*Complex Adaptive System of Systems (CASoS) Engineering Initiative*
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# Evaluation of policy options using uncertainty analysis of complex-system model results

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# Overview

- Intro to uncertainty analysis
  - Get more information out of model runs
  - Provide estimate of quality and reliability of results
  - Determine when the model sufficiently detailed
- Robust policy options overview
  - What makes a policy robust?
  - Why are robust policies superior?
- Example of robust policy design:
  - Sandia/VA pandemic influenza study
  - Lessons learned
  - Methods for uncertainty-driven policy design

# Terms

- Uncertainty analysis: Determining sources and effects of uncertainties in model design and inputs
- Categories of uncertainty
  - Aleatory: Related to chance
  - Epistemic: Related to (lack of) knowledge
- Aleatory: aka Stochastic
- Epistemic: aka Parametric
- Structural uncertainty (Type III)
- Design of Experiment (DOE): Planning model runs and parameter variations to answer question adequately and efficiently

# Basics of uncertainty analysis

- Create design of experiment to answer your question efficiently
- Perform Sensitivity Analysis (SA) to determine which inputs have the most effect on outputs
- Run uncertainty quantification (UQ) to identify sources of model uncertainty and how best to reduce it
- Run statistical significance tests to gauge reliability and quality of study results
- Repeat until satisfactory level of confidence reached.



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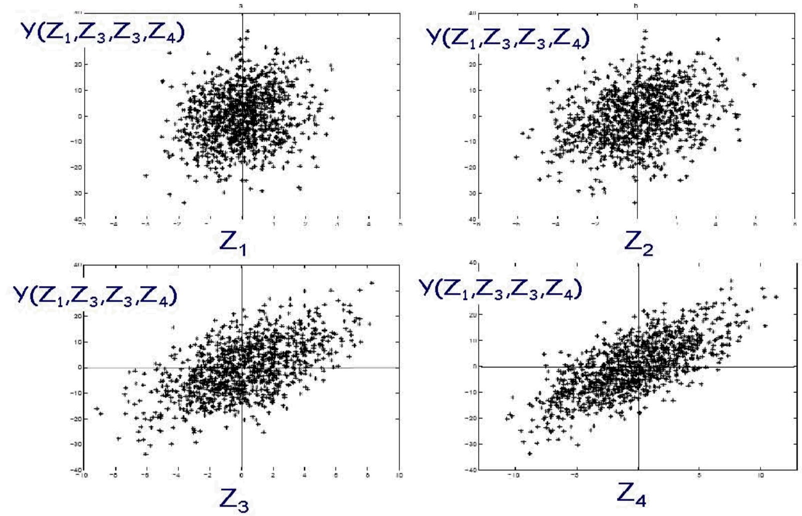
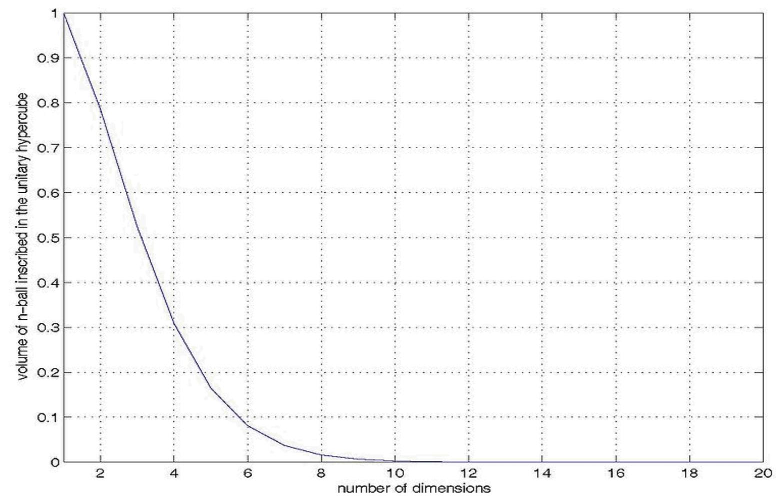
# Simple sensitivity analysis

- Parameter sweeps
  - Run model many times
  - Vary single model input while holding all others fixed
  - Plot output vs. each input
- Pros:
  - Fast to set up
  - Easy to interpret
- Cons:
  - Takes a lot of runs
  - Ignores interactions
  - Only looks at small portion of parameter space.



