Using structured decision-making to manage an infectious disease outbreak: an influenza case study tutorial

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Background

How do we keep an infectious disease outbreak from becoming a major epidemic? Simulation modeling, statistical analyses, and expert opinion are often used to help direct public health strategies by predicting the likely outcomes of proposed actions. But these calculations are only one part of the decision process.

Beyond applying science and data, developing a public health strategy to manage a disease outbreak requires value judgments for prioritizing competing objectives, and for determining risk tolerance to uncertainties in these outcomes. That is, after predicting likely consequences of alternative strategies, a decision maker may need to choose between one that is more cost-efficient versus another that enjoys greater popular support, or to decide if it is worth paying an additional $18 million to increase the likelihood of achieving the desired outcome, from 40% to 65%. These are the kinds of subjective judgments inherent in multi-objective public health decisions.

Many decision analysis methods used in public health focus on the technical aspects of decision-making, e.g., calculating costs and benefits or the relative risks of different strategies. Once decision makers are presented with the technical data, values-based trade-offs may be implicitly addressed through vaguely described mental calculations. The resulting decision can appear arbitrary, making it more vulnerable to public criticism, legal challenge, or accusations of a hidden agenda.

Structured decision-making (SDM) provides an organized framework for explicitly recognizing and incorporating subjective considerations in deliberations, on more equal footing with the conventionally accepted roles of science and data (Gregory et al. 2012). SDM is related to cost-benefit analysis, risk analysis, and other common decision analysis methods, but puts comparatively greater emphasis on making transparent the subjective part of decision-making that translates data to a policy decision.

While SDM has been increasingly adopted by federal agencies in natural resources (especially endangered species) management, it has received less attention in public health. The purpose of this tutorial is to introduce SDM concepts, through a hypothetical scenario exercise, to students and practitioners of public health. I present a case study scenario in which the Director of the Fulton County Board of Health requests assistance to develop a strategy for mitigating an anticipated severe influenza season.

The case study is presented in three parts. First, I set the hypothetical scenario and specify example fundamental objectives, performance measures, and alternative strategies for mitigating an influenza outbreak. Second, I describe the use of expert elicitation and simulation modeling to predict the spread of influenza under alternative strategies. Third, I present results from multi-attribute trade-off (MATO) and sensitivity analyses to identify the preferred influenza mitigation strategy.

The following supplementary information is provided with this tutorial:

- Appendix 1: Calculations of predicted costs for implementing strategies
- Appendix 2: Shiny app for swing weighting and multi-attribute trade-off analysis to identify preferred strategies

For disease modelers and other researchers who are not directly involved in public health decision-making, the expected outcome of this case study tutorial is a better understanding of the roles (and limitations) of data and science in policy decision-making, under an SDM approach. For public health decision-makers, the tutorial presents ways to clarify and explicitly integrate value judgments with scientific data in decision-making.

Part 1: Setting the Scenario and First Steps in SDM

Fulton County, Georgia, includes the city of Atlanta and supports a population of approximately 1 million people. The Fulton County Board of Health works with the Georgia Department of Public Health (DPH) to manage the spread of influenza and other infectious diseases in Fulton County.

Influenza is a highly contagious respiratory disease caused by influenza viruses. Symptoms (chills, aches, cough, fever, and headache) can be severe, lasting as long as two weeks and sometimes leading to death, especially in young children and people over 65 years of age. In the United States, the annual influenza season may begin in October and run through May, with incidences typically peaking in January or February. The disease is easily spread through contact or transmission of virus particles in aerosols or large droplets when infected persons cough or sneeze. Rates of spread in schools and other densely populated venues can be especially high.

Before each influenza season, manufacturers develop vaccines targeting the three or four most likely strains anticipated to predominate in the coming season based on global influenza surveillance data and recommendations from the Centers for Disease Control (CDC). Influenza vaccines are typically 40% to 60% effective against the disease (CDC website, a). In the United States, almost 50% of the population was vaccinated against influenza during the 2014–15 season, with highest coverage among persons up to 17 years of age (CDC website, b). This vaccination coverage is approximately 8% higher than a decade ago, but still well below the targeted 70% annual influenza vaccination coverage for the US population (U.S. Department of Health and Human Services 2015). The combination of moderate vaccine coverage and moderate efficacy means a rather small proportion of the population is protected against influenza each year. Nevertheless, vaccination is widely considered the best available protection against the disease.

In summer 2016 the World Health Organization indicated, based on surveillance reports, that a particularly virulent strain of influenza may be on the horizon. The Fulton County Board of Health needed to develop a strategy for mitigating this potentially severe influenza season. The Board's Director knew that additional intervention efforts beyond the standard roll-out could require several months of preparation, so wanted to finalize a strategy as soon as possible.

An SDM approach is appropriate for this context. Although a public health decision on disease management should be informed by data, it also requires subjective decisions such as, "How much are we willing to pay to reduce the predicted number of infected persons by 1000 cases?" and "If the most likely outcome of an alternative strategy is a moderate attack rate but there is a small risk of a severe outbreak, are we willing to take that risk?"

To begin, we briefed the Director and a small group of SDM participants (public health specialists, social science epidemiologists, community representatives, and disease modelers) on steps we would take to facilitate their decision-making (Table 1). The first five SDM steps can be remembered with the acronym PrOACT: Problem, Objectives, Alternatives, Consequences, Trade-offs. The sixth step addresses uncertainties, limitations, and the value of obtaining additional information.

Table 1. Steps in the SDM process.

