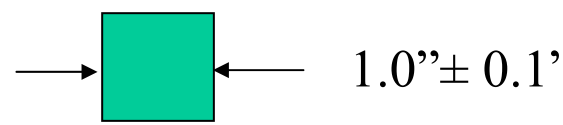
- Worst case stack up
- Root sum of squares
- Numerical integration
- Monte Carlo simulation

Tolerance Analysis Problem

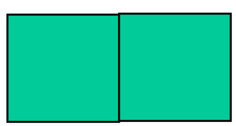
- Extruded aluminum bar stock



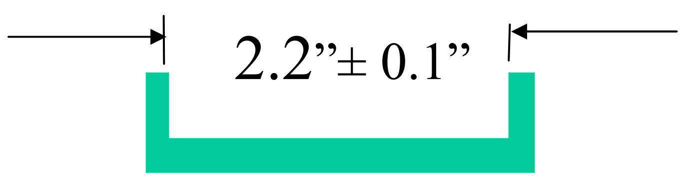
- Cut two pieces



- Stacked end to end

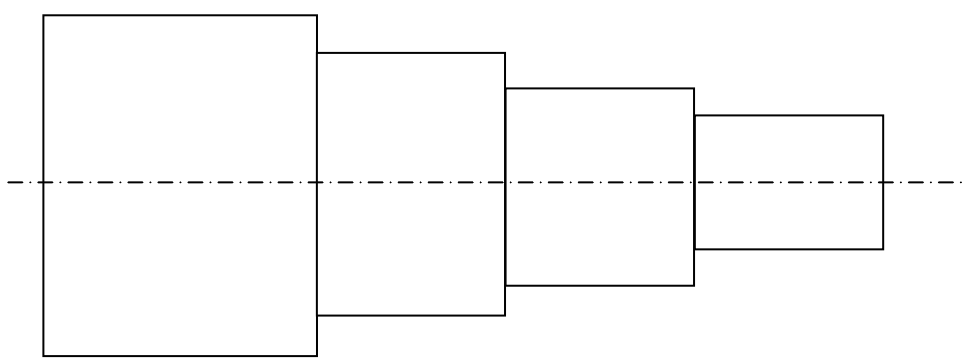


- What is the probability that the stack will fit in this bracket?



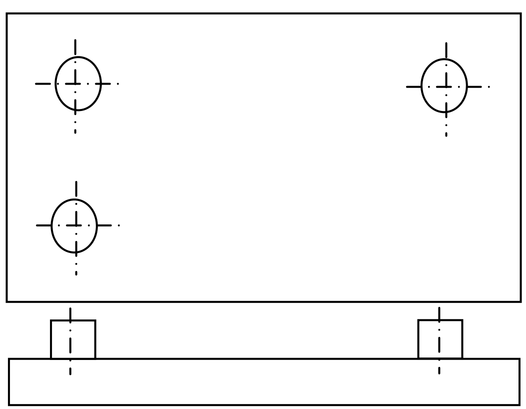
Specifying Tolerances to Minimize Required Precision

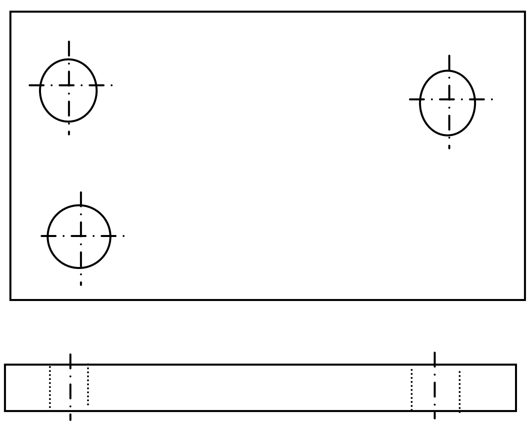
- How should this part be dimensioned?
- How is optimal dimensioning determined by function?



