Accelerating Product Design with Simulation and Stochastic Optimization

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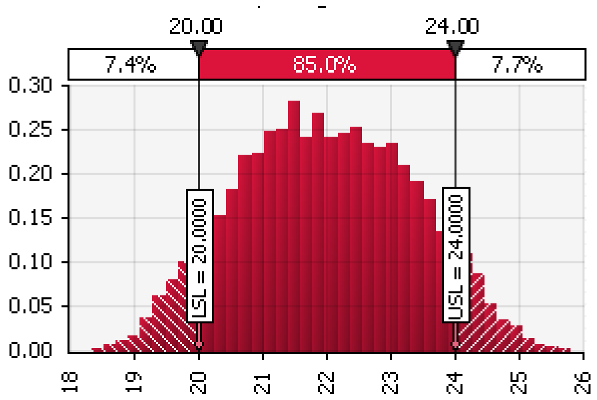
Outline

- The optimization challenge
- Overview of simulation and optimization tools in product development
- Optimal design example

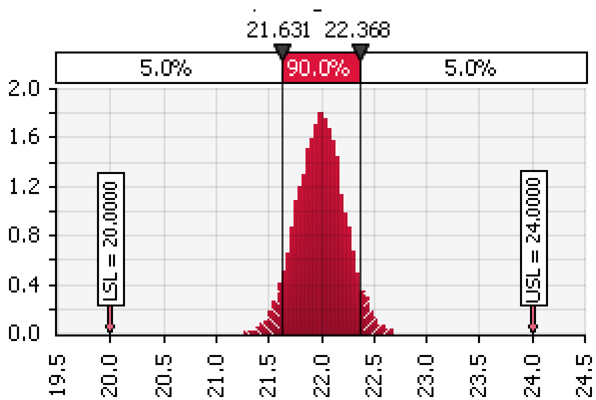
The Optimization Challenge

How can we reduce the variation of a system, relative to the specification limits?

How can we go from this ...



To this?



Four ways to improve capability:

- Challenge the specification limits – can they be wider?
- Challenge the assumptions in the analysis
- Reduce variation of the components and inputs to the system
- Change the average or nominal values of the components and inputs to the system

Which strategy would you choose?

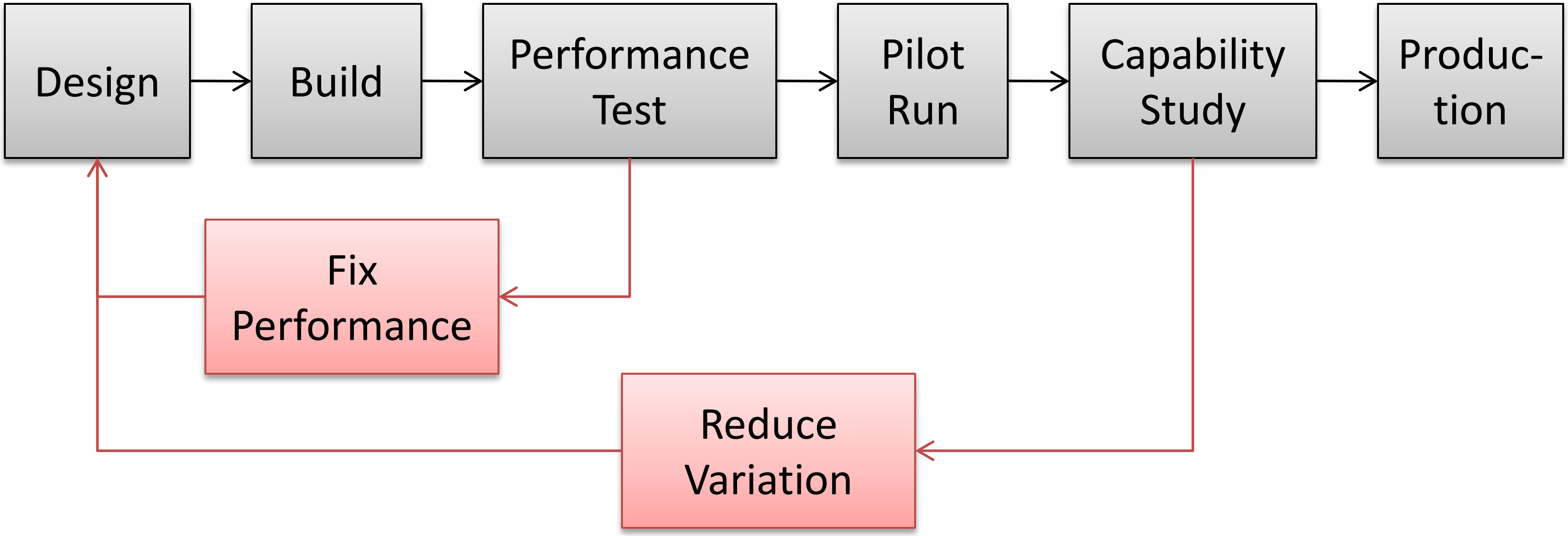
Generic Product Design System

Design → Prototype → Pilot Production → Production

Design	Prototype	Pilot Production	Production
Objective: Design system that meets customer requirements	Objective: Make a small number that satisfy performance tests	Objective: Make a large number with acceptable process capability	Objective: Make money

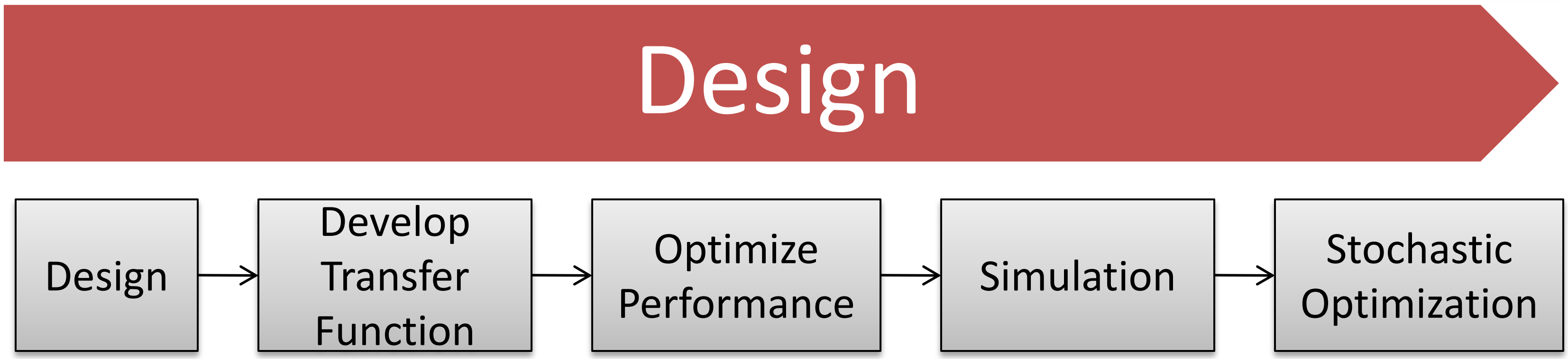
- Unexpected problems create costs and delays
- Good engineering should identify and prevent problems
- Design for Six Sigma (DFSS) tools, including simulation and optimization, are the keys to preventing performance and capability problems