Step	Description
1. Clarify the problem	Identify the decision-maker and decision-making process, the spatial and temporal scope of the decision and alternative strategies, and any consultation and tools required to inform the decision
2. Define fundamental objectives and their performance measures	Specify what matters and the metrics that will be used to evaluate how well each alternative strategy performs against each fundamental objective
3. Propose alternatives	Identify alternative strategies (actions to achieve the fundamental objectives); sketch an influence diagram to show how strategies are linked to the decision problem
4. Predict consequences	Use expert elicitation, existing data, simulation models, and other information resources to predict the consequences of each alternative strategy with respect to each fundamental objective; explicitly structure uncertainties into these predictions; present results in a consequence table, highlighting the most likely predictions for risk-neutral decision makers and the worst plausible predictions for risk-averse decision makers
5. Evaluate trade-offs	Identify and eliminate dominated and practically dominated alternatives and insensitive performance measures; use even swaps to simplify the decision further; if additional analysis is required, use multi-attribute trade-off analysis to identify a preferred alternative
6. Evaluate uncertainties, limitations, and value-of-information	Conduct sensitivity analysis on critical disease model parameters and trade-off weighting to identify uncertainties and limitations of analyses; if relevant, calculate value-of-information (VOI) to determine if the value of reducing particular uncertainties might warrant the additional time and effort for data collection

The SDM steps in Table 1 are sequential but iterative, i.e., it is often necessary to revisit previous steps as new considerations or findings (such as initial simulation model results) come to light. Sometimes, a decision can be reached without going through all the steps. For example, clarifying the problem, fundamental objectives, and alternatives may be enough to come to an “obvious” conclusion about a preferred course of action. An SDM approach can be highly quantitative or mostly qualitative. It is flexible enough to be relevant for day-to-day decisions, more involved decisions spanning several days with multiple participants, or complex multi-year decisions involving many government agencies and representatives for competing stakeholder groups.

Step 1: Clarify the problem

The first step in SDM is to identify the decision-maker and decision-making process, clarify the spatial and temporal scope of the decision and alternative strategies, and ensure that consultation and tools required to inform the decision are readily available.

In our case study, the decision at stake was what public health strategy to employ in Fulton County for mitigating an expected worse-than-usual upcoming influenza season. Interventions related to school closures and policies restricting travel quarantines were not within the scope of the decision process because the

Fulton County Board of Health does not have full decision-making authority for these extreme actions. The focus instead was on proactive influenza control strategies that could be implemented within four months.

In Fulton County, the Director of the Board of Health works with other Board members and key contacts in the DPH to make decisions regarding influenza management. For this SDM process, the Director was authorized to represent the larger group of decision makers, consulting them only for critical decisions.

The small group of public health specialists and community representatives were present to contribute ideas and provide feedback during the SDM process, but they had no decision-making authority. Budget analysts were involved in estimating costs of alternative strategies, but did not directly participate in the SDM process. Step 4 (Predict consequences) involved only the scientific "experts"—the disease modelers and social science epidemiologists. Simulation models were run using the spatially explicit agent-based disease modeling software, Framework for Reconstructing Epidemiological Dynamics (FRED; Grefenstette et al. 2013), and the most recent synthetic population dataset for Fulton County, GA (RTI International 2010; Wheaton 2014).

SDM participants decided to go through a quick first round of the SDM process—a decision "sketch"—to identify the most promising influenza mitigation strategies and key uncertainties affecting the decision. If useful, further analysis could then focus on finding ways to reduce or hedge against important uncertainties, comparing modified versions of the most promising strategies, and running analyses using different simulation models to see if results are sensitive to model choice. The first-round decision sketch is presented in this case study tutorial.

Step 2: Define fundamental objectives and their performance measures

This step entails specifying what matters (the fundamental objectives) and the metrics that will be used to evaluate how well each alternative strategy performs against each objective. In SDM, fundamental objectives are simple statements of what matters and the preferred direction of change (such as maximize/minimize or increase/decrease).

Fundamental objectives often include statements of value and ethics such as "maximize public support", "maximize spiritual feel" (e.g., of a Native American cultural site), or "minimize harm to legacy trees". Although it may be difficult to define metrics by which to measure these qualitative objectives, it is critical to include them if they are considerations in the decision. Hidden objectives (i.e., important but unstated factors that influence decisions) lead to either suboptimal decisions or decisions that subvert the transparency of the decision process. In an SDM approach, the set of fundamental objectives defined for a decision should include ALL the things that matter in a particular decision context, and each fundamental objective should have a corresponding performance measure.

In our case study, the SDM participants identified five fundamental objectives for an influenza mitigation strategy:

- Minimize implementation cost
- Minimize economic productivity loss
- Minimize infected population
- Maximize public support
- Maximize future benefits

This was a reasonable set of fundamental objectives to start with. The objectives are simple, complete (i.e., cover all the essential factors that matter in the decision), independent (i.e., predicted performance of alternatives can be judged independently against each fundamental objective, without knowing how another objective is affected), and fall within the Director's decision mandate.

Table 2. Fundamental objectives and performance measures for influenza mitigation.

Fundamental objective	Description of performance measure	Unit
Minimize implementation cost	Estimated total costs of strategy implementation.	\$(in 1000's)
Minimize economic productivity loss	Predicted person-days of missed work due to influenza, multiplied by the median daily wage for an employed person in Fulton County. Predicted person-days includes work missed to care for children ($<$ 15 years old) with influenza.	\$(in 1000's)
Minimize infected population	Predicted number of persons that become sick with influenza.	Number of persons (in 1000's)
Maximize public support	Key issues of concern regarding influenza planning, and their relative importance to the public, were identified based on complaints received by the County Board of Health over the prior five years. Anticipated public support for a strategy was measured by the proportion of these complaints that each strategy addressed. For example, 38% of complaints from the past five years were about high vaccine costs making them inaccessible to low-income persons. A strategy to subsidize vaccine costs for low-income persons would therefore get a public support score of 38%.	% of complaints addressed
Maximize future benefits	Strategies such as public education campaigns may have long-term benefits (e.g., reduced disease risk behaviors) that extend beyond a single influenza season. A qualitative listing of future benefits is presented for each strategy, but the objective is scored simply as 'yes' or 'no' future benefits.	1=yes future benefits; 0=no future benefits

The simplicity of fundamental objectives in SDM means they are necessarily vague. But this ambiguity was resolved by participants in the next task, which was to identify performance measures (Table 2, previous page). A performance measure is a specific metric that clearly indicates how each alternative strategy should be scored with respect to each fundamental objective. The performance measures for a decision represent the full set of metrics by which the consequences of alternative strategies will be compared. Any other information about the impacts of an alternative strategy—if not included as a performance metric—should not be considered when choosing among strategies.

Step 3: Propose alternatives

Alternative strategies are the choices presented to decision-makers for achieving fundamental objectives. In the early rounds of an iterative SDM process, alternative strategies should represent a range of *different* actions (or combinations of actions) for addressing the fundamental objectives—not simply minor variations of a single idea. After the first round of analysis is completed and the most promising strategies identified, nuanced variations of these preferred strategies may be evaluated in greater detail.