Tolerance Analysis Geometric / Kinematic Issues

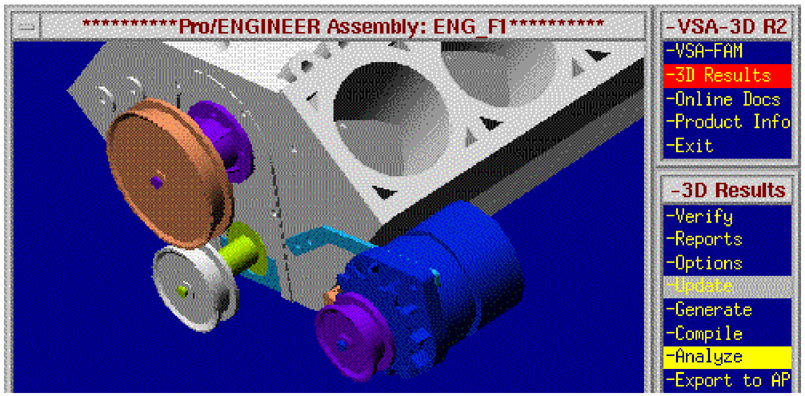
- Will these parts mate?
- Solution approaches
  - Kinematic modeling
  - Assembly simulation

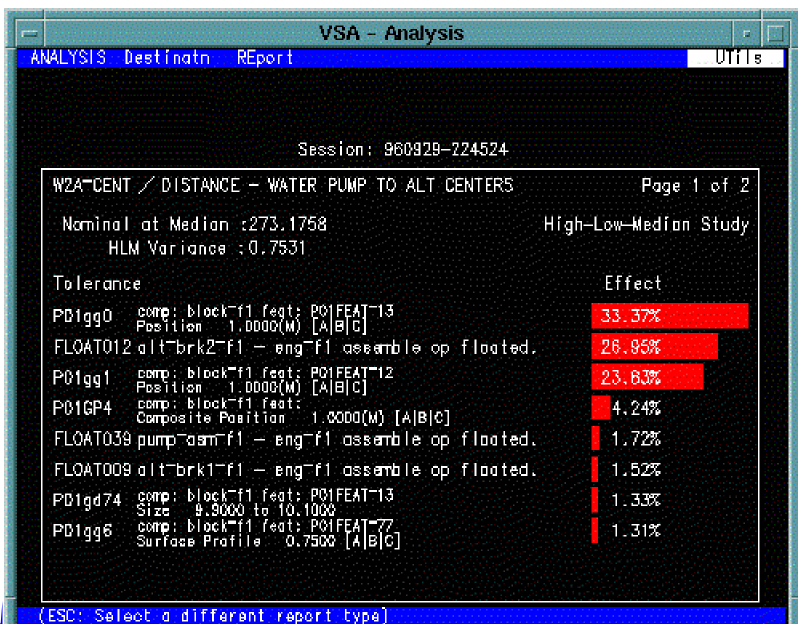




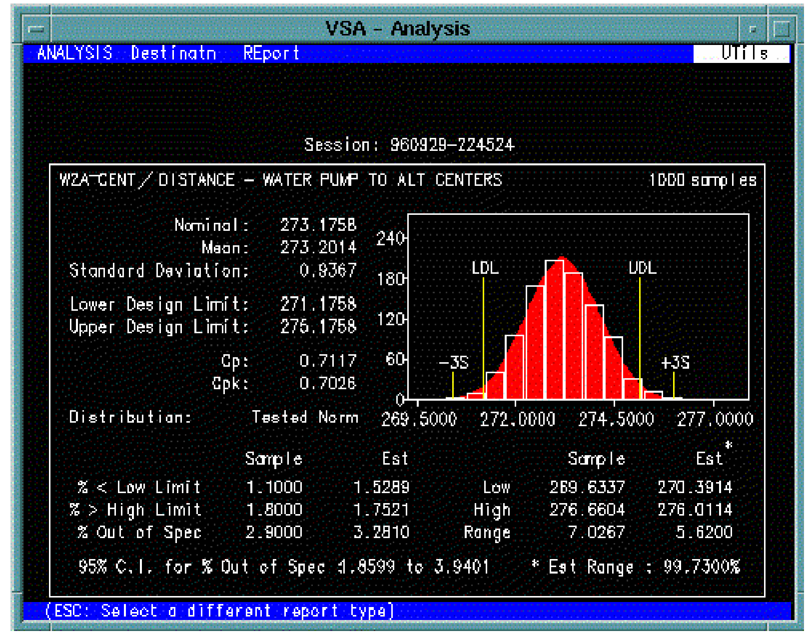
Variation Systems Analysis

You supply geometry





You define distributions



Software provides:

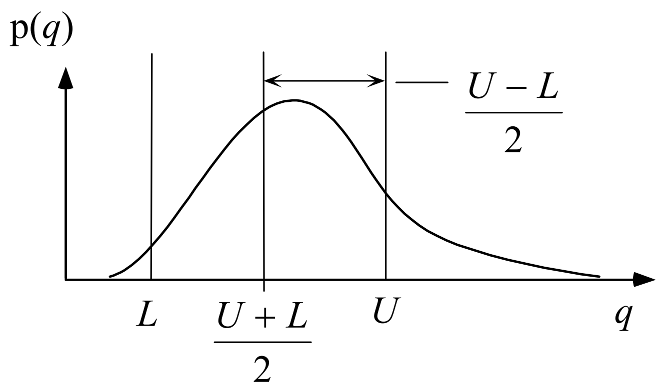
- Variance
- Defect rate
- Pareto diagram

MIT

Computer Aided Tolerancing

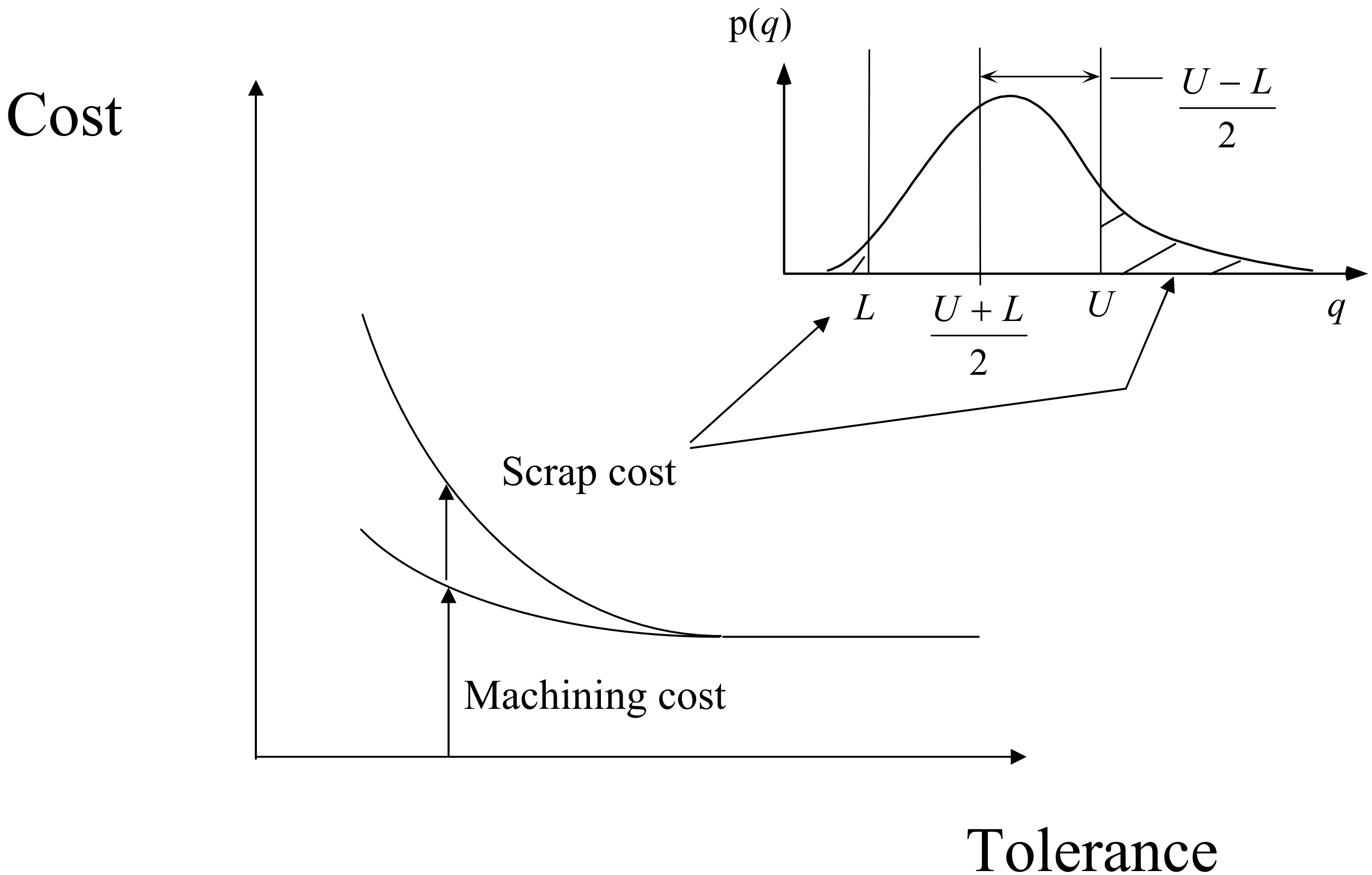
- Strengths
  - Requires few probabilistic assumptions
  - Can account for real assembly considerations
    - Tooling
    - Gravity
  - Integrated with many CAD environments
- Major Pitfalls
  - Compliance of parts
  - Source of input data