# Better Sensitivity Analysis Methods

- Multivariate Global Sensitivity Analysis
  - Run model many times
  - Vary all of the input parameters at once
  - Analyze relationship of inputs to outputs
- Pros:
  - Looks at all possible values of all parameters.
  - Lets you see interaction effects
- Cons
  - Can't directly interpret results
  - Standard methods require HUGE numbers of runs

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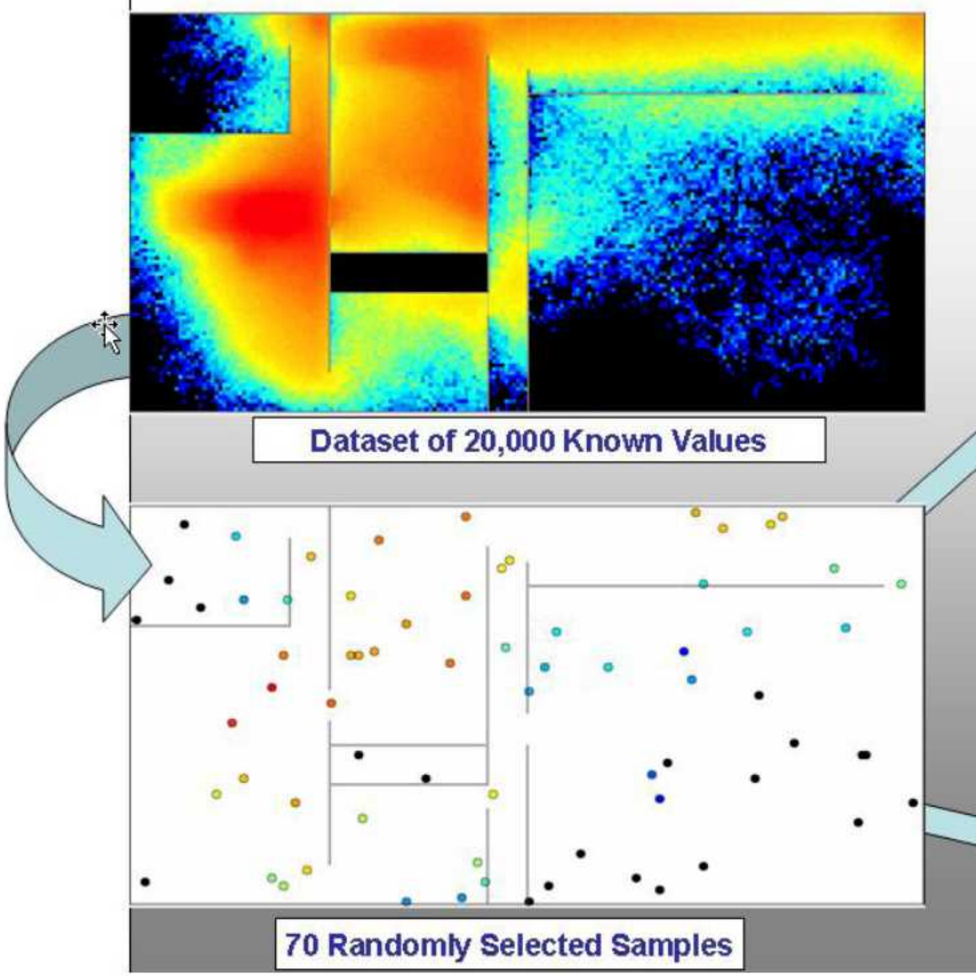
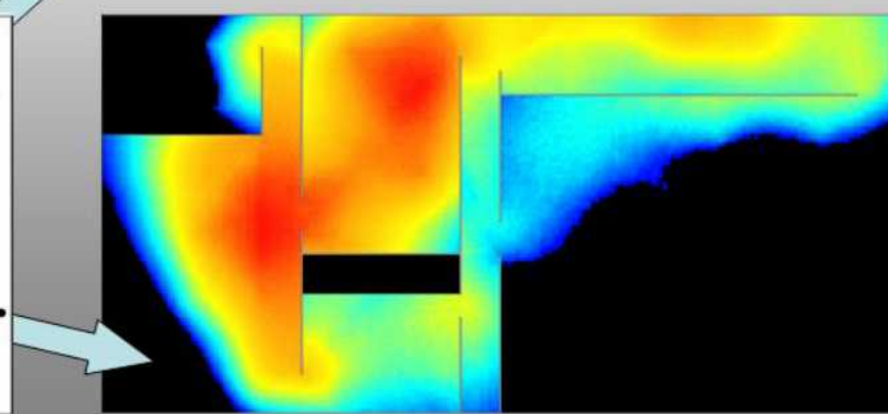
# Meta-models for Sensitivity Analysis