In our case study, SDM participants identified three core actions for influenza mitigation:

- ISOLATE (stay-home-sick): A public education campaign run on local television channels to foster a habit and expectation of self-quarantine when persons are sick with influenza. The campaign would use peer pressure tactics similar to those shown to improve hand-washing compliance in healthcare facilities (Monsalve et al. 2014). The campaign's message would focus on the negative consequences for work colleagues, and ultimately for the bottom line of a business, when a person ill with influenza goes to work. The expectation is that employers and work colleagues may then be more inclined to persuade sick colleagues to stay away from work, for the good of other employees. Among the three core strategies, this is the only one expected to have obvious future benefits. Specifically, an effective stay-home-sick campaign could instill long-term good habits for reducing influenza spread. In addition, television commercial production would be a one-time cost—the commercials could be re-run in future years, only paying for air time.
- SUBSIDIZE: While the Affordable Care Act ensures private insurance and group health plans cover influenza vaccines with no cost-sharing, people who live below the federal poverty level may not have health insurance (they are not required to if their income is below the tax filing threshold). This core action would provide free influenza vaccination at county health centers and influenza walk-in clinics, to Fulton County residents living below the federal poverty level. This action would address a common public complaint that influenza vaccines are not affordable for poor people.
- SCHOOL: Multi-day vaccination clinics would be set up at each of the 250 elementary, middle, and high schools of Fulton County, to provide influenza vaccinations for interested students. Vaccination would be free for students living below the federal poverty level. Vaccinations at all schools would be completed by the end of the first month of the influenza season. This strategy would address public complaints about the cost of vaccines for poor people, and also complaints about inconvenient locations and hours of vaccination facilities.

The three core actions formed the basis for five alternative strategies considered in this case study, plus a baseline strategy representing the county's status quo roll-out of influenza mitigation actions (Table 3):

Table 3. Alternative strategies for influenza mitigation. *The six strategies considered in this case study (columns) each implement up to two core actions for influenza mitigation (row). For example, the 'Iso_Subsidize' strategy implements the ISOLATE education campaign (stay-home-sick) and SCHOOL vaccination clinics, as described in the main text.*

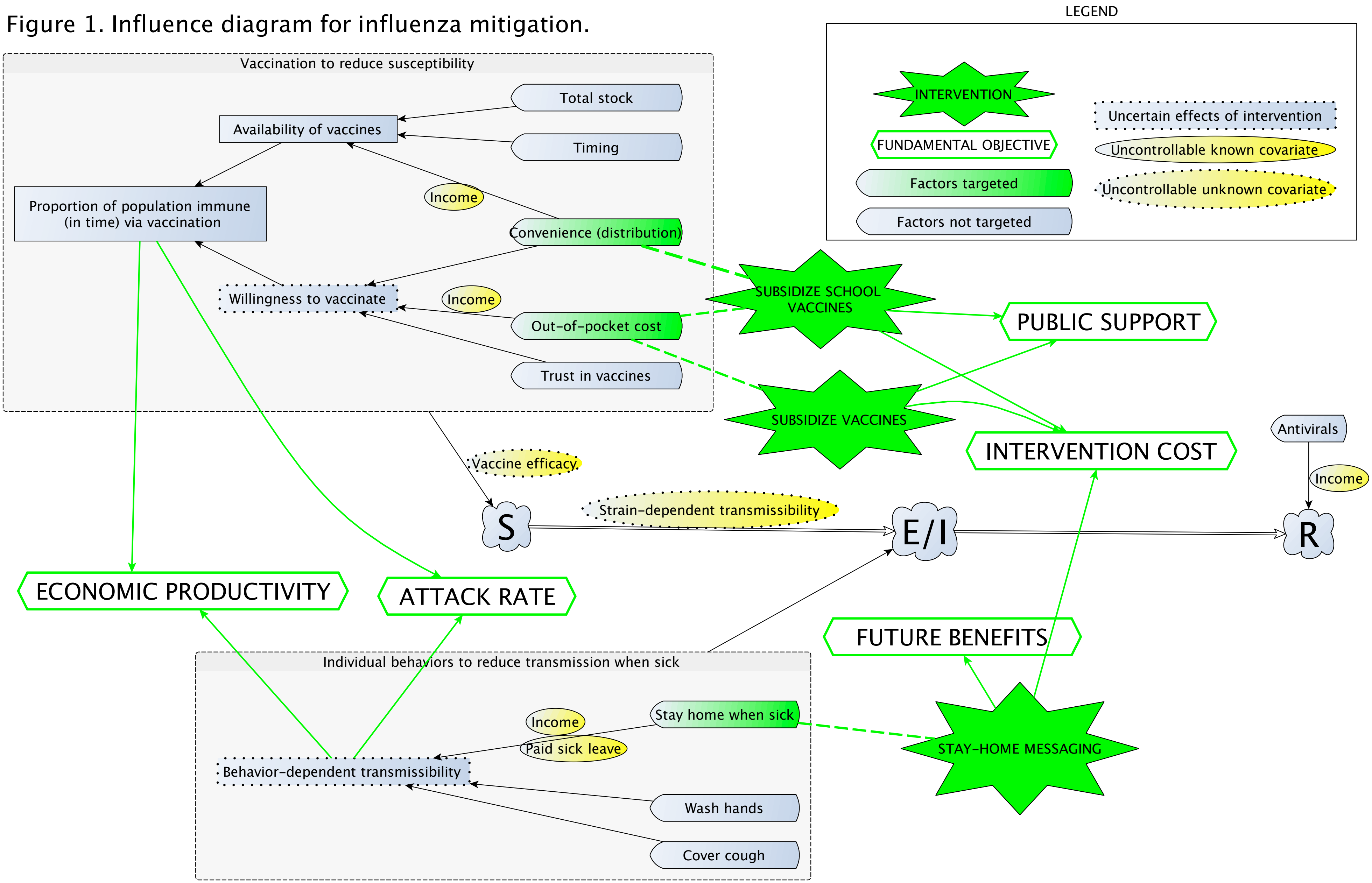
	Base	Isolate	Subsidize	School	Iso_Subsidize	Iso_School
ISOLATE		X			X	X
SUBSIDIZE			X		X	
SCHOOL				X		X

Part 2: Expert Elicitation and Simulation Modeling

The outputs from Part 1 of this tutorial are summarized in an influence diagram showing the relationships between fundamental objectives, core actions, human behaviors, and disease dynamics (Figure 1). After SDM participants agree on objectives and alternative strategies, the next step is to predict the consequences of each strategy with respect to each objective.