The Old Way: Test – Fix – Test – Repeat



- Rework loops requiring redesign add months or years to the schedule

Design For Six Sigma Prevents Problems in the Design Phase

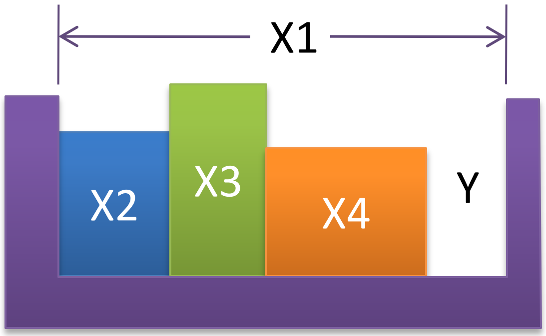


- Every critical characteristic Y needs a transfer function f(X)
- Optimize to find the best X values
    - Prevents performance problems
- Simulate to predict variation caused by tolerances and noise variables
- Stochastic optimization finds X values for the least variation and best process capability
    - Prevents capability problems
- No bad surprises in later phases!

Transfer Functions

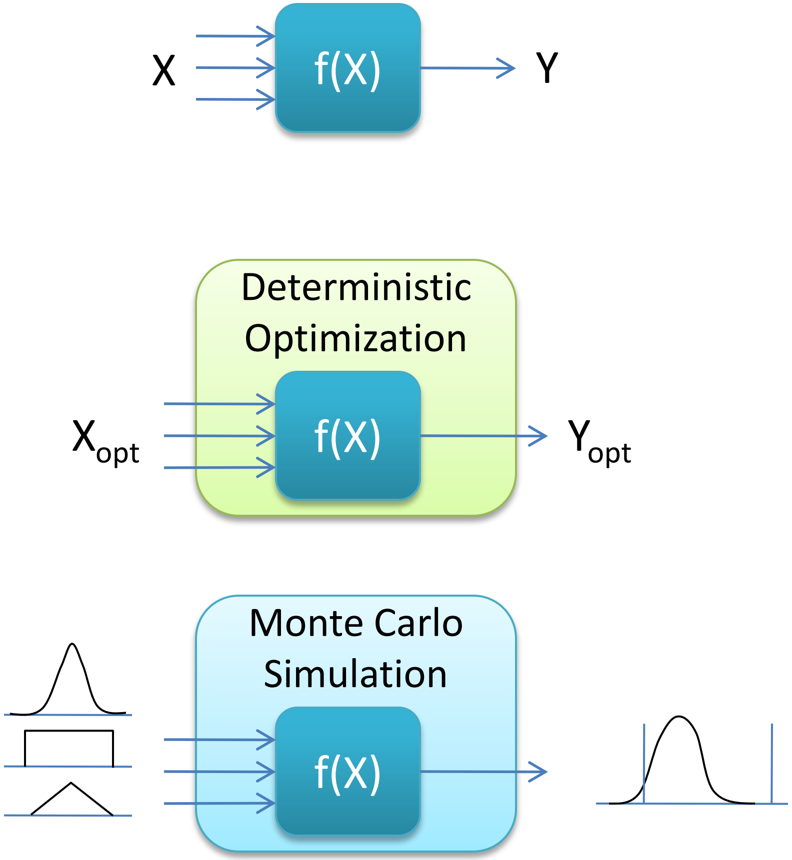
- A transfer function is an equation Y = f(X)
- Can be calculated in Microsoft Office Excel
- White box transfer function is calculated from first principles
- Black box transfer function is a model estimated from a designed experiment run on a physical system
- Gray box transfer function is a metamodel estimated from an experiment run on a computer model

- Example shown below:
- White box transfer function:
  Y = X1 – X2 – X3 – X4



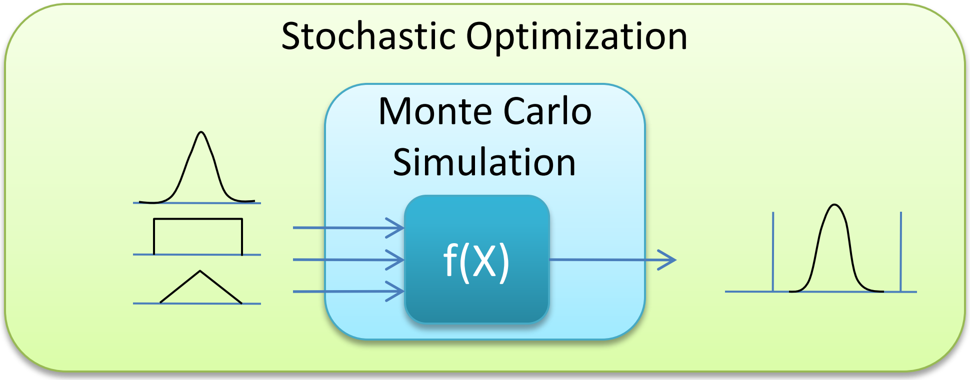
Simulation and Optimization Methods

- After a Y = f(X) is expressed by Excel formulas, many options are available
- (Deterministic) optimization finds single X values so that
  Y is max / min / target
  - Excel Solver
  - Palisade Evolver
  - TKSolver
- Monte Carlo simulation predicts the distribution of Y, by generating random values for X
  - @Risk



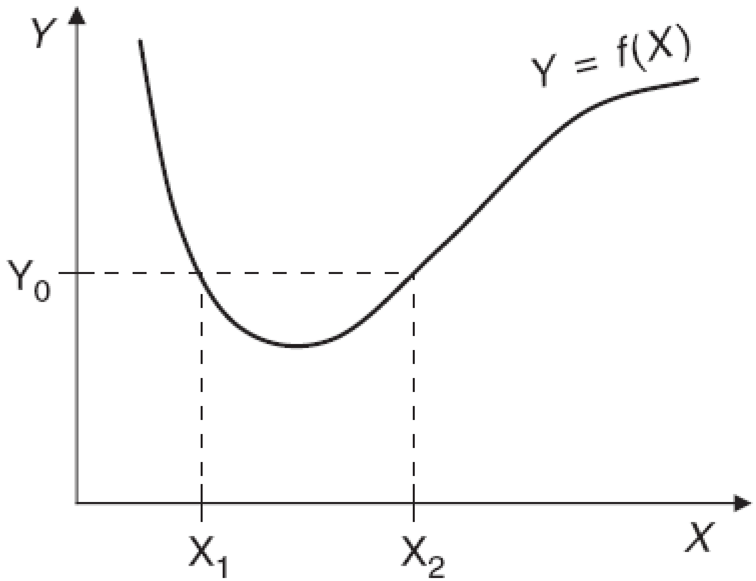
Stochastic Optimization

- Stochastic optimization
  - wraps a numerical optimizer around Monte Carlo simulation
  - runs a simulation in each loop of the optimizer
  - searches for settings of selected variables so that a statistical parameter (mean, standard deviation, C_{PK}, etc.) is minimized, maximized, or hits a target
- RISKOptimizer is a stochastic optimizer that uses @Risk to perform Monte Carlo simulation



