Complex Adaptive System of Systems (CASoS) Engineering Initiative
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Integrating Uncertainty Analysis into Complex-System Modeling for Public Policy Design

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Simple Answers about Complex Systems

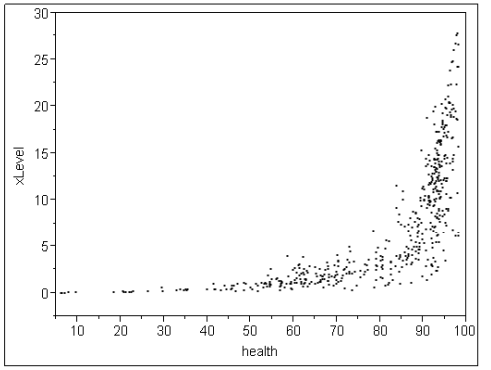
- Model to learn how to influence complex systems of national or global scale
- Public policy is vehicle for influencing large complex systems
- Policy people want simple answers to complex questions
  - How to nudge the system toward good outcomes
  - How to avoid pushing the system to catastrophic failure modes
  - How risky is each option
- Different levels of focus characterize complexity modelers and policy people.
- Uncertainty analysis sometimes helps provide metrics and information to bridge the gulf

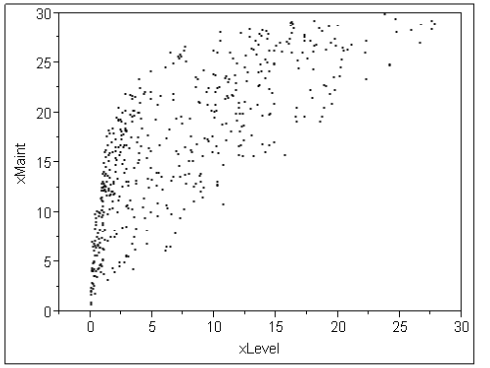
Routine Uncertainty Analysis as Due Diligence

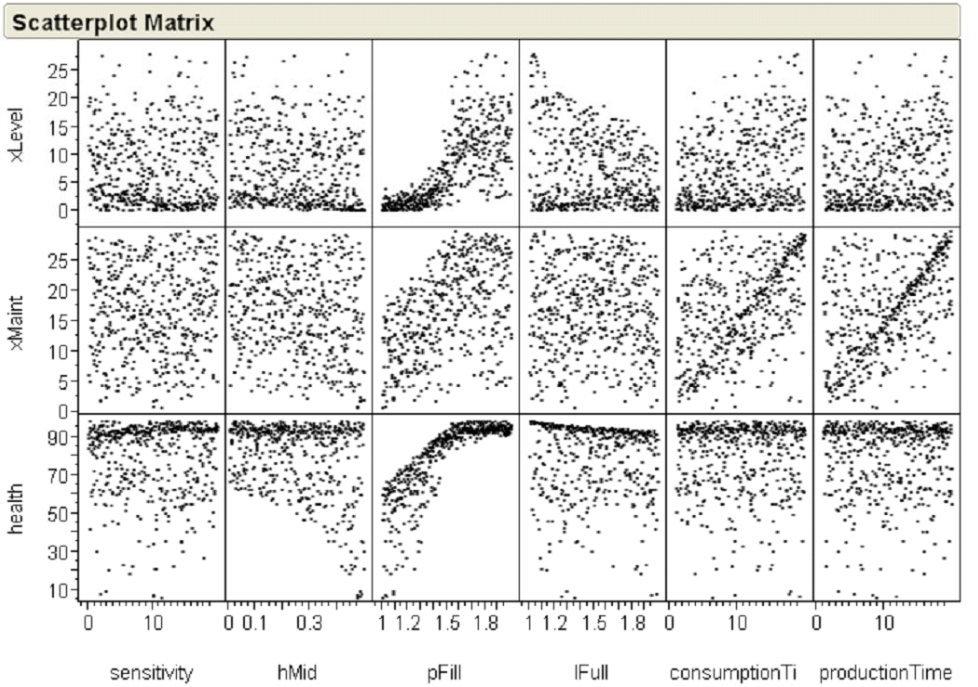
- Create design of experiment to answer the question efficiently
- Run the model many times with different inputs.
- Perform Sensitivity Analysis (SA) to determine which inputs have the most effect on outputs
- Run uncertainty quantification (UQ) to identify sources of model uncertainty and how best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

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.