Influenza Influence Diagram

Figure 1. Influence diagram for influenza mitigation.



Information for predicting consequences may come from expert elicitation, prior studies, predictive modeling, or group deliberations and peer review. The predictions are summarized in a consequence table, which is used in trade-off analysis to identify a preferred strategy among those considered. Uncertainties in model parameters, model structure, and expert judgment should be explicitly structured into predictions, reflecting the risk tolerance of the decision maker. For example, if a decision maker has low tolerance for risk, then she may want to know the worst plausible consequence predicted for each strategy in addition to the most likely consequence.

In our case study, expert elicitation, group deliberations, and simulation modeling were used to predict consequences for six strategies with respect to five objectives. In addition, worst plausible consequences were estimated for all strategies except baseline. We defined worst plausible consequence as the boundary of a predicted 95% confidence interval (lower boundary if the goal was to maximize an objective; upper boundar if the goal was to minimize).

We also explored the potential effects of vaccine supply timing—an uncontrollable source of uncertainty—on predicted consequences with respect to two objectives, economic productivity loss and infected population. Specifically, in typical years, most vaccination providers in Fulton County (e.g., hospitals, county health centers, CVS and other pharmacies) are fully stocked with influenza vaccines just before the start of the season. But in some years timing is a couple weeks early or a couple weeks late. Therefore, simulation models evaluated consequences with early, typical, and late vaccine timing for all strategies.

Table 4 shows predicted consequences for the six strategies in this case study, assuming typical vaccine timing. In the next few pages I present methods and key outcomes from expert elicitation and simulation modeling that were used to generate this consequence table. Unless otherwise stated, results are the *most likely* predictions and assume *typical* vaccine timing. In Part 3, Step 6 (Evaluate uncertainties, limitations, and VOI) I compare these results to those for *worst plausible consequences*, and for *early* and *late* vaccine timing.

Table 4. Consequence table for influenza mitigation strategies, assuming typical vaccine timing. *'GOAL' is the desired direction of change for each fundamental objective (rows). For example, the preferred strategy should minimize weighted cost and maximize public support. Columns 3–8 are the alternative strategies. The numbers in the cells are predicted consequences of each alternative strategy, with respect to the fundamental objectives.*

OBJECTIVE	GOAL	Base	Isolate	Subsidize	School	Iso_Subsidize	Iso_School
Weighted cost	MIN	$14,829	$15,268	$13,508	$10,091	$14,004	$10,350
Infected	MIN	274	251	229	166	211	150
Public support	MAX	0%	0%	38%	54%	38%	54%
Future benefits	MAX	Yes	No	Yes	No	Yes	Yes

Step 4: Predict consequences—expert elicitation

Consequences for the first fundamental objective—implementation cost—were determined by budget experts (Table 5; detailed calculations in Appendix 1). For each strategy, implementation cost was then combined with a model-generated prediction of economic productivity loss to compute a weighted cost. The decision to use a weighted cost in the final consequence table was a value judgment that reflected the much higher importance that the Director placed on implementation cost, for selecting a preferred strategy.

Table 5. Estimated costs for each influenza mitigation strategy. *Columns 2–7 in this table are the alternative strategies. All costs are presented in units of $1000. For example, base implementation cost is $15,000 and base productivity loss is $59,256,000. Weighted cost was calculated by adding the full implementation cost to 25% of the economic productivity loss for each strategy.*

COST $(1000)	Base	Isolate	Subsidize	School	Iso_Subsidize	Iso_School
Implementation cost	$15	$170	$1128	$1109	$1298	$1279
Economic productivity loss	$59,256	$60,390	$49,522	$35,929	$50,824	$36,283
WEIGHTED COST	$14,829	$15,268	$13,508	$10,091	$14,004	$10,350

Public support and future benefit—the fourth and fifth objectives in the consequence table—were determined for each alternative strategy through deliberation and consensus among SDM participants. Consequence predictions for the remaining objectives—economic productivity loss and infected population—proceeded in two stages. First, social science epidemiologists were asked to use prior studies and their expertise to make predictions about the degree to which each strategy would influence people's risk behaviors related to influenza (Table 6; Kim and Yoo 2015; Shropshire et al. 2013; Suryadevara et al. 2014). Next, these expert judgments on human behavior were incorporated as parameters in a disease simulation model.

Table 6. Expert elicitation to predict behavioral responses to three core actions for influenza mitigation. *Five social science epidemiologists were independently presented with the following questions and asked to estimate the most likely response and a 95% confidence interval bound. Their responses were averaged and used to parameterize the disease simulation model.*

Question 1 (ISOLATE): Historically, averaged across the population of Fulton County, working persons who exhibit symptoms of influenza have a 55% chance of staying home from work. This estimate is similar for the probability a working person will stay home when his/her school-age child exhibits symptoms of influenza. How much do you think this percentage would change if we conducted a public education campaign to encourage people to stay home when sick (details of the televation campaign were provided to each expert)? (enter a value between 0% and 100)

EXPERT ID	lower 95%CI	most likely estimate	upper 95%CI
1	5%	12%	20%
2	10%	15%	25%
3	2%	10%	15%
4	8%	15	20%
5	10%	18%	25%
Average	7%	14%	21%

Question 2 (SUBSIDIZE): What percentage of people living below the federal poverty level do you think would get vaccinated if we provided the service free-of-charge at county health centers? (enter a value between 0% and 100%)

EXPERT ID	lower 95%CI	most likely estimate	upper 95%CI
1	28%	52%	64%
2	32%	60%	65%
3	23%	55%	72%
4	35%	65%	70%
5	32%	67%	75%
Average	30%	60%	69%

Question 3 (SCHOOL): What percentage of schoolchildren living below the federal poverty level do you

think would get vaccinated if vaccination clinics were set up in their schools and we provided the service free-of-charge? (enter a value between 0% and 100%)

EXPERT ID	lower 95%CI	most likely estimate	upper 95%CI
1	69%	85%	90%
2	68%	90%	93%
3	53%	89%	95%
4	58%	78%	91%
5	52%	90%	97%
Average	65%	86%	93%

Step 4: Predict consequences—simulation modeling

The social science epidemiologists made predictions about the probability that proposed actions could convince people (who wouldn't otherwise) to adopt behaviors that would reduce influenza transmission. Disease modellers then incorporated these behavior predictions in a simulation model to understand how they might impact influenza-caused economic productivity loss and infected population size.