Process Capability Indices

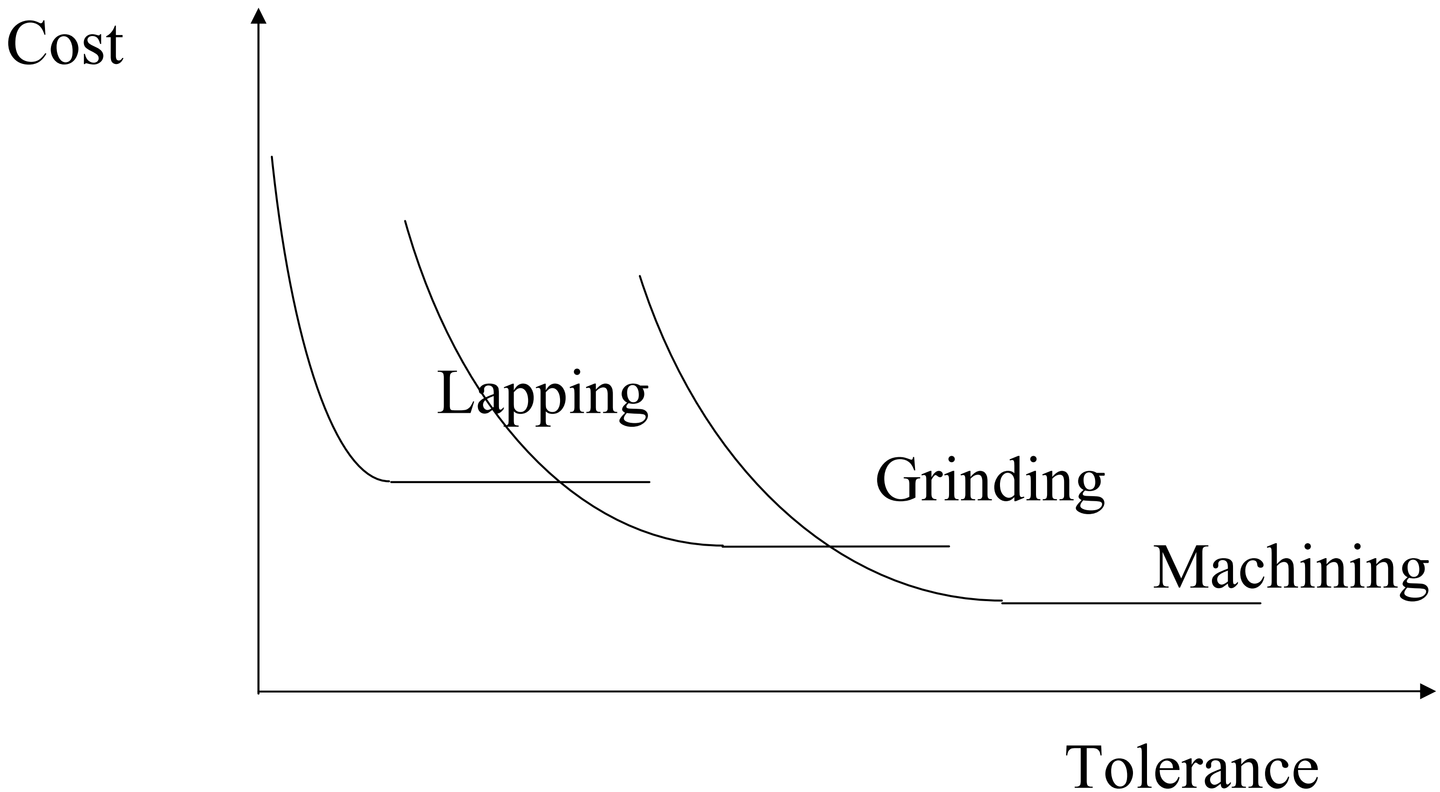


- Process Capability Index $C_p \equiv \dfrac{(U-L)/2}{3\sigma}$
- Bias factor $k \equiv \dfrac{\left|\mu - \dfrac{U+L}{2}\right|}{(U-L)/2}$
- Performance Index $C_{pk} \equiv C_p(1-k)$

Tolerance Cost Models



Tolerance Cost Models Multiple Processes



Traditional Tolerance Design

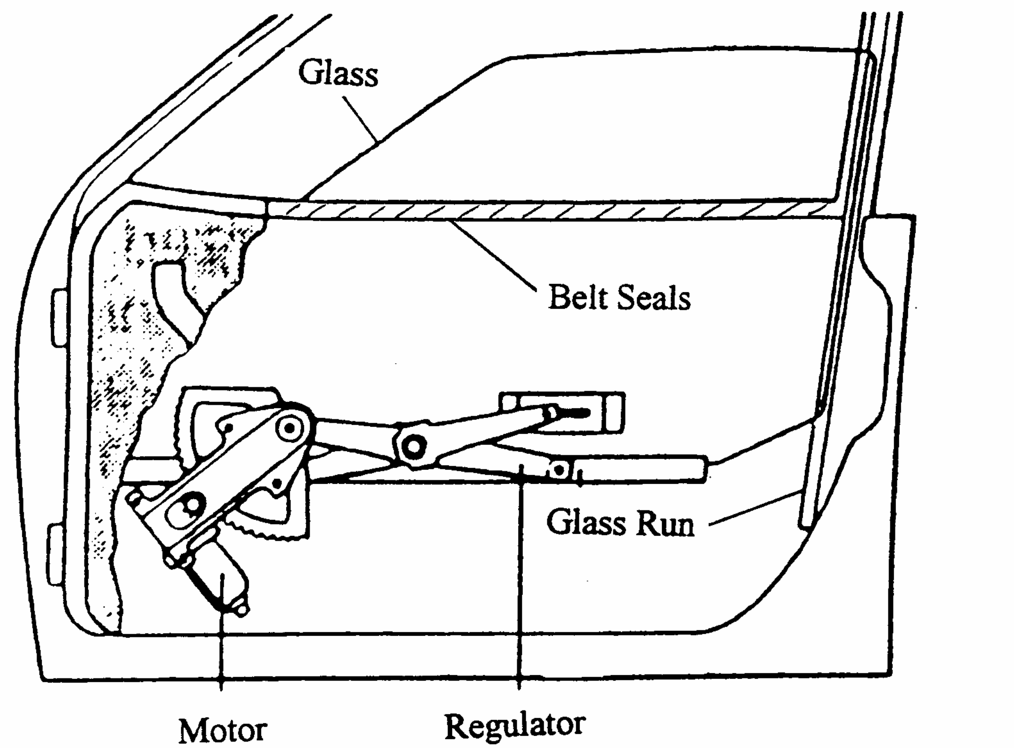
- Select tolerances on components that optimize profitability
  - Tighter tolerances - higher costs of manufacture
  - Looser tolerances - higher scrap rates
- Approaches
  - Linear programming
  - Discrete optimization

Taguchi Tolerance Design

- Use OAs in a noise experiment to determine the magnitude of tolerance factor effect
  - How many levels would you choose?
- Use the quality loss function as a basis for the trade off between higher manufacturing costs and lower customer satisfaction

Tolerance Design Case Study

Who would you involve in the tolerance design study?



Singh, K., R. Newton, and C. Zaas, "Tolerance Design on a Moveable Window System of an Automobile Door", ASI 3rd International Symposium, 1997.