Meta-model is a
model of the model's output.

Small sample of possible inputs
to interpolate model results.



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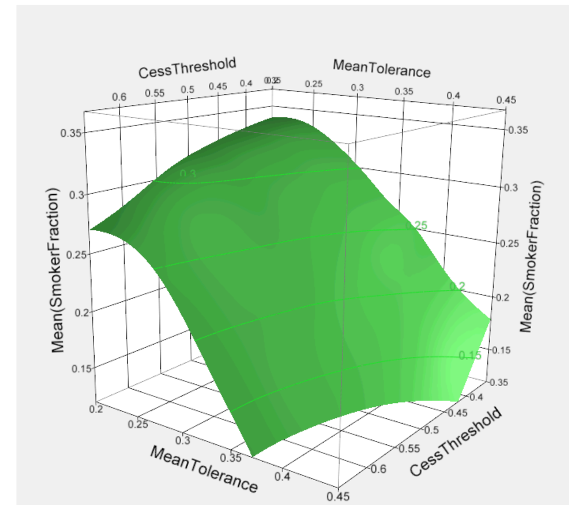
# Why use meta-models?

- Far fewer model runs needed (~1%)
- More flexible and stable estimates
- Determine interaction effects
- Fast, approximate model results for input combinations that weren't run
- Best bets: Gaussian process, radial basis functions , adaptive splines, and polynomial chaos expansion




**Model Report**

| Column | Theta | Total Sensitivity | Main Effect | sensitivity Interaction | hMid Interaction | pFill Interaction | lFull Interaction | consumptionTime Interaction | productionTime Interaction |
|---|---|---|---|---|---|---|---|---|---|
| sensitivity | 0.0071275 | 0.0013994 | 0.0007988 | . | 2.7455e-5 | 0.0004133 | 0.0001599 | 1.3507e-8 | 1.1883e-9 |
| hMid | 1.0880024 | 0.2295383 | 0.1078837 | 2.7455e-5 | . | 0.1215762 | 3.3322e-5 | 0.0000177 | 7.1324e-9 |
| pFill | 1.111107 | 0.8873233 | 0.7630665 | 0.0004133 | 0.1215762 | . | 0.0022544 | 1.1846e-5 | 9.9351e-7 |
| lFull | 0.1427269 | 0.0059568 | 0.0035089 | 0.0001599 | 3.3322e-5 | 0.0022544 | . | 2.3506e-7 | 5.8587e-9 |
| consumptionTime | 0.0010747 | 0.0000354 | 0.0000056 | 1.3507e-8 | 0.0000177 | 1.1846e-5 | 2.3506e-7 | . | 0 |
| productionTime | 8.7114e-5 | 1.0103e-6 | 2.6351e-9 | 1.1883e-9 | 7.1324e-9 | 9.9351e-7 | 5.8587e-9 | 0 | . |

| μ | σ² |
|---|---|
| 63.366829 | 527.00581 |

**-2*LogLikelihood**

864.15235

Fit using the Cubic correlation function.