The simulations in this case study were implemented using a spatially explicit, agent-based modeling platform (FRED, the Framework for Reconstructing Epidemiological Dynamics; Grefenstette et al. 2013). We simulated 23 influenza outbreak scenarios (6 mitigation strategies X 3 vaccine timings + worst plausible consequences for the 5 strategies excluding baseline = 23 scenarios). Each scenario was replicated for 150 runs. For each scenario we calculated the median person-days of missed work (for calculating economic productivity loss) and the median infected population size. We first describe general model parameters used in most model runs, then explain parameter changes for simulating specific strategies.

Agent daily behaviors

We incorporated a synthetic population dataset for Fulton County, GA, with a population size of nearly 1 million agents (RTI International 2010; Wheaton 2014). The agents in our model were classified by sex and age and mapped to household, school, and work locations, and employment and income distributions matching population patterns for Fulton County, GA, based on 2005–2009 data (U.S. Census Bureau 2010).

A model run began with 10 randomly selected agents infected on Day 1 and continued for a timespan of 200 days, with the movements, infection status, and disease transmission behavior of each agent recorded daily. On weekdays, schoolchildren and workers went to their schools and offices. On weekends, contacts primarily took place in neighborhoods, within 20 miles of home.

Influenza parameters

We retained the default influenza transmission parameters provided with the model. That is, our simulations employed a basic reproductive rate of R0 ~ 1.4, mimicking a severe influenza outbreak similar to the H2N2 Asian influenza of 1957–58 (Biggerstaff et al. 2014). We assumed agents did not retain immunity from prior year vaccinations.

A susceptible agent exposed to an infectious individual had some probability of getting sick. We used the default place-specific contact and disease transmission rates provided in the model (Grefenstette et al. 2013). These rates were calibrated to Ferguson et al.'s (2006) estimates that in the United States, 70% of influenza transmission occurs outside the home (33% in the community and 37% in schools and work places) and rates of contact are twice as high in schools compared to workplaces.

An exposed agent who proceeded to the infectious stage incubated the virus for an average of two days and was infectious for an average of seven days. Approximately 66% of infectious persons were symptomatic. A symptomatic schoolchild or worker had a 55% chance of staying home from school or work, and reconsidered the decision each day (s)he was symptomatic. Recovered individuals were immune to re-infection.

Vaccination parameters

We set model vaccination parameters based on CDC statistics of recent vaccine efficacy and coverage (CDC website, a, b). Approximately 50% of the simulated population was vaccinated for influenza. If the vaccination was effective, the person became immune to influenza approximately two weeks after vaccination. Vaccine efficacy was a random variable from a uniform distribution ranging from 0.40 to 0.65. Vaccine supply was not a limitation in our simulations (CDC website, c).

Parameter variations for alternative strategies

To simulate the alternative strategies in this case study, we varied vaccine availability and timing, ages prioritized for vaccines, and agent decisions regarding self-quarantine and vaccination (Table 7). Parameter estimates for self-quarantine and vaccination choice were calculated from predictions by social science epidemiologists regarding people's response to proposed strategies (Table 6). For example, experts predicted that if vaccination were provided free for persons living below the federal poverty level, 60% of those persons (who probably wouldn't otherwise get vaccinated) would choose to get vaccinated. Considering that approximately 18% of the Fulton County population lives below the federal poverty level (U.S. Census Bureau 2010), this strategy was predicted to increase vaccination coverage from 50% to 61%.

Table 7. Simulation model parameters that differed among considered alternatives, assuming typical supply timing. *Values in parentheses were calculated from the lower bound of expert-predicted 95% confidence intervals, representing worst plausible cases for each scenario. For simulations of early vaccine supply timing, we shifted vaccine availability earlier by two weeks; for late vaccine supply timing, shifted later by two weeks (parameter changes not shown in table).*

PARAMETER	Base	Isolate	Subsidize	School	Iso_Subsidize	Iso_School
Probability of staying home when symptomatic	55%	61.3% (58.15%)	55%	55%	61.3% (58.15%)	61.3% (58.15%)
Younger ages prioritized for vaccines	No	No	No	Yes	No	Yes
% of population vaccinated (not all successfully)	50%	50%	61.5% (56.3%)	55.5% (53.5%)	61.5% (56.3%)	

Simulation model results

Simulation models were used to estimate economic productivity loss and infected population size for alternative strategies and early, typical, or late vaccine supply timing. The key findings from simulations were:

- School vaccination strategies had the lowest predicted values for economic productivity loss and infected population (Figures 2–4). The outcomes for these two fundamental objectives were often related because the fewer people infected, the fewer missed work days.
- Providing free vaccination for the poor had very little impact on economic productivity loss and infected population size, with results similar to baseline.
- Vaccine supply timing generally did not change the relative ranking of results. The exception was that school vaccination with early vaccine timing generated unusual results—only 31 (21%) of 150 simulation replicates led to influenza outbreaks (Figure 5). Cases of NO OUTBREAK seemed to occur when infection was unable to establish at schools in the first couple weeks of the influenza season. If an

infection was able to establish at schools during this initial period, then transmission at schools seemed to sustain a regular influenza season.