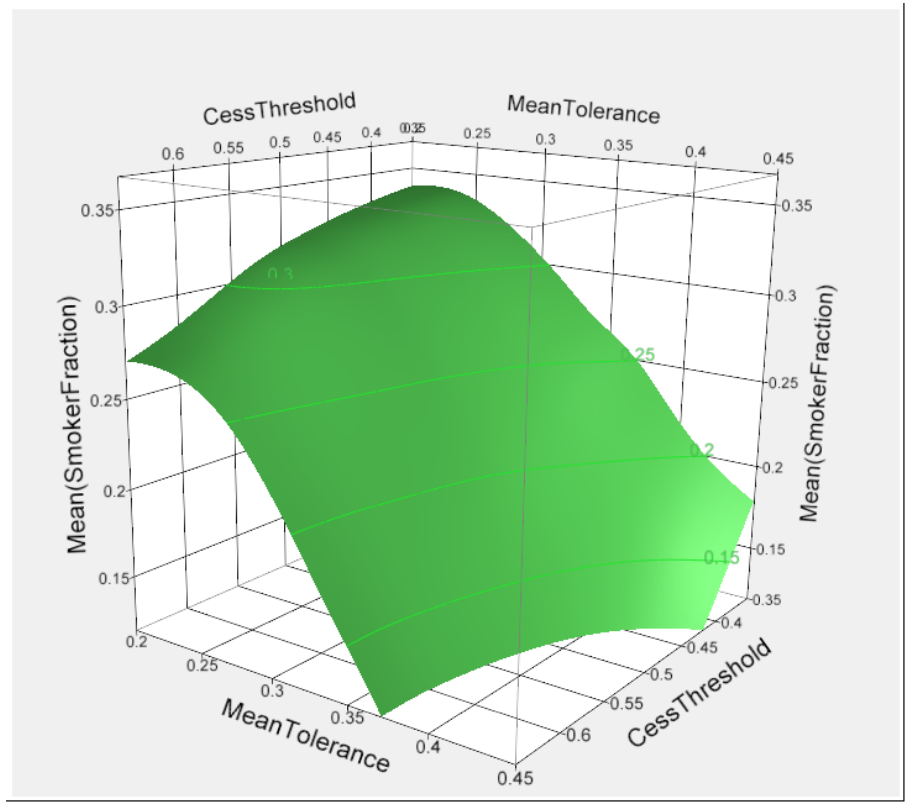






Meta-modeling for Sensitivity Analysis

- 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	0.0071275	0.0013994	0.0007988
hMid	1.0880024	0.2295383	0.1078837
pFill	1.111107	0.8873233	0.7630665
lFull	0.1427269	0.0059568	0.0035089
consumptionTime	0.0010747	0.0000354	0.0000056
productionTime	8.7114e-5	1.0103e-6	2.6351e-9

Best Practices for Uncertainty Analysis of Complex Models

- 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
- Trace uncertainty from sources to results
- Apply uncertainty to rank policy options
- Look for interesting peaks and troughs in state space and distributions
- Use uncertainty to guide further refinement

Pandemic Influenza Case Study: Communicate Modeling Results

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Effective, Robust Design of Community Mitigation for Pandemic Influenza: A Systematic Examination of Proposed US Guidance

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Abstract

Background: The US government proposes pandemic influenza mitigation guidance that includes isolation and antiviral treatment of ill persons, voluntary household member quarantine and antiviral prophylaxis, social distancing of individuals, school closure, reduction of contacts at work, and prioritized vaccination. Is this the best strategy combination? Is choice of this strategy robust to pandemic uncertainties? What are critical enablers of community resilience?

Methods and Findings: We systematically simulate a broad range of pandemic scenarios and mitigation strategies using a networked, agent-based model of a community of explicit, multiply-overlapping social contact networks. We evaluate illness and societal burden for alterations in social networks, illness parameters, or intervention implementation. For a 1918-like pandemic, the best strategy minimizes illness to <1% of the population and combines network-based (e.g. school closure, social distancing of all with adults' contacts at work reduced), and case-based measures (e.g. antiviral treatment of the ill and prophylaxis of household members). We find choice of this best strategy robust to removal of enhanced transmission by the young, additional complexity in contact networks, and altered influenza natural history including extended viral shedding. Administration of age-group or randomly targeted 50% effective pre-pandemic vaccine with 7% population coverage (current US H5N1 vaccine stockpile) had minimal effect on outcomes. In order, mitigation success depends on rapid strategy implementation, high compliance, regional mitigation, and rigorous rescinding criteria; these are the critical enablers for community resilience.