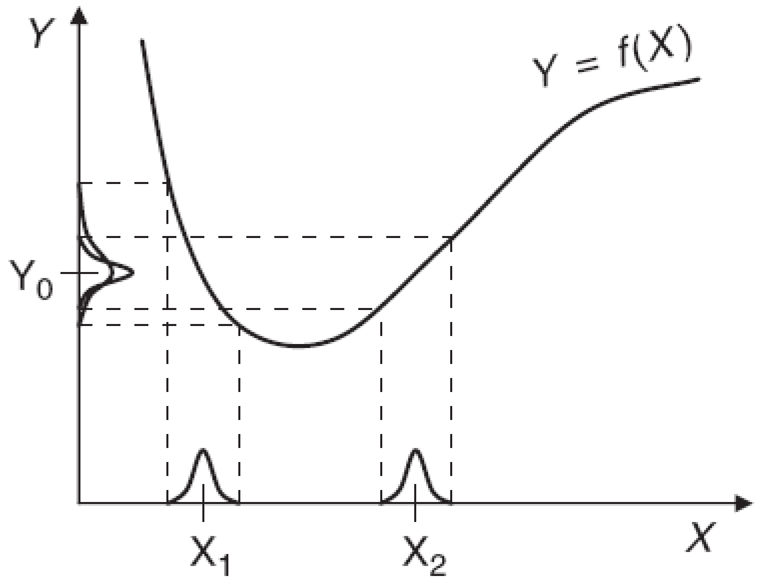
Deterministic and Stochastic Optimization

Deterministic Optimum



- Two X values result in Y_0. Deterministic optimizers pick one of these two

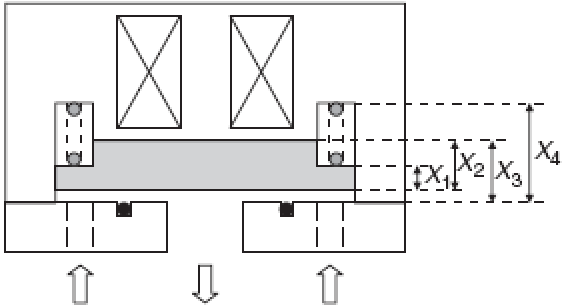
Stochastic Optimum

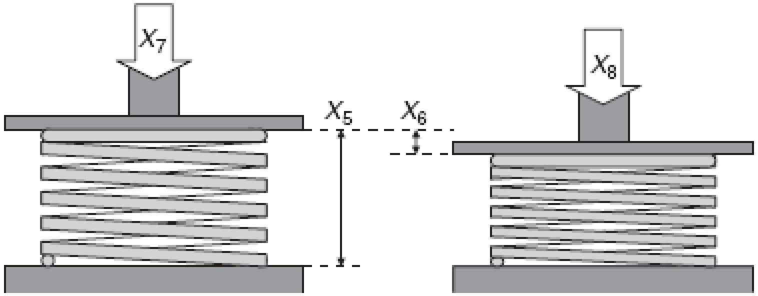


- X_2 results in less Y variation. Stochastic optimizers find X_2

Example: Solenoid Operated Gas Shutoff Valve

- In this valve, the solenoid pulls up a plate against a spring, opening the valve. When current flow stops, the spring closes the valve
- Spring force Y is a critical characteristic
  - If force is too low, gas forces might push the valve open
  - If force is too high, the solenoid might not open the valve
  - Tolerance: Y = 22 ± 2 N
- The spring is tested by compressing to length X_5, measuring force X_7, then compressing to length $X_5 - X_6$, and measuring force X_8





Example: Transfer Function and Initial Component Selections

Design → Develop Transfer Function

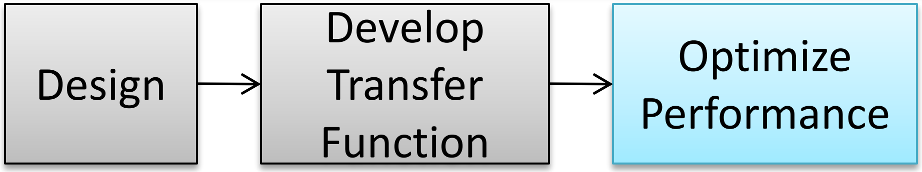
- White box transfer function:
- Y is force in Newtons
  - Y = X7 + R × (X5 – L)
- R is spring rate in N/mm
  - R = (X8 – X7) / X6
- L is length of space containing spring
  - L = – X1 + X2 – X3 + X4

- Initial component values:

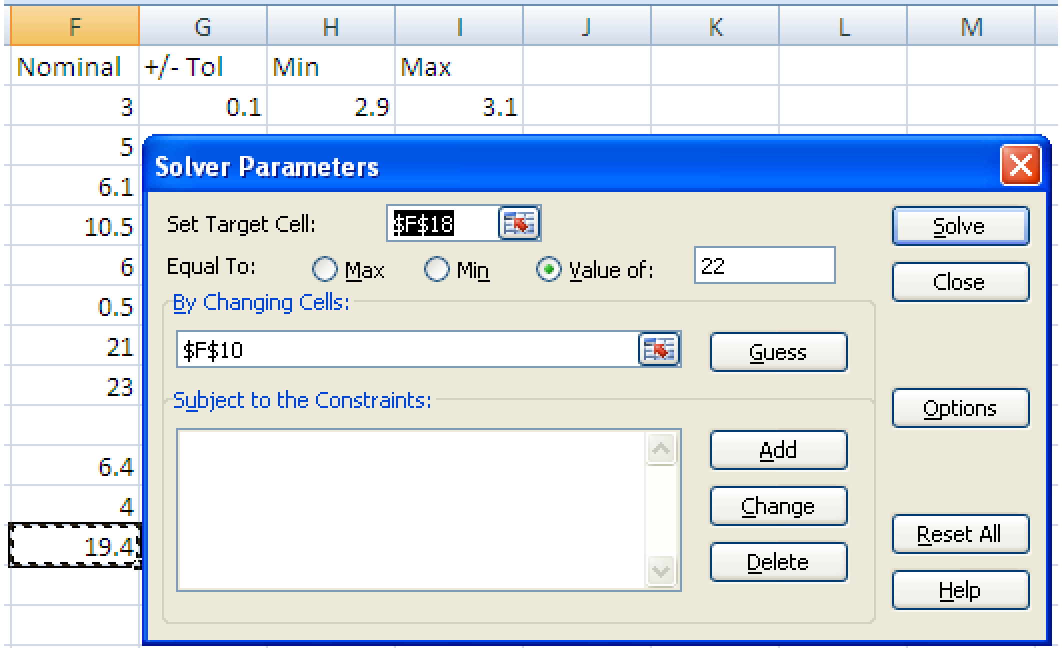
F18 =F13+F17*(F11-F16)