Customer Requirements

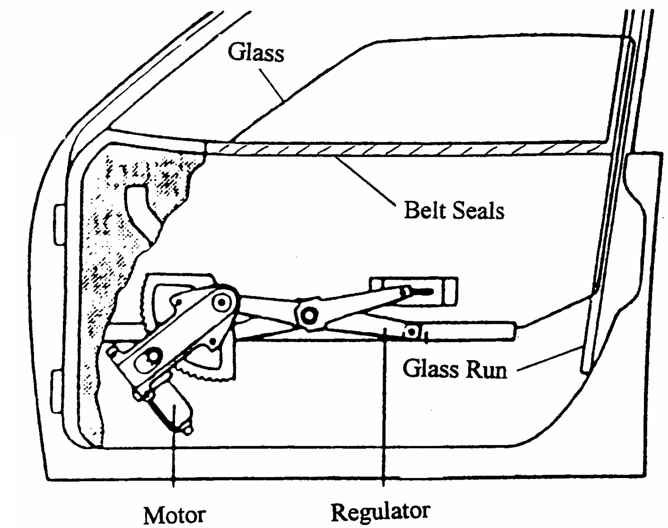
- Smooth and quiet operation under all weather conditions
- Consistent closing and opening speeds
- No wind noise or water leakage
- Long life and high reliability

System P-Diagram

Door Window System → Y=Glass Velocity
Stall Force

<u>Controllable Factors</u>:
CLD Belt W/S
Motor Power
Counter Balance Spring Rate
CLD Glass Run Channel

<u>Non-controllable Factors</u>:
Glass Off-Form
Belt Opening Variation
Flange Angularity
Regulator Efficiency



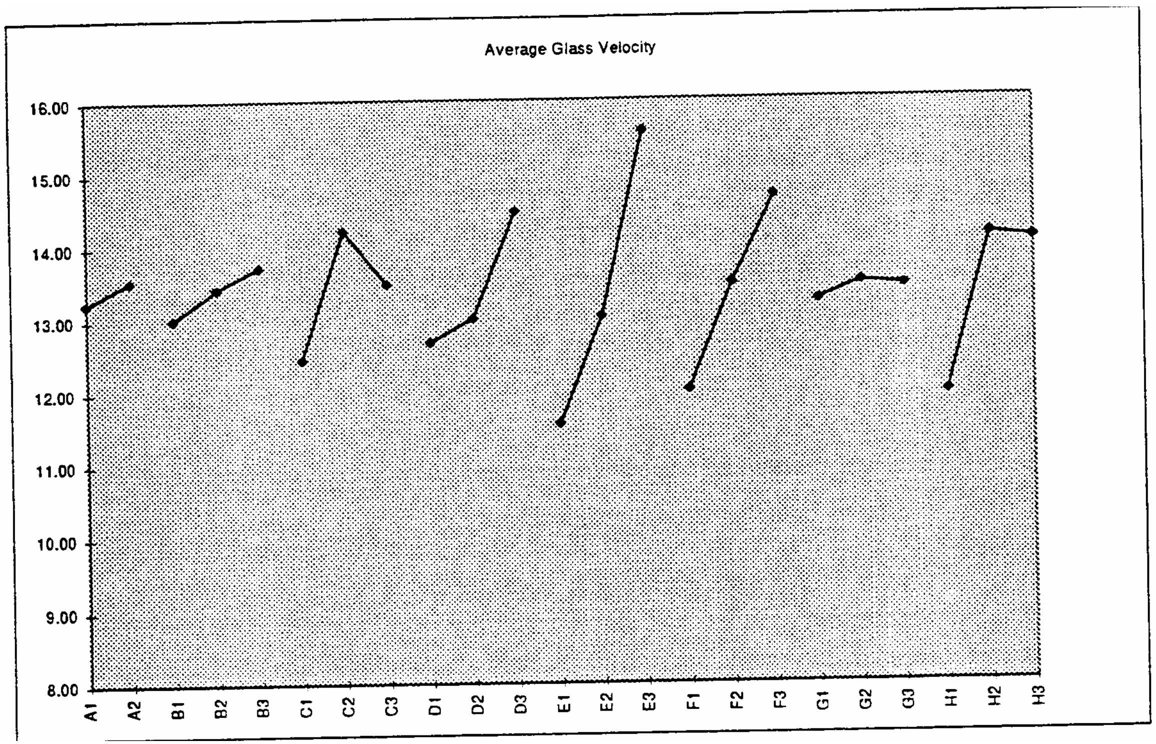
Noise Factors & Levels

- Why use three level noise factors?
- Why is there a difference in spread of the levels between a three level and two level factor?