Conclusions: Systematic evaluation of feasible, recommended pandemic influenza interventions generally confirms the US community mitigation guidance yields best strategy choices for pandemic planning that are robust to a wide range of uncertainty. The best strategy combines network- and case-based interventions; network-based interventions are paramount. Because strategies must be applied rapidly, regionally, and stringently for greatest benefit, preparation and public education is required for long-lasting, high community compliance during a pandemic.

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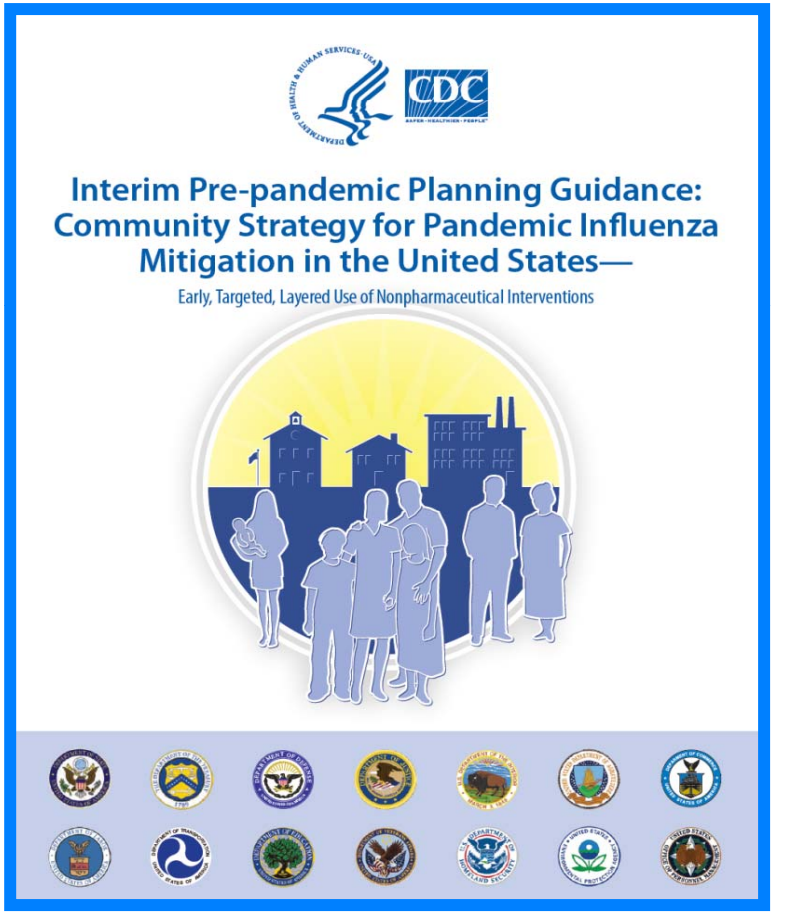
Introduction

Background

Human influenza pandemics of unpredictable severity and consequence are considered inevitable. Studies using computational models have examined roles of border controls, internal travel restrictions, treatment and prophylaxis with antivirals, isolation of cases, quarantine of household members, school closure, and partially effective vaccine on limiting outbreak sizes [1–7]. Others have modeled a pandemic at large scale either from a source in SE Asia [8,9], or within the US or Great Britain [10,11] in order to describe effects of vaccination, school closures, and voluntary or imposed partial or total community member quarantine. Still others have focused at the community scale to consider community containment options [12–14]. The findings from these and other large and small scale simulation studies underpin the US government's *Interim Pre-pandemic Planning Guidance: Community Strategy for Pandemic Influenza Mitigation in the United States* [15].