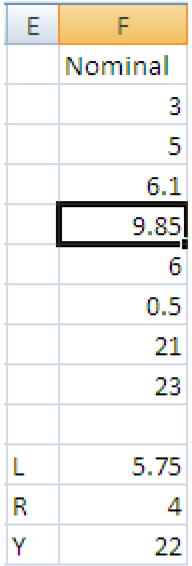
	A	B	C	D	E	F	G	H	I
6		Part	Feature	Units		Nominal	+/- Tol	Min	Max
7	X1	Plate	Lip Height	mm		3	0.1	2.9	3.1
8	X2	Plate	Height	mm		5	0.1	4.9	5.1
9	X3	Stator	Wall Depth	mm		6.1	0.1	6	6.2
10	X4	Stator	Spring gap depth	mm		10.5	0.25	10.25	10.75
11	X5	Spring	Initial compression	mm		6	0.5	5.5	6.5
12	X6	Spring	Incremental compression	mm		0.5	0.02	0.48	0.52
13	X7	Spring	Force 1	N		21	0.2	20.8	21.2
14	X8	Spring	Force 2	N		23	0.2	22.8	23.2
15									
16					L	6.4			
17					R	4			
18					Y	19.4			

Example: (Deterministic) Optimization of Nominal Values



- Use Excel Solver
- Pick one X (like X4), to change
- Changing nominal X4 to 9.85 adjusts nominal Y to 22





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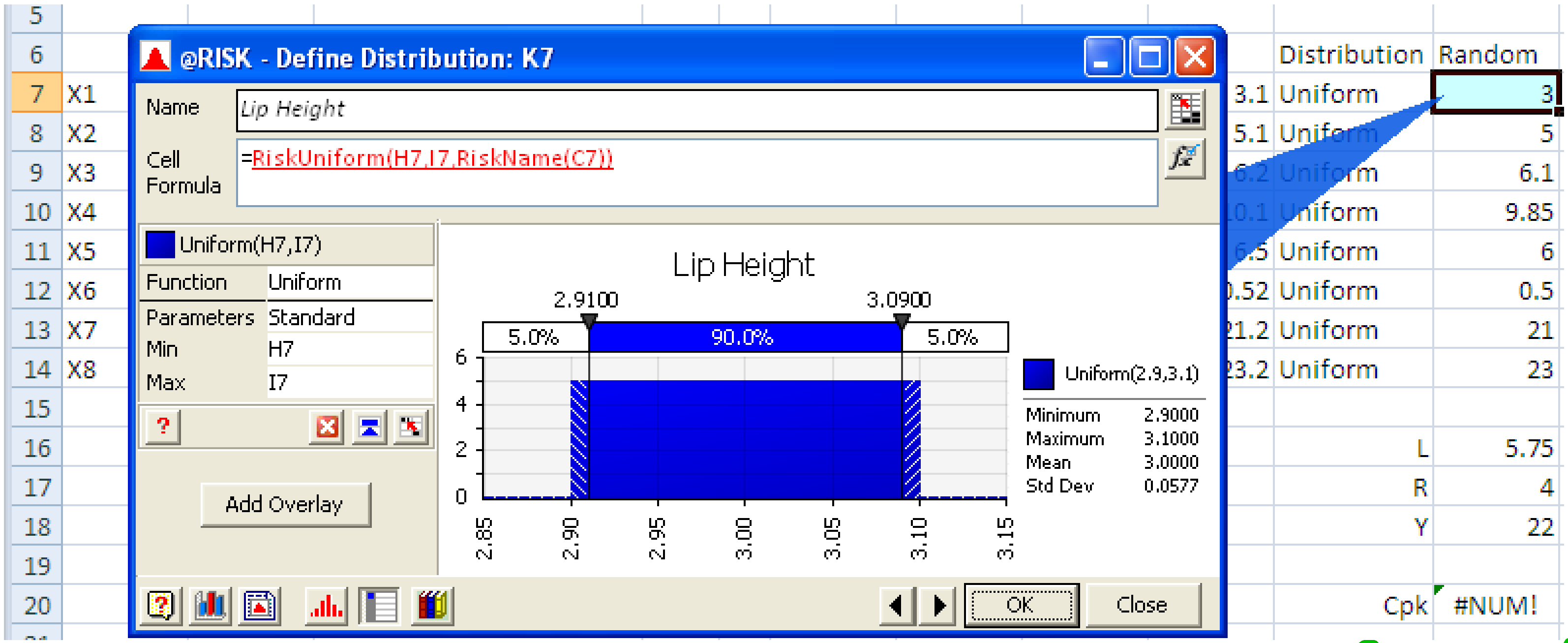
Example: Monte Carlo Simulation to Predict Variation in Y

Design → Develop Transfer Function → Optimize Performance → Simulation

- Using @RISK, specify distributions for inputs
- By default, choose uniform for all inputs



Example: Monte Carlo Simulation Specify Output and Settings

- Specify output variable
- Optionally, add units and tolerance limits

=RiskOutput("Spring force",,RiskUnits("N"),RiskSixSigma(20,24))+K13+K17*(K11-K16)

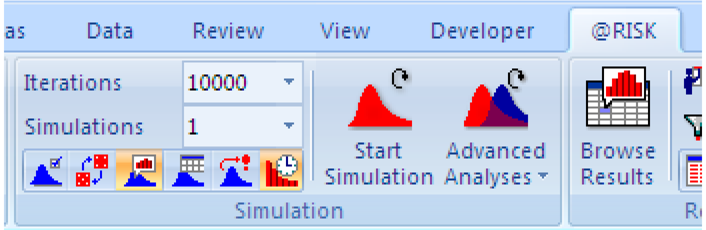
H	I	J	K	L	M	N	O	P
		L	5.75					
		R	4					
		Y	22					

- Calculate C_{PK} with RiskCpk function

=RiskCpk(K18)