	Tolerance Factors	Tolerance Source	Levels 1	Levels 2	Levels 3
A	Glass Off Form	Surrogate Process Capability Data	$m-\sigma$	$m+\sigma$	
B	Belt Opening	Assembly Stackup	$m-\sqrt{(3/2)}\sigma$	m	$m+\sqrt{(3/2)}\sigma$
C	Flange Angularity	Print Tolerance	$m-\sqrt{(3/2)}\sigma$	m	$m+\sqrt{(3/2)}\sigma$
D	Belt W/S CLD	CAE Calculations	$m-\sqrt{(3/2)}\sigma$	m	$m+\sqrt{(3/2)}\sigma$
E	Motor Power	Print Tolerance	$m-\sqrt{(3/2)}\sigma$	m	$m+\sqrt{(3/2)}\sigma$
F	Regulator Efficiency	Supplier's Estimate	$m-\sqrt{(3/2)}\sigma$	m	$m+\sqrt{(3/2)}\sigma$
G	Regulator Counter Balance Spring Rate	Print Tolerance	$m-\sqrt{(3/2)}\sigma$	m	$m+\sqrt{(3/2)}\sigma$
H	Glass Run W/S CLD	CAE Calculations	$m-\sqrt{(3/2)}\sigma$	m	$m+\sqrt{(3/2)}\sigma$

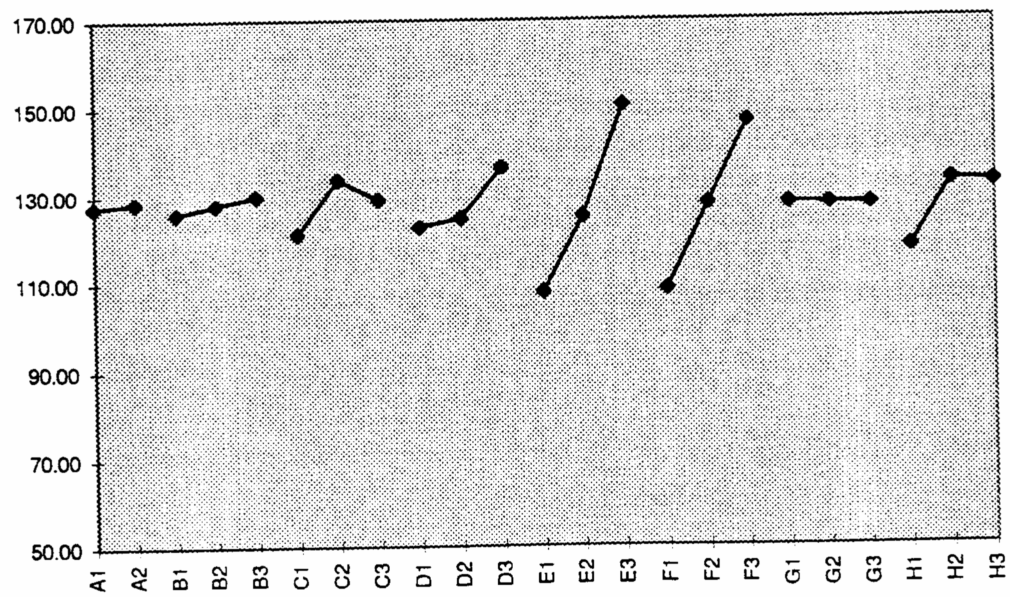
Noise Factor Effects on Average Glass Velocity

- What is the significance of the range?
- What is the significance of non-linearity?



Noise Factor Effects on Stall Force

- How would you use this to make a Pareto diagram?



Window System Case Study
Conclusions

- Cross functional team included design, manufacture, reliability, and suppliers
- Motor power and regulator efficiency identified as major contributors to variation
- Computer simulation allowed redesign prior to prototyping
- Product development cycle time and cost reduced

Next Steps

- Next off-campus session
  - SDM Conference room

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