Yet, these studies have explored the influence of mitigation strategies through a limited set of defining scenarios. Many questions are left unanswered: Which combinations of interven-



CASoS Engineering

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

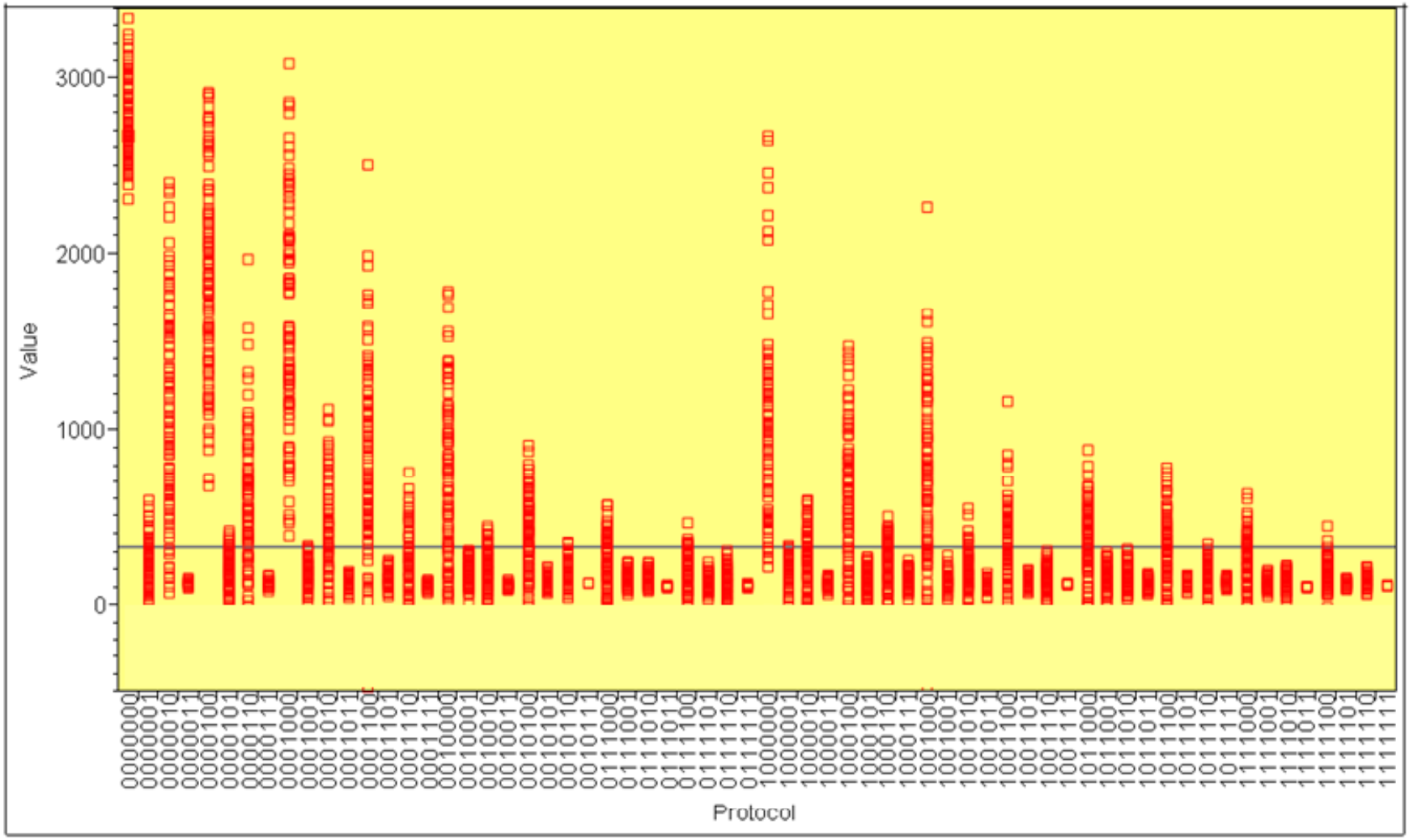
Table 2: Example model run results. Cell values represent mean number of infected people from 100 runs. Infectivity=0.75, Compliance=90%

	None	A	C	C,A	S	S, A	S,C	S,C,A
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
E	251	208	149	150	146	134	106	111
Q,E	267	187	138	145	122	117	104	108