Figure 2. S-E-I-R dynamics, assuming typical vaccine timing. *S-E-I-R dynamics for baseline and three alternative strategies. Results for vaccine subsidizing strategies are not shown because they were the least effective, with results similar to baseline. Each figure represents the results from 150 simulation replicates.*

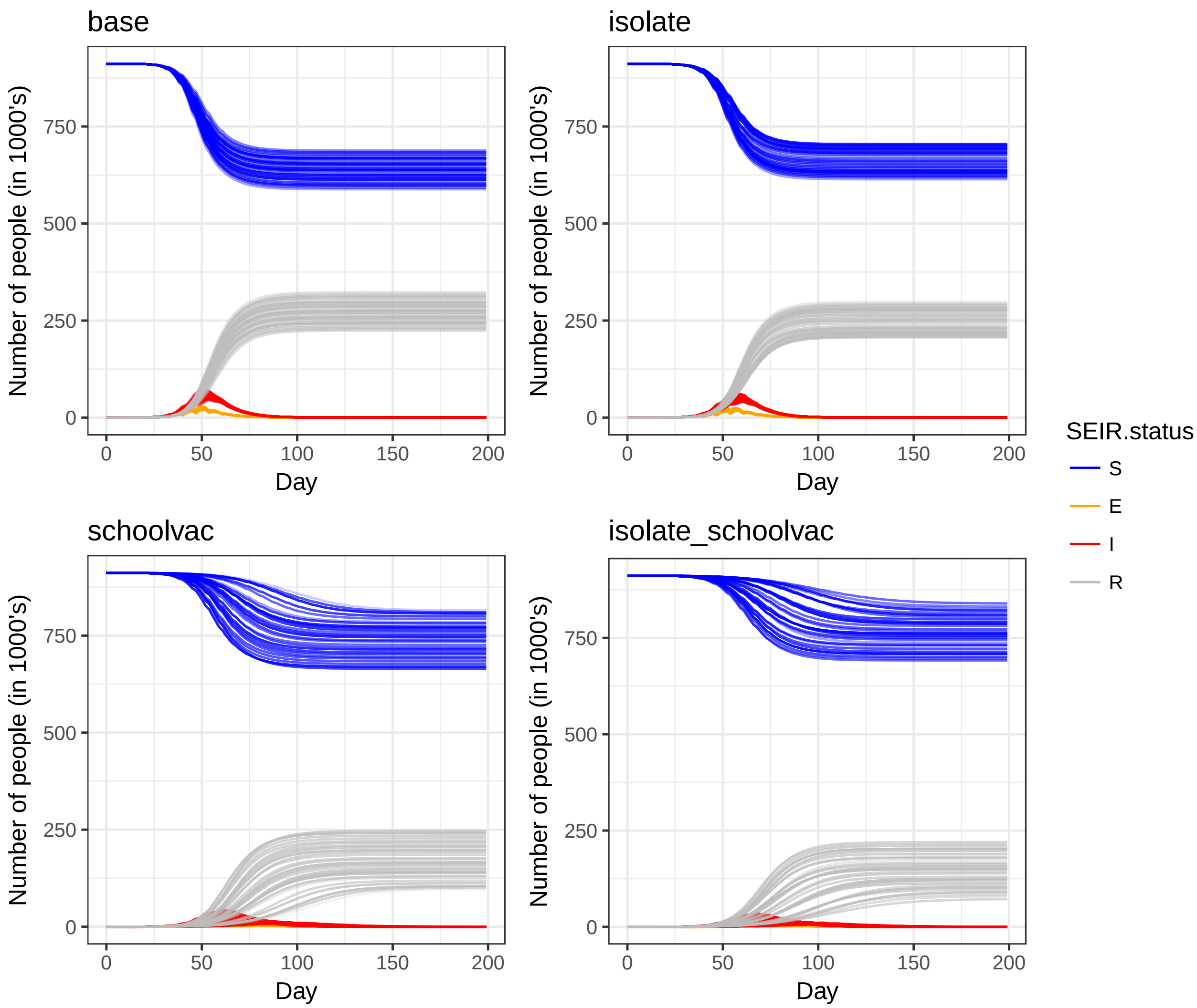


Figure 3. Infected population size. *Model-based predictions of infected population size for considered strategies (x-axis). The three vertical facets show results for early (left), typical (middle), and late (right) timing of vaccine supply. Each boxplot shows the results from 150 simulation replicates.*

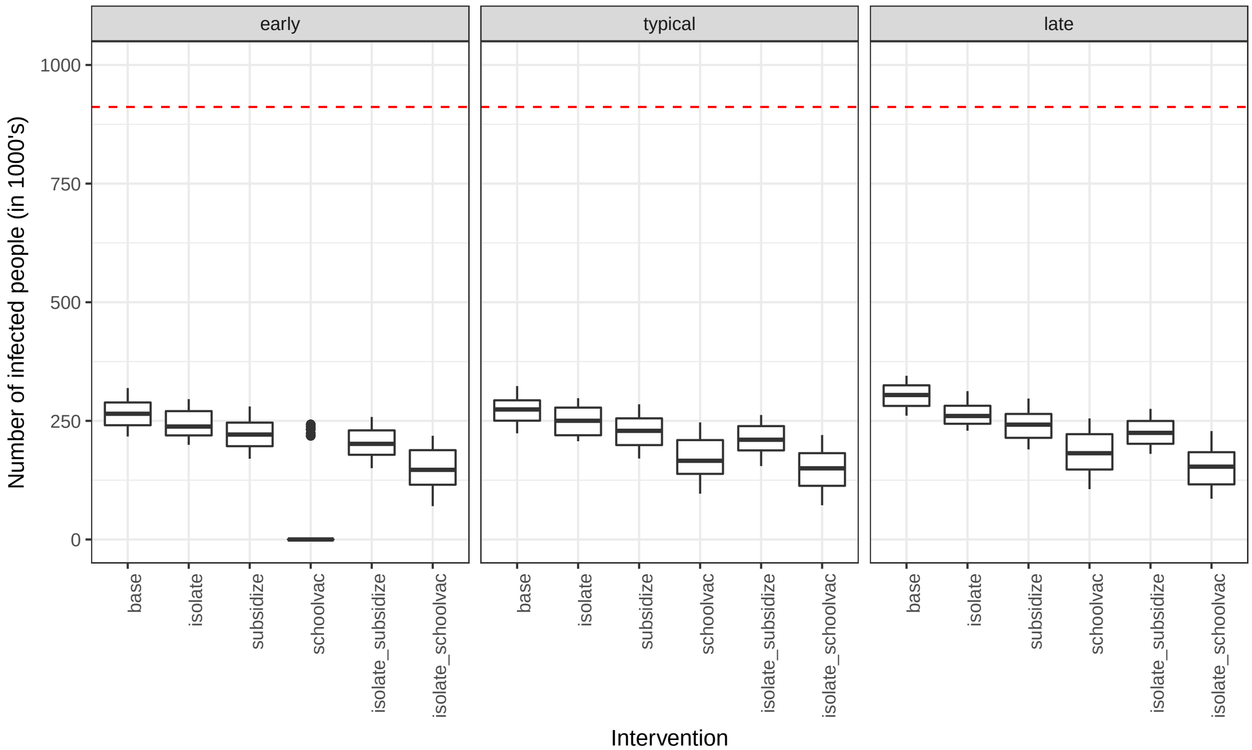


Figure 4. Economic productivity loss. *Model-based predictions of economic productivity loss (person-days of missed work X median daily wage, $191) for considered strategies (x-axis). The three vertical facets show results for early (left), typical (middle), and late (right) timing of vaccine supply. Each boxplot shows the results from 150 simulation replicates.*