# What does uncertainty analysis provide?

- Determines which parameters are most effective in changing model results
- Shows where improved data are needed
  - Better estimates of insensitive parameters not important
  - Important but poorly known parameters can use better data.
- Shows what you can safely ignore in your model
- Gives hard estimates on quality of model results under different scenarios.
- Answers questions of how trustworthy model results really are.



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# Robust policy options

- Single policies or combinations which create the desired outcome under a wide range of possible scenarios
- Options or interventions often designed for specific scenario conditions
- Policies are implemented in a wide range of scenarios
- Some policies may not perform well under unexpected conditions.
- Modeling policy outcomes over all conceivable implementation scenarios helps to find robust options.

# Example of Robust Policy Design

- *Effective, Robust Design of Community Mitigation for Pandemic Influenza: A Systematic Examination of Proposed US Guidance* (Davey, Glass, Min, Beyeler, Glass, 2008)
- Evaluated seven interventions (e.g. school closing, quarantine, etc.) on severity of influenza outbreak for variety of assumptions.
- About 2 million model runs to explore combinations of parameters
- Ranked treatment and mitigation strategies

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# Pandemic study generated lots and lots of data

**TABLE 1: 90% compliance**

**Combinations with infected attack rate 10% or less are green, 25% to10% are pink**

| ID Factor | | None | ASsd | CTsd | CTsd,ASsd | S | S, ASsd | S,CTsd | S,CTsd,ASsd |
|---|---|---|---|---|---|---|---|---|---|
| 0.75 | None | 2780 | 1872 | 1111 | 624 | 221 | 207 | 124 | 119 |
| | T | 1560 | 765 | 373 | 241 | 164 | 150 | 122 | 117 |
| | Q | 984 | 562 | 267 | 237 | 178 | 151 | 125 | 141 |
| | P | 711 | 379 | 217 | 184 | 161 | 138 | 114 | 123 |
| | Q,T | 600 | 324 | 218 | 159 | 140 | 132 | 119 | 120 |
| | Q,P | 329 | 298 | 166 | 160 | 148 | 129 | 121 | 130 |
| | Pex | 251 | 208 | 149 | 150 | 146 | 134 | 106 | 111 |
| | Q,Pex | 267 | 187 | 138 | 145 | 122 | 117 | 104 | 108 |
| 1.00 | None | 4965 | 3843 | 3941 | 3013 | 2274 | 1296 | 199 | 170 |
| | T | 4111 | 3064 | 2741 | 1815 | 666 | 399 | 157 | 129 |
| | Q | 3599 | 2665 | 2007 | 1321 | 718 | 420 | 174 | 145 |
| | P | 3192 | 2190 | 1214 | 735 | 278 | 250 | 143 | 129 |
| | Q,T | 2823 | 1880 | 924 | 638 | 334 | 213 | 135 | 133 |
| | Q,P | 2545 | 1531 | 617 | 415 | 249 | 196 | 144 | 128 |
| | Pex | 1776 | 1035 | 598 | 371 | 218 | 194 | 140 | 130 |
| | Q,Pex | 1287 | 614 | 323 | 257 | 207 | 178 | 128 | 144 |
| 1.25 | None | 6246 | 4916 | 5436 | 4375 | 4723 | 3588 | 506 | 278 |
| | T | 5554 | 4228 | 4581 | 3540 | 3268 | 2090 | 233 | 173 |