Table 1: Intervention Strategies

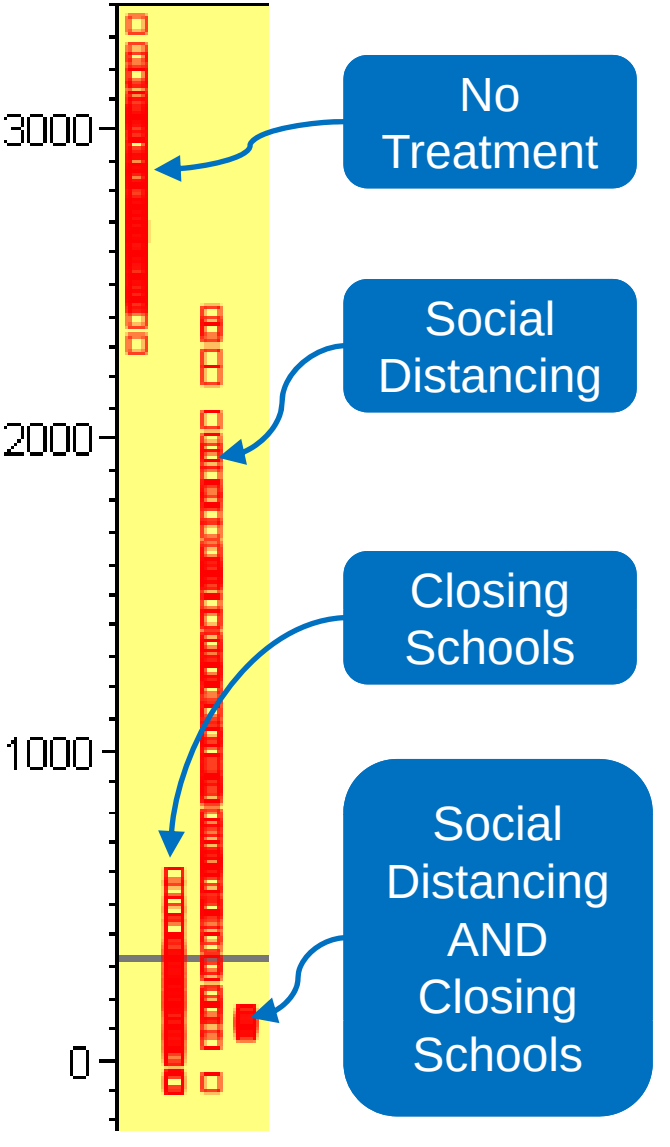
Category	Symbol	Intervention
Network-Based	S	Schools closed.
Network-Based	C	Social distancing of children and teenagers.
Network-Based	A	Social distancing of adults and seniors.
Case-Based	Q	Household quarantine.
Case-Based	T	Antiviral treatment.
Case-Based	P	Household member antiviral prophylaxis.
Case-Based	E	Extended contact prophylaxis