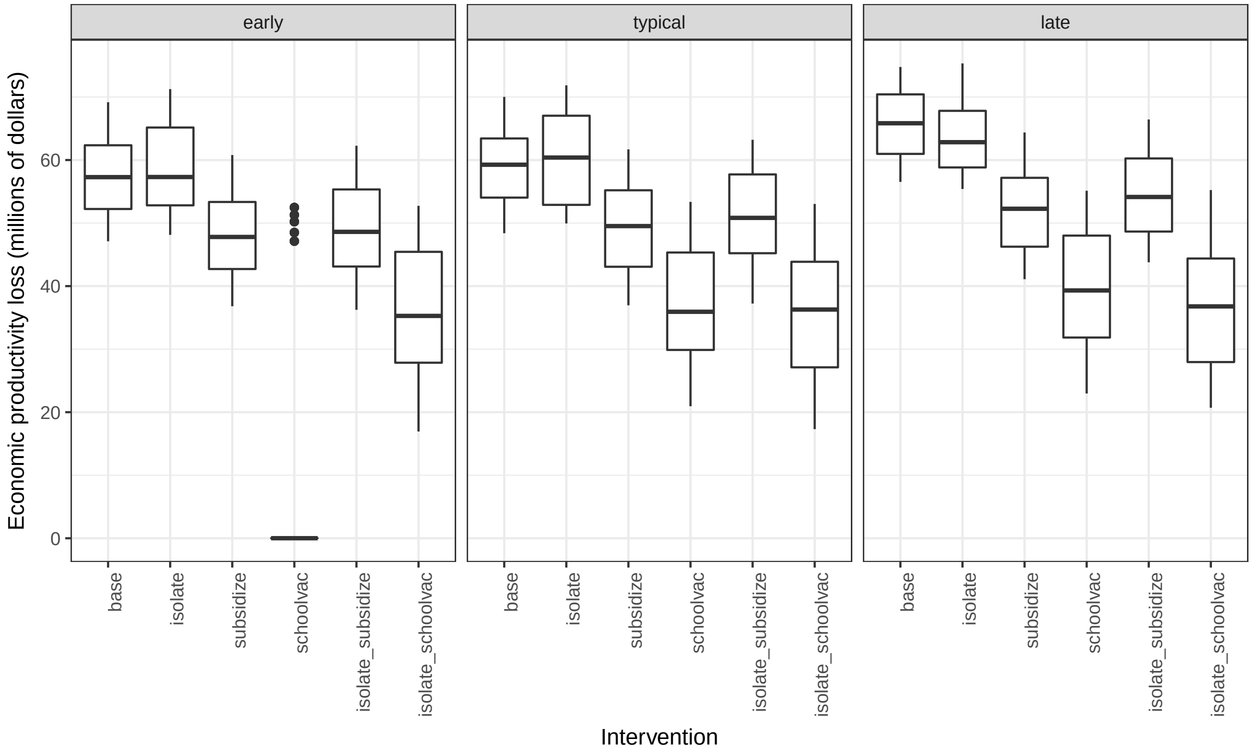
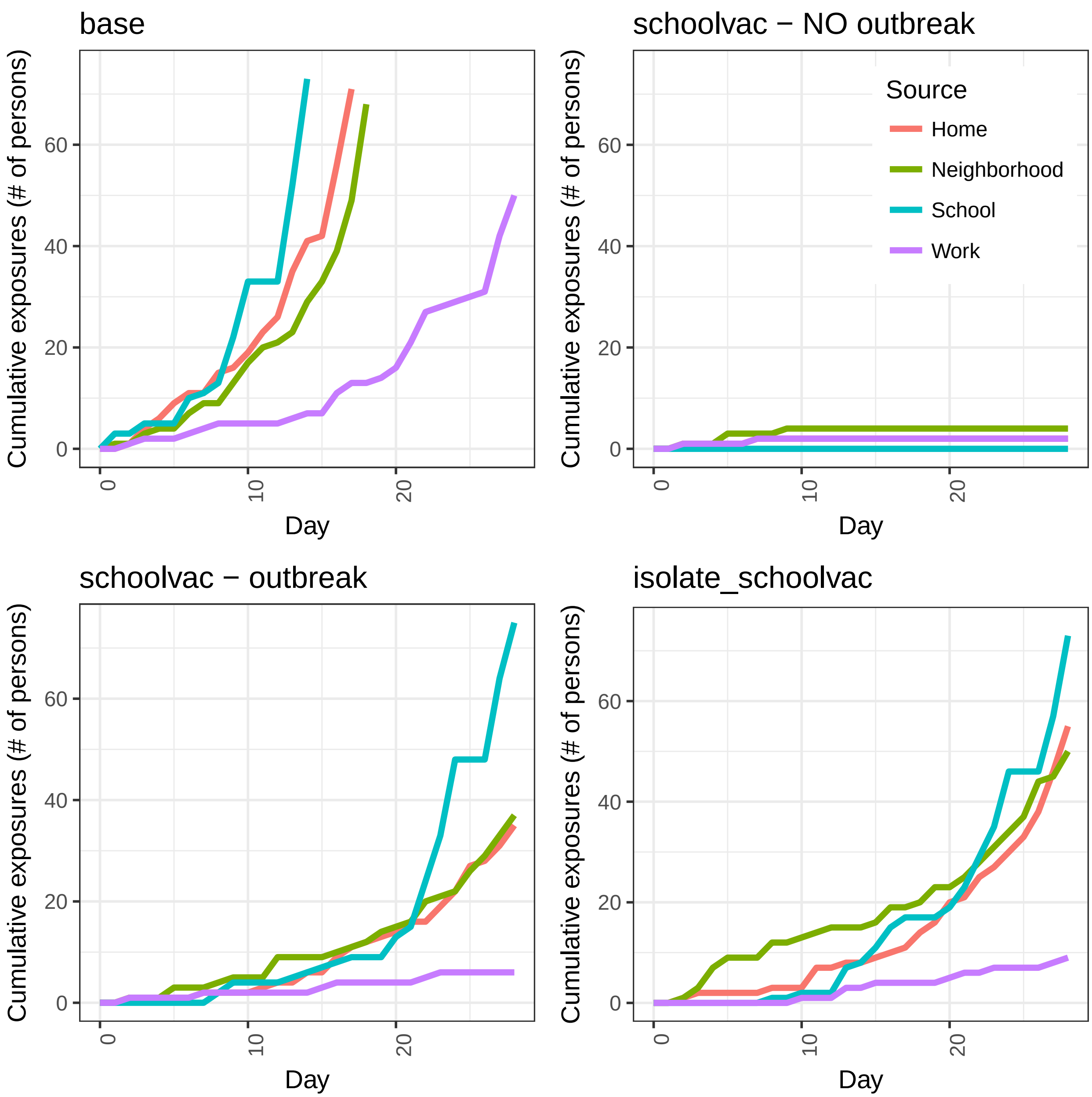