| | Q | 4989 | 4064 | 3963 | 3239 | 2810 | 1964 | 314 | 230 |
| | P | 4587 | 3480 | 3344 | 2551 | 1455 | 791 | 180 | 162 |
| | Q,T | 4334 | 3353 | 2925 | 2174 | 1350 | 767 | 200 | 172 |
| | Q,P | 3952 | 3007 | 2432 | 1513 | 670 | 504 | 173 | 172 |
| | Pex | 3117 | 2291 | 2007 | 1338 | 675 | 350 | 168 | 137 |
| | Q,Pex | 2686 | 1889 | 1138 | 641 | 422 | 285 | 163 | 153 |
| 1.50 | None | 7134 | 5625 | 6462 | 5264 | 6104 | 5007 | 1659 | 534 |
| | T | 6541 | 5038 | 5743 | 4527 | 5120 | 3882 | 484 | 239 |
| | Q | 5986 | 4979 | 5166 | 4353 | 4566 | 3709 | 867 | 438 |
| | P | 5573 | 4293 | 4632 | 3592 | 3627 | 2278 | 293 | 197 |
| | Q,T | 5288 | 4268 | 4328 | 3460 | 3362 | 2297 | 338 | 239 |
| | Q,P | 4902 | 3854 | 3778 | 2900 | 2706 | 1465 | 270 | 220 |
| | Pex | 3967 | 3053 | 3124 | 2370 | 2046 | 1117 | 246 | 179 |
| | Q,Pex | 3485 | 2660 | 2376 | 1618 | 1285 | 702 | 247 | 189 |
| 2.00 | None | 8230 | 6525 | 7729 | 6334 | 7790 | 6675 | 5256 | 2241 |
| | T | 7794 | 6001 | 7192 | 5721 | 7139 | 5903 | 3100 | 641 |
| | Q | 7285 | 6084 | 6701 | 5732 | 6636 | 5736 | 3873 | 2108 |
| | P | 6923 | 5307 | 6227 | 4938 | 5964 | 4704 | 1246 | 389 |
| | Q,T | 6687 | 5445 | 6002 | 4987 | 5744 | 4720 | 1771 | 639 |
| | Q,P | 6182 | 4940 | 5478 | 4394 | 5141 | 3943 | 855 | 400 |
| | Pex | 5233 | 4020 | 4611 | 3559 | 4144 | 3156 | 659 | 336 |
| | Q,Pex | 4710 | 3652 | 3984 | 3030 | 3492 | 2459 | 559 | 335 |
| 2.50 | None | 8850 | 7107 | 8473 | 6996 | 8610 | 7631 | 7035 | 4310 |
| | T | 8540 | 6619 | 8075 | 6449 | 8159 | 7034 | 5676 | 2004 |
| | Q | 8087 | 6791 | 7649 | 6570 | 7721 | 6885 | 5996 | 4135 |
| | P | 7777 | 5997 | 7246 | 5761 | 7268 | 6038 | 3788 | 860 |
| | Q,T | 7584 | 6187 | 7042 | 5867 | 7077 | 6051 | 4429 | 1765 |
| | Q,P | 7112 | 5662 | 6519 | 5308 | 6534 | 5417 | 3014 | 813 |
| | Pex | 6131 | 4698 | 5617 | 4378 | 5413 | 4306 | 2043 | 602 |
| | Q,Pex | 5604 | 4389 | 5031 | 3897 | 4764 | 3780 | 1469 | 581 |
| 3.00 | None | 9237 | 7545 | 8929 | 7465 | 9091 | 8213 | 8062 | 5656 |
| | T | 9003 | 7054 | 8623 | 6956 | 8776 | 7722 | 7157 | 3758 |
| | Q | 8626 | 7261 | 8259 | 7139 | 8410 | 7606 | 7216 | 5447 |
| | P | 8384 | 6472 | 7933 | 6302 | 8052 | 6902 | 5687 | 1897 |
| | Q,T | 8188 | 6697 | 7768 | 6515 | 7861 | 6921 | 6004 | 3465 |
| | Q,P | 7753 | 6194 | 7284 | 5909 | 7396 | 6340 | 4983 | 1786 |
| | Pex | 6803 | 5216 | 6353 | 4964 | 6327 | 5155 | 3803 | 1135 |
| | Q,Pex | 6276 | 4906 | 5832 | 4561 | 5758 | 4663 | 3124 | 971 |

| | None | ASsd | CTsd | CTsd,ASsd | S | S, ASsd | S,CTsd | S,CTsd,ASsd |
|---|---|---|---|---|---|---|---|---|
| None | 2780 | 1872 | 1111 | 624 | 221 | 207 | 124 | 119 |
| T | 1560 | 765 | 373 | 241 | 164 | 150 | 122 | 117 |
| Q | 984 | 562 | 267 | 237 | 178 | 151 | 125 | 141 |
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| Pex | 251 | 208 | 149 | 150 | 146 | 134 | 106 | 111 |
| Q,Pex | 267 | 187 | 138 | 145 | 122 | 117 | 104 | 108 |