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

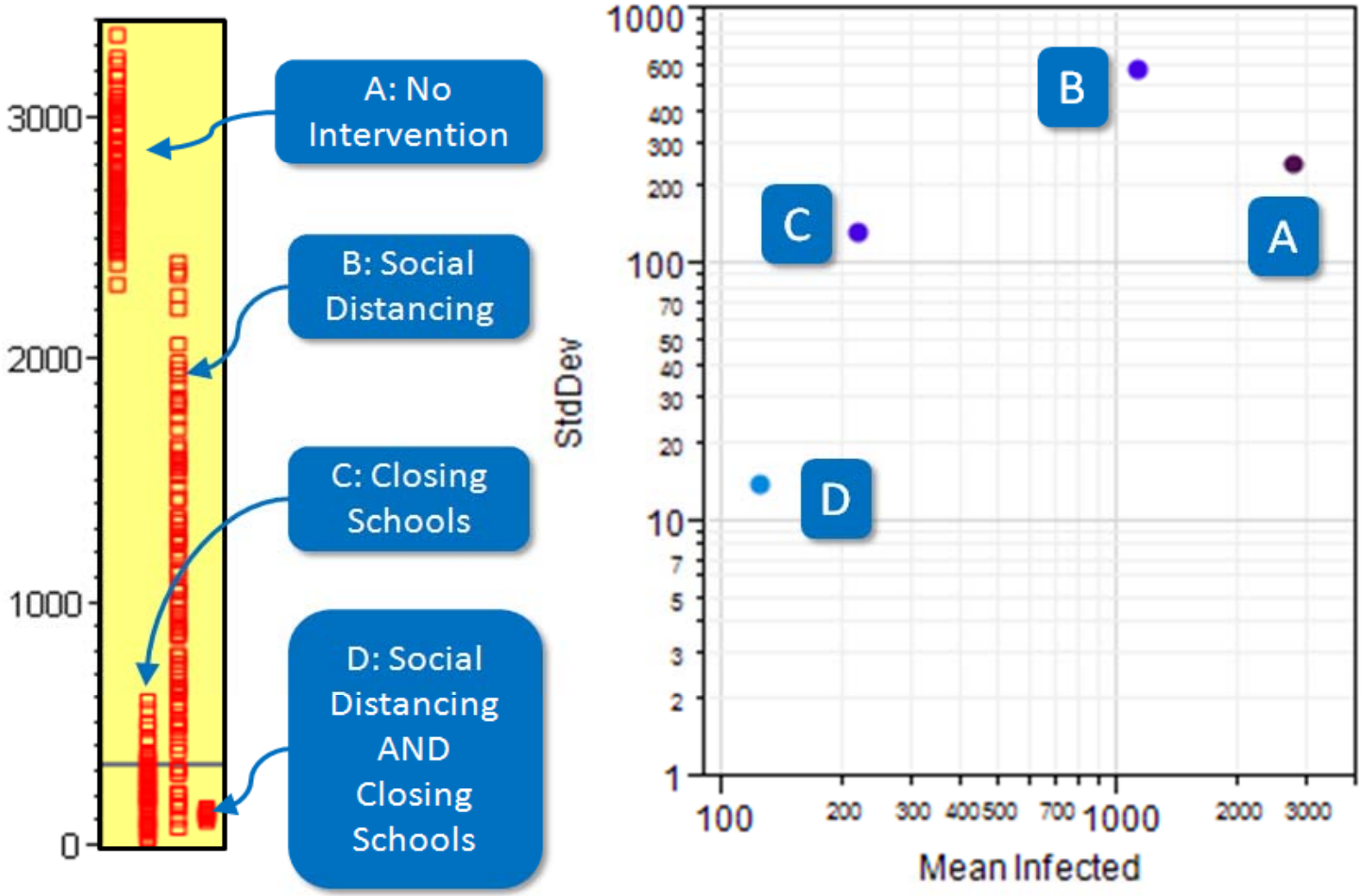


Desirable Outcomes and Low Variability Characterize Robust Policies

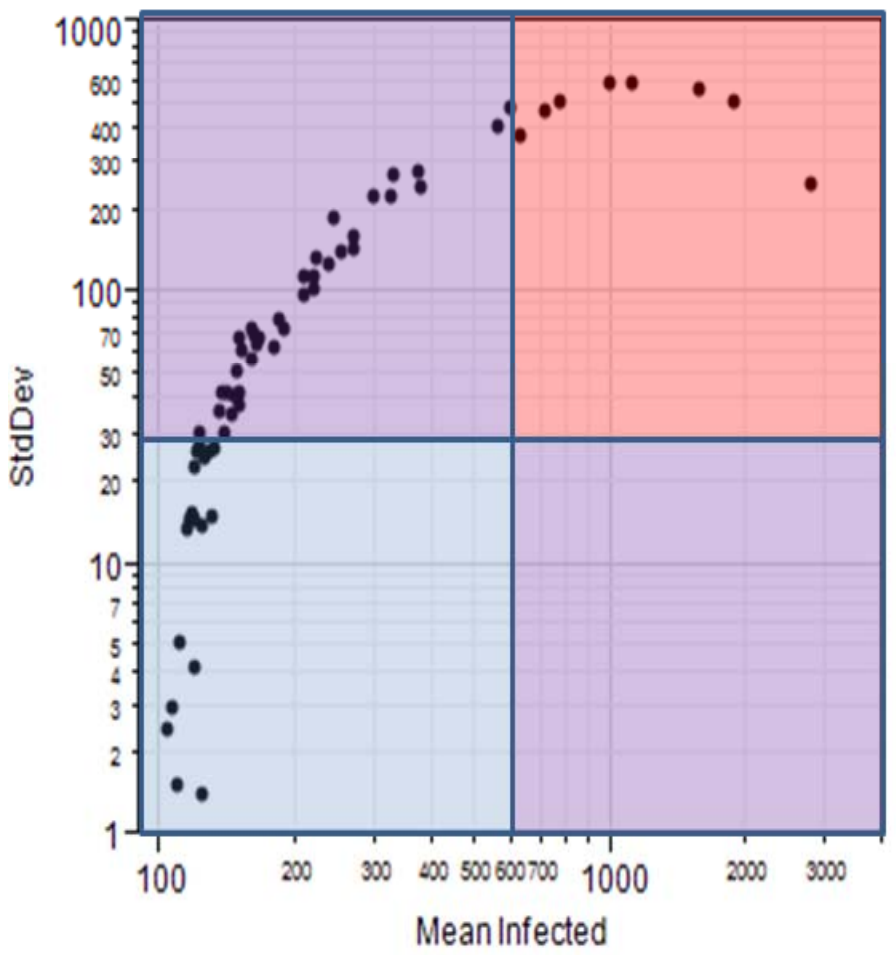
- Each policy tried on 100 random social networks
- 2,780 cases expected with no treatment
- Closing schools is best single option
  - Mean = 137 cases
  - Moderate variation
- Social distancing is not as effective
  - Mean = 987 cases
  - Wide variation
- Both policies in conjunction create robust solution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