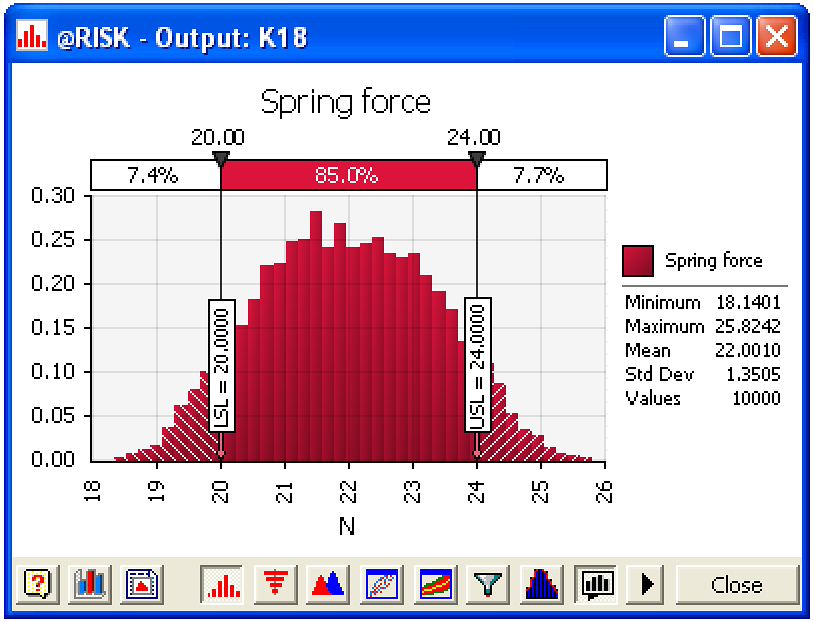
H	I	J	K
		L	5.75
		R	4
		Y	22
		Cpk	#NUM!

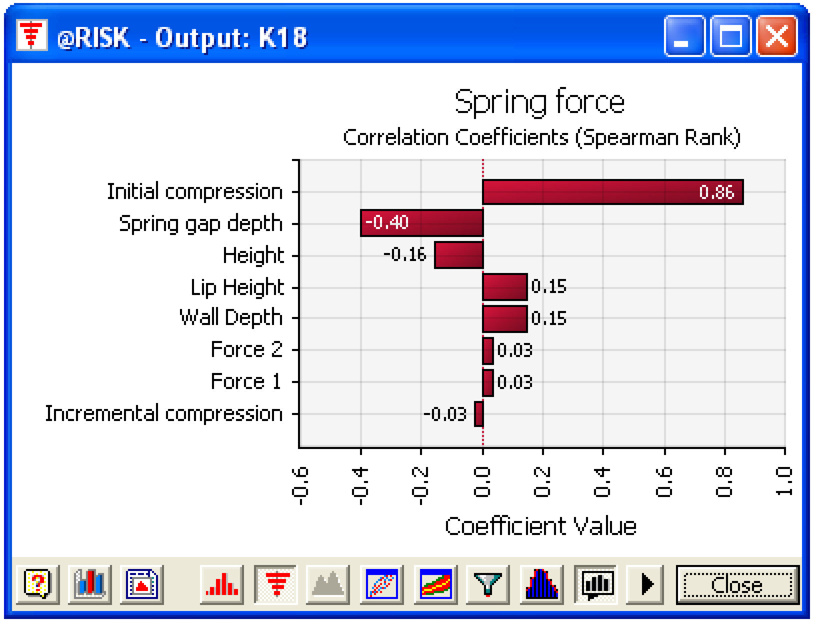
- Simulation settings



Example: Monte Carlo Simulation Predicted Variation, Initial Design

- Results after 10,000 trials:
- Predicted $C_{PK} = 0.49$
- Only 85% in tolerance limits
- Major culprit: Initial compression of spring
- Suppose capability study found that X5 is normally distributed with mean on target and standard deviation = 0.1 mm