Each cell represents mean of 100 model runs

Colors indicate quality of solution

Key:

T = Treatment

Q = Quarantine

P = Prophylaxis

Pex = Extended Prophylaxis

S = School Closure

ASsd = Adult distancing

CTsd = Child distancing



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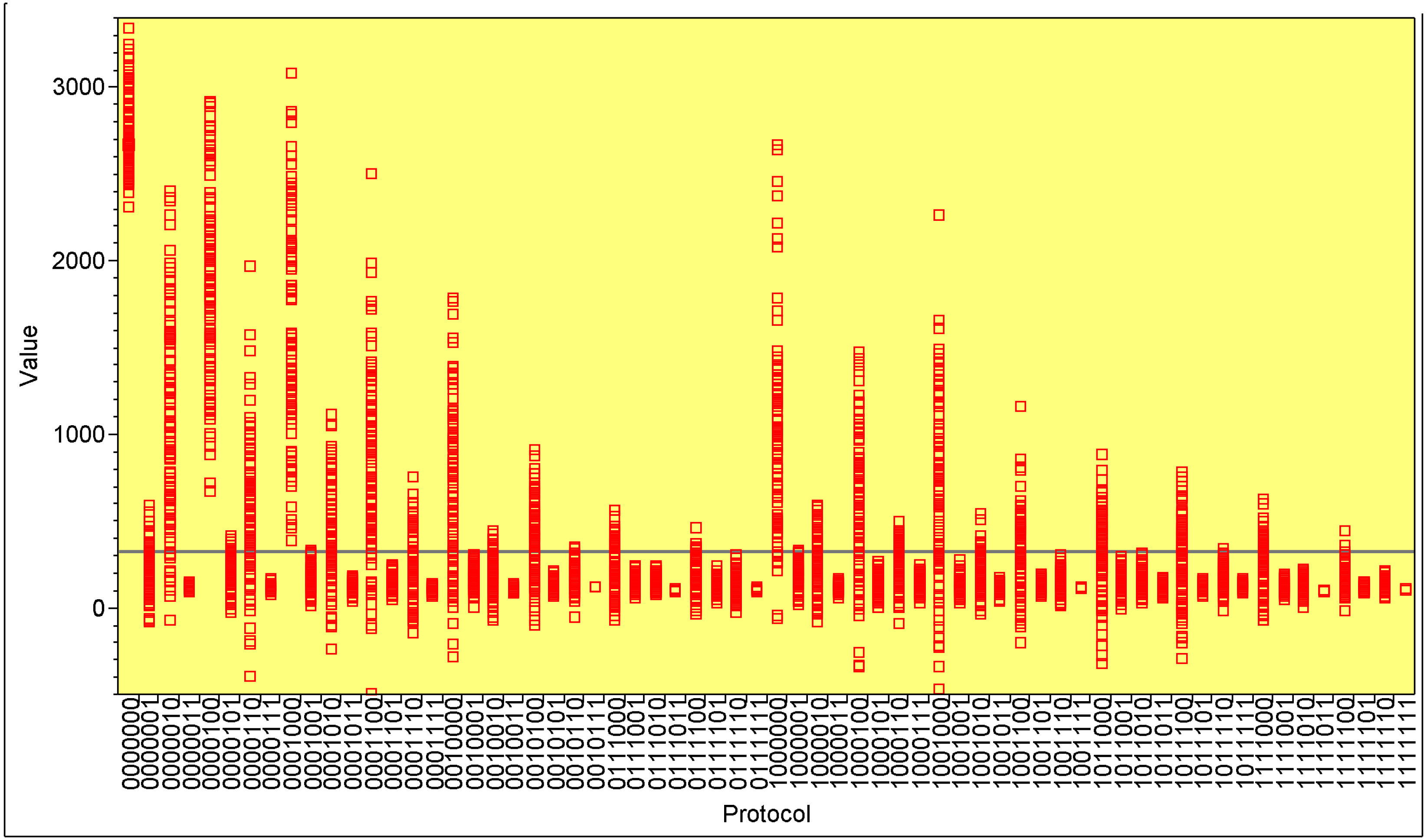
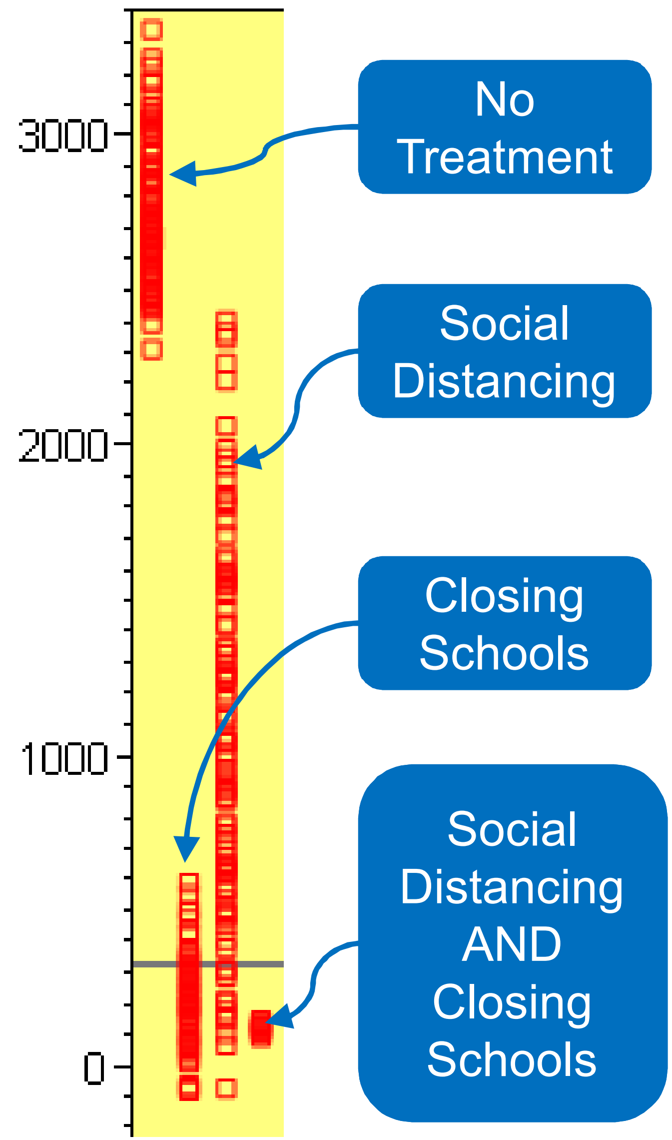
Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

# Scatter plot of pandemic study results shows numbers of people infected and variability in model



# Desirable outcomes and low variability characterize Robust Policies.

- Each policy tried on 100 random social networks
- 2,780 cases expected with no treatment
- Closing schools is best single option
  - Mean = 137 cases
  - Moderate variation
- Social distancing is not as effective
  - Mean = 987 cases
  - Wide variation
- Both policies in conjunction create robust solution
  - Mean = 118 cases
  - Narrow variation
- Robust solution:
  - Good outcome
  - Most stable to uncertainty



# Uncertainty analysis best practices for complex adaptive system model evaluation

- Define policy inputs as numerical ranges rather than categorical choices whenever possible
- Run simple parameter scans to get a feel for effects
- Run near-orthogonal Latin hypercube space-filling design on small sets of runs (n = ~200)
- Document sensitivity and interactions with meta-models
- Look for interesting peaks and troughs in state space and distributions
- Trace uncertainty from sources to results
- Apply uncertainty to rank policy options
- Use uncertainty to guide further refinement