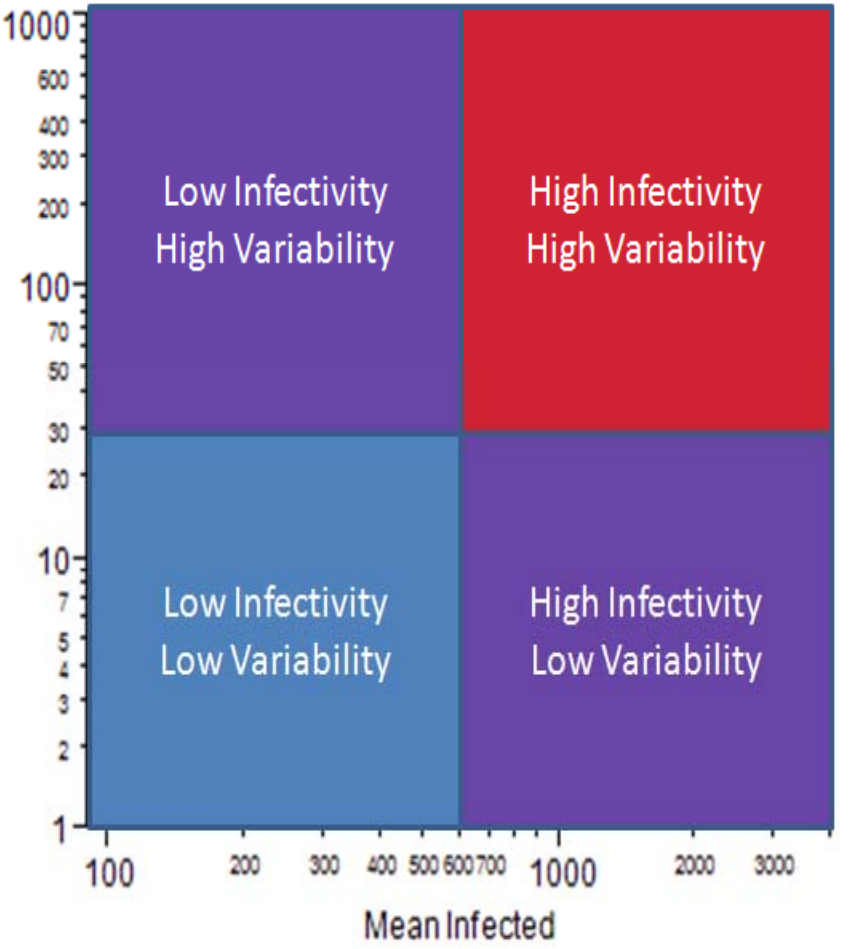


Re-casting model results

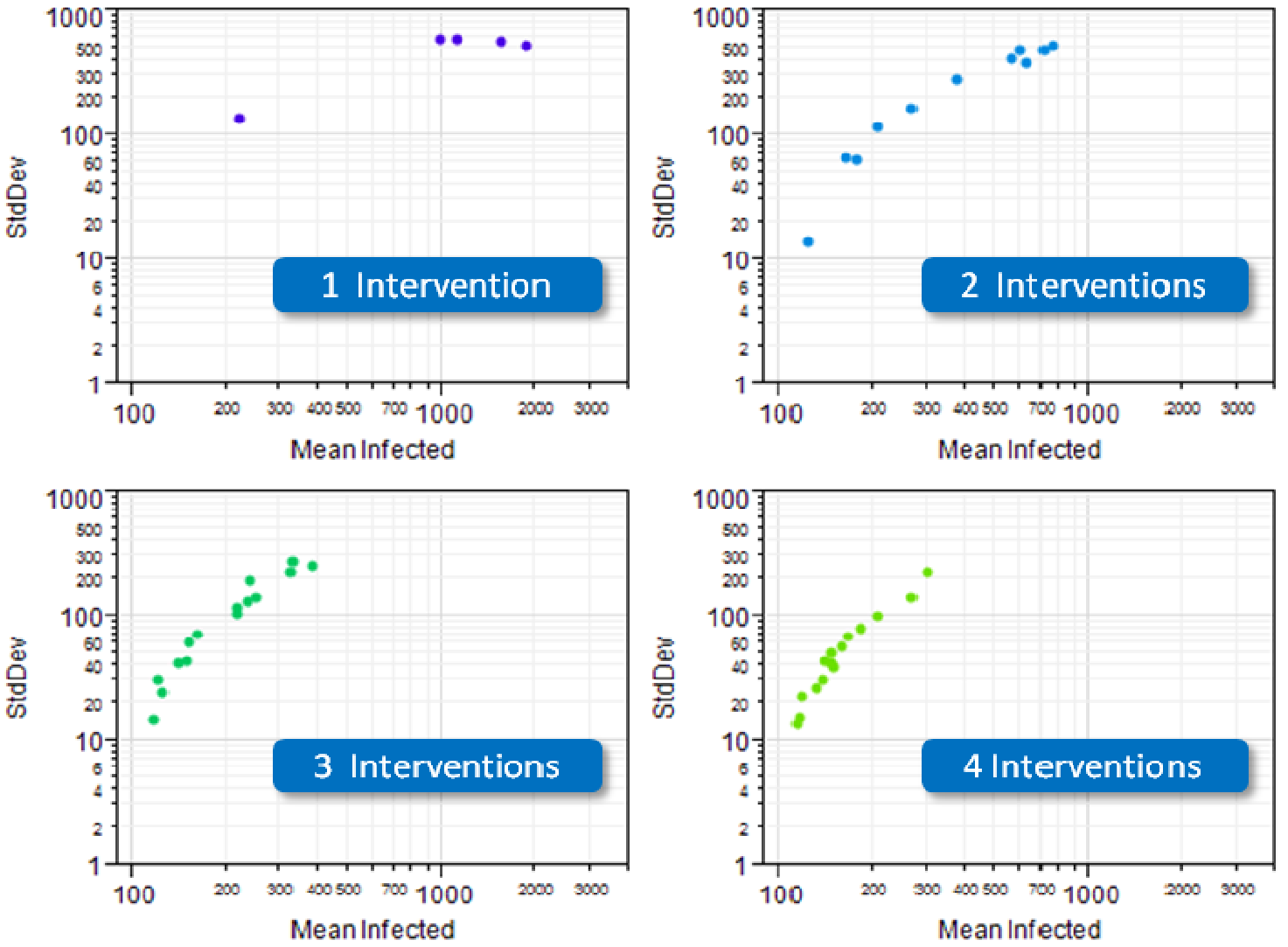


Tradeoffs: Effectiveness and Predictability





Isolating Categories for Layered Interventions



Rankings by Categories

Number of Interventions	Rank of Effectiveness	Intervention	Mean Infected	Standard Deviation
1	1	_____S	220.5273	133.8141
	2	___Q___	984.4853	595.5609
	3	_____C_	1111.12	586.9511
2	1	_____CS	124.1364	13.89174
	2	T_____S	163.9688	65.28918
	3	___Q__S	178.0909	62.91812
3	1	____ACS	118.6429	14.75235
	2	___Q_CS	125.1429	24.43471
	3	T____CS	121.875	30.07342
4	1	TP___CS	114	13.6504
	2	T___ACS	116.75	15.32272
	3	T__Q_CS	118.5714	22.619
5	1	TP__ACS	123	1.414214
	2	TPE__CS	106	3
	3	T__QACS	119.6667	4.163332
6	1	TPEQ_CS	103.6	2.50998
	2	TPE_ACS	110.75	5.188127
	3	TPEQA_S	116.5	14.47165
7	1	TPEQACS	108.3333	1.527525

- Behind the scenes analysis permits confident assignment of best approaches
- Simple presentation helps convey results in actionable form
- Policy makers desire robust options: concurrently good performance and low risk options

Summary

- Routine uncertainty analysis of complex system models
  - Which policies can make good changes
  - Which policies can create undesirable changes
  - How risky is each policy option
- Communication between modelers and policy people is paramount
  - Eyes often glaze over at tables, equations and graphs
  - Colorful graphs and 3-d response surface plots work
  - Conceptually, uncertainty analysis is easy for many policy people to grasp, but details are not