Figure 5. Comparison of cumulative disease exposure by source, assuming early vaccine timing. *Each line shows the cumulative number of new exposures for each source location, over the first 25 days of the influenza season. For example, the top left figure shows a single simulation replicate of the base scenario, for early supply timing. By Day 14, more than 70 persons had been exposed to influenza while at school (aqua blue line). Two simulation runs are shown for the school vaccination strategy—one in which an outbreak occurred (bottom left) and one in which no outbreak occurred (top right).*



Part 3: Multi-attribute trade-off and sensitivity analyses

Results from expert elicitation, simulation modeling, and other methods for predicting consequences may each provide insight into preferred alternatives with respect to particular objectives. But to make a decision on a preferred alternative, a decision maker needs to consider strategy performance across ALL the fundamental objectives simultaneously. How can she identify an optimal solution when she must judge strategies based on sometimes competing objectives with very different performance measures? This is the stage of SDM where a decision maker makes explicit her values and decides how much of one objective she is willing to sacrifice for another. She should also consider the robustness of the preferred alternative to prediction uncertainties, model or data limitations, and subjective weighting decisions.

Steps 5 & 6: Evaluate trade-offs and uncertainties

When decisions involve multiple attributes that cannot be easily compared on a single scale, it is useful to first simplify the decision to a smaller set of alternatives. Simplifying a consequence table entails:

1. Identifying and removing dominated alternatives and practically dominated alternatives
2. Identifying and removing insensitive performance measures
3. Conducting even swaps, if possible

In SDM, a dominated alternative is one in which another alternative performs equally well or better for all objectives. We can eliminate dominated alternatives from the decision process because they cannot possibly be the preferred alternative. Swing weighting and multi-attribute trade-off (MATO) analysis can be used to complete trade-off evaluations on a simplified consequence table, and also to conduct sensitivity analyses on full or simplified consequence tables.

Swing weighting and MATO analysis are quantitative approaches to weight the relative importance of the various fundamental objectives for making a decision, giving attention to differences in how much the score for each objective may vary across considered alternatives. For example, if the cost difference between the least and most expensive disease mitigation strategies is $2 million, and all mitigation strategies have fairly similar predicted infected population sizes, then cost might be a more important objective for selecting among considered strategies than infected population size in this case. After objectives are normalized to a scale of 0 to 1 by their relative importance, a weighted average can be calculated for each alternative strategy, using the normalized objective values as weights. The higher the weighted average of a strategy, the more preferred it is.

We use our case study to show how to simplify a consequence table to identify the highest ranked alternatives. We do not demonstrate swing weighting and MATO analysis in this tutorial, but instead provide explanations in a Shiny app created for implementing these methods with the case study data. User instructions for running the app are also provided in the app itself. We used the Shiny app to evaluate sensitivity of case study results to prediction uncertainties and different objective weighting schemes. These results are presented in the final section of this tutorial.

Simplify the consequence table

Simplifying a consequence table can sometimes yield (or nearly yield) a preferred strategy. For example, in our consequence table we had four dominated alternatives that could be removed without further analysis. These dominated alternatives were Base, Isolate, Subsidize, and Iso_Subsidize (Table 8). They were dominated because the Iso_School strategy performed equally well or better than these strategies for all five fundamental objectives. Once we removed the dominated alternatives, the fundamental objective Public Support became an insensitive performance measure. That is, there were only two alternatives left (School and Iso_School) and they both had the same predicted consequence for Public Support (54%). Therefore, this objective could be deleted from the consequence table.

We further simplified the table by combining two objectives—weighted cost and infected population—into a single metric of cost per uninfected person (an 'even swap' because two performance measures were combined into one). Note that we first converted infected persons to uninfected persons, because cost/uninfected person makes more sense as a metric. The final simplified consequence table identified School and Iso_School as highly preferred alternatives that differed only in per capita weighted cost and in predicted future benefits.

Table 8. Simplifying the consequence table. *Originial consequence table, shown again for reference. Remove four dominated alternatives and one insensitive performance measure.*

OBJECTIVE	GOAL	Base	Isolate	Subsidize	School	Iso_Subsidize	Iso_School
Weighted cost	MIN	$14,829	$15,268	$13,508	$10,091	$14,004	$10,350
Infected	MIN	274	251	229	166	211	150
Public support	MAX	0%	0%	38%	54%	38%	54%
Future benefits	MAX	Yes	No	Yes	No	Yes	Yes

The simplified consequence table. Merge weighted cost and uninfected population into a single metric of cost/uninfected.

OBJECTIVE	UNITS	GOAL	School	Iso_School
Weighted cost	$(in 1000's)	MIN	$10,091	$10,350
Infected	# people (in 1000's)	MIN	166	150
Future benefits	1=Yes; 0=No	MAX	No	Yes

The final simplified consequence table.

OBJECTIVE	UNITS	GOAL	School	Iso_School
Weighted cost/Uninfected	$ per person	MIN	$13.53	$13.58
Future benefits	1=Yes; 0=No	MAX	No	Yes

Swing weighting and MATO analysis If many