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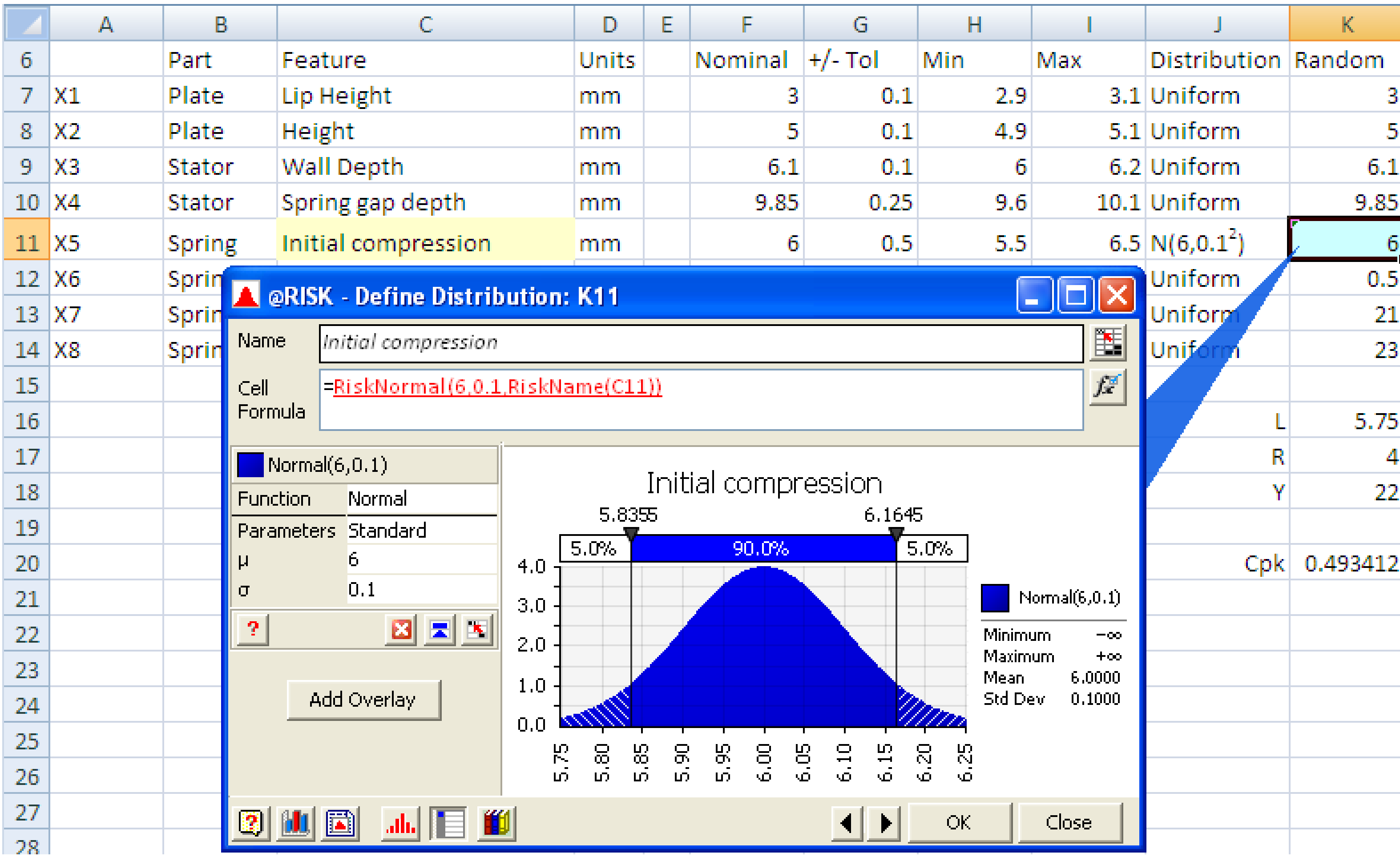
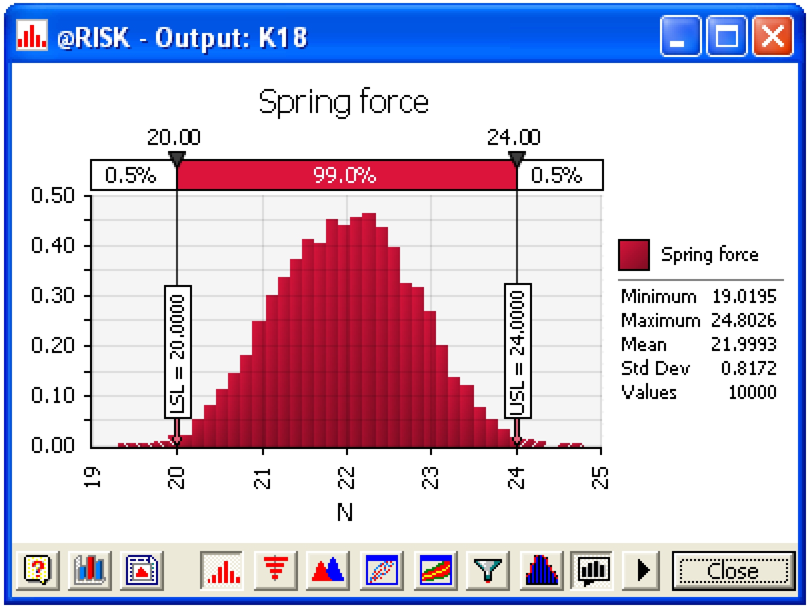
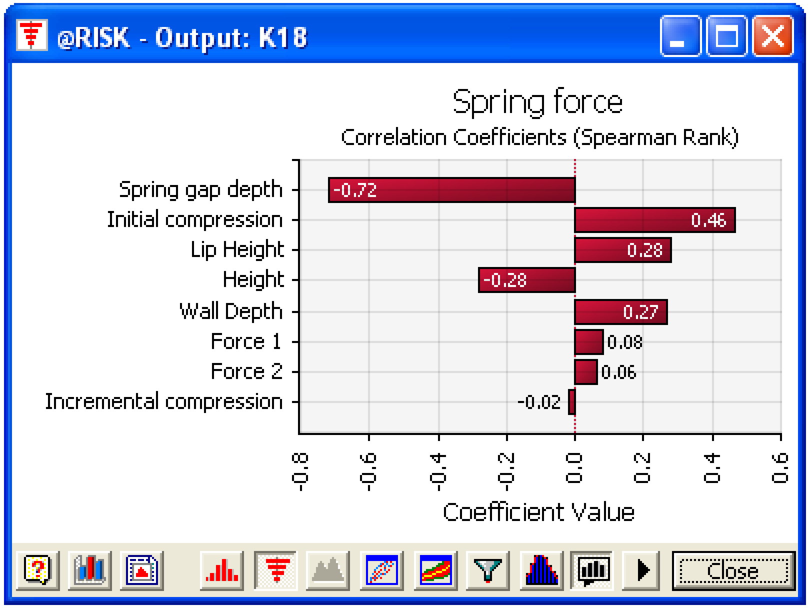
Example: Monte Carlo Simulation Update Distribution from Data



Example: Monte Carlo Simulation Predicted Variation, Updated Design

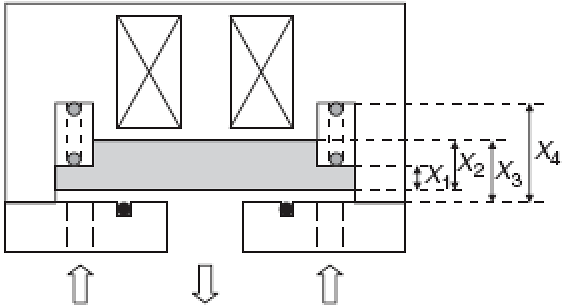
- Results after 10,000 trials:
- Predicted C_{PK} = 0.82
- Only 99% in tolerance limits
- Better, but far from Six Sigma quality (C_{PK} = 2.00)

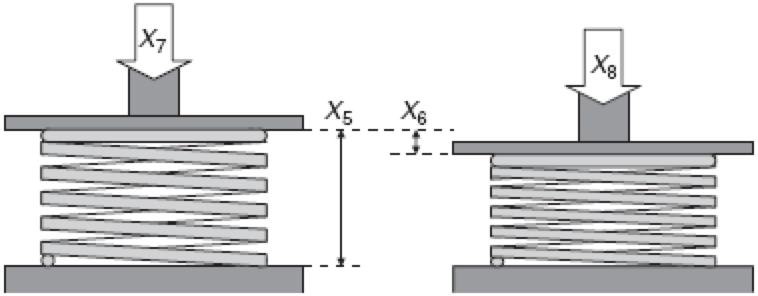




The Optimization Challenge

- We need to dramatically improve the capability of this system. How can we do it?
  - ✓ Challenge the specification limits
    - Here, the tolerances are determined by the needs of the next assembly level
  - ✓ Challenge the assumptions
    - One assumed distribution replaced by actual data
  - – Tighten all component tolerances
    - Costly – should be a last resort
  - – Change nominal values, with no change in tolerances
    - How? Let the computer figure it out





Example: Stochastic Optimization

- Consider each input variable and select a range of possible nominal values
- Where needed, identify constraints on input variables
- Change nominal values only – not tolerances

	A	B	C	D	E	F		K	L	M	N	O
4												
5									Optimization Criteria			
6		Part	Feature	Units		Nominal	+/-	Random	Lower	Upper	Constraints	
7	X1	Plate	Lip Height	mm		3		3	2	5		
8	X2	Plate	Height	mm		5		5	4	7	2	X2 - X1 > 1
9	X3	Stator	Wall Depth	mm		6.1		6.1	5	7		
10	X4	Stator	Spring gap depth	mm		9.85		9.85	8	20		
11	X5	Spring	Initial compression	mm		6		6	5	10		
12	X6	Spring	Incremental compression	mm		0.5		0.5	0.5	1		
13	X7	Spring	Force 1	N		21		21	20	21.5		
14	X8	Spring	Force 2	N		23		23	22.5	24		

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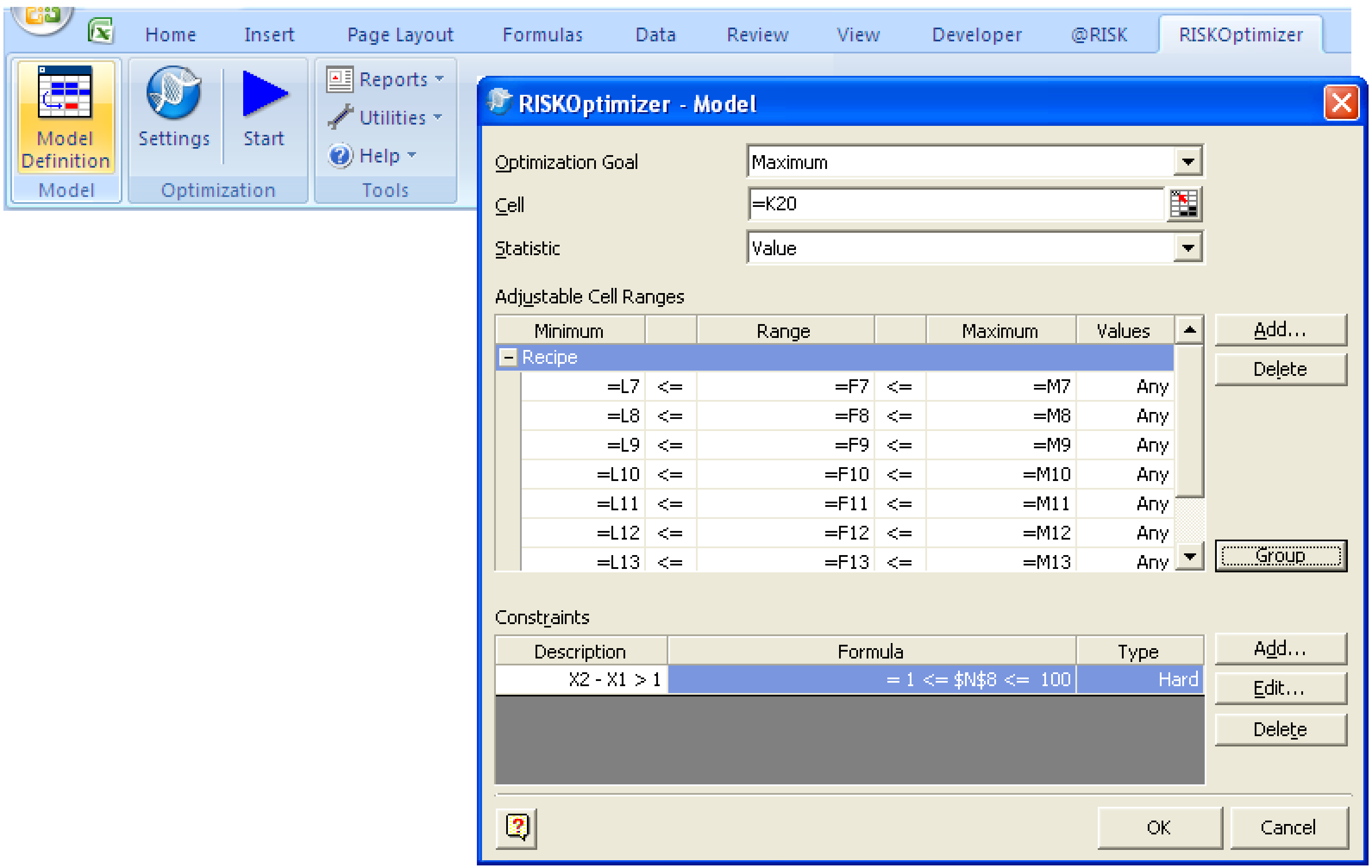
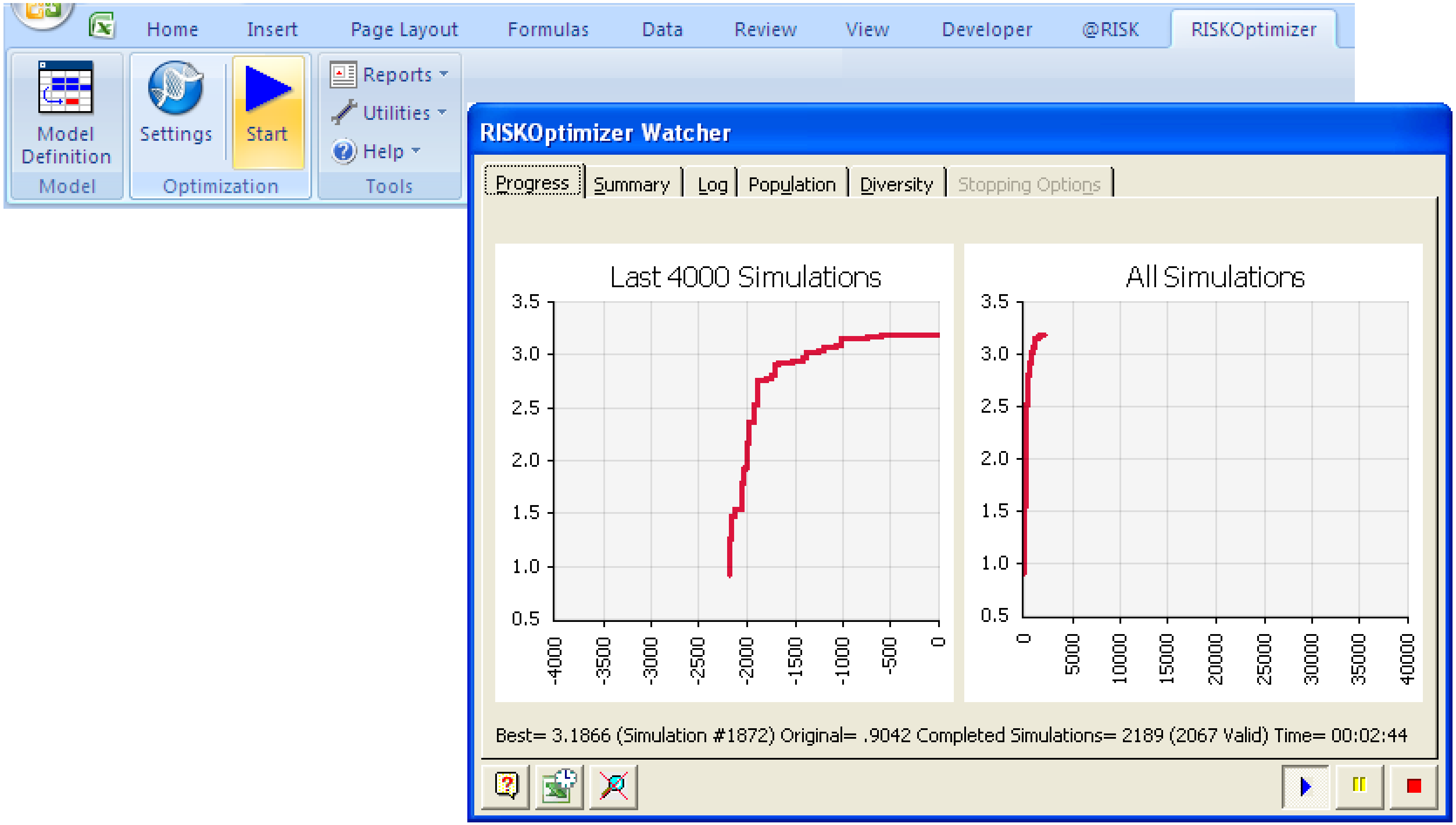
Example: Stochastic Optimization Specify Model in RISKOptimizer



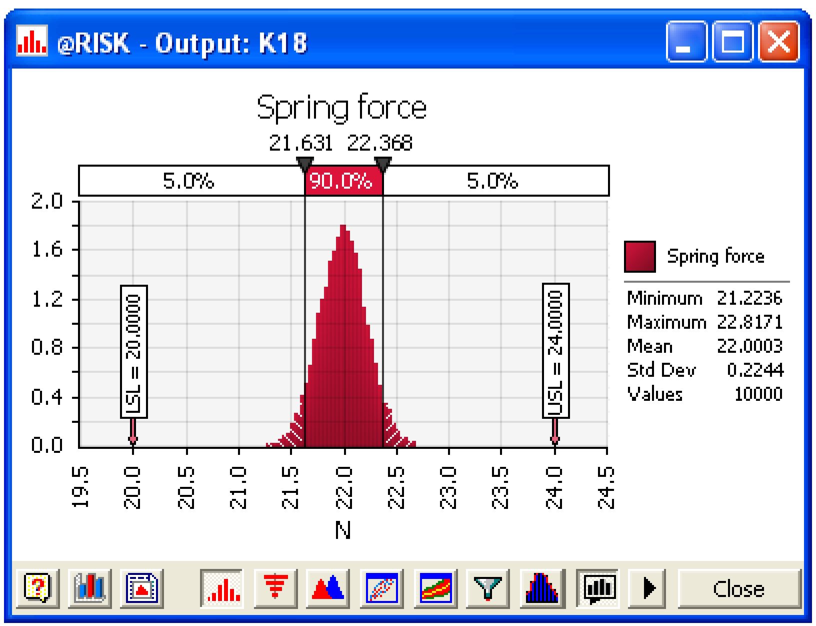
Example: Stochastic Optimization Watch the Improvements in C_{PK}

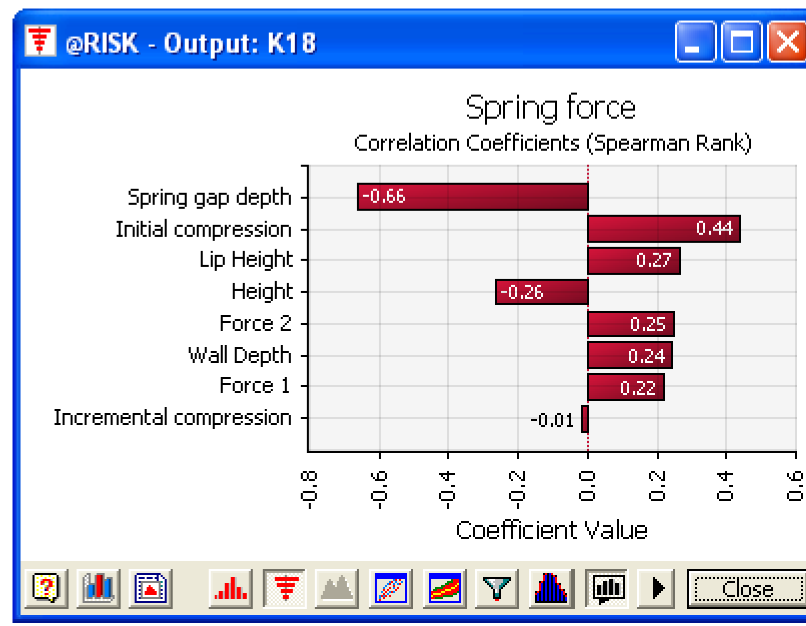


Example: Optimized Design

- Predicted $C_{PK} = 2.95$
- Now what should we do with tolerances?

	A	B	C	D	E	F	+/
6		Part	Feature	Units		Nominal	+/
7	X1	Plate	Lip Height	mm		3.007852	
8	X2	Plate	Height	mm		5.01775	
9	X3	Stator	Wall Depth	mm		5.845372	
10	X4	Stator	Spring gap depth	mm		9.85	
11	X5	Spring	Initial compression	mm		6.505472	
12	X6	Spring	Incremental compression	mm		0.996172	
13	X7	Spring	Force 1	N		21.49653	
14	X8	Spring	Force 2	N		22.51746	
15							
16					L	6.014527	
17					R	1.024852	
18					Y	21.99967	





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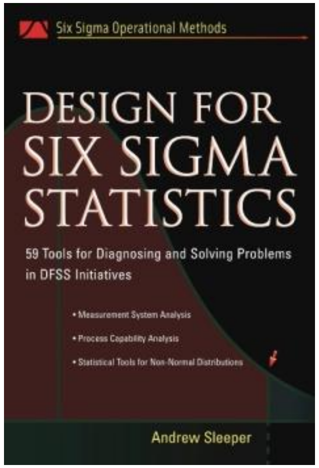
Example Summary

- Next steps:
  - Review optimized components for practicality. If necessary, add more constraints and optimize again
  - Since capability is now "too good," consider wider tolerances to lower cost
  - When prototypes are available, verify the transfer function
- If the transfer function is correct and complete, performance and capability problems will not happen
- This can all be done in a few minutes, before the first prototype is built
- Next steps for you: Try this on your systems!

Shameless Self-Promotion



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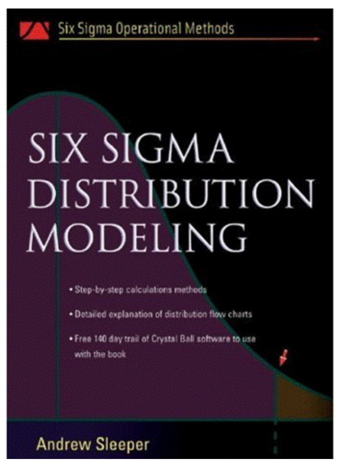

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- Tolerance design (3-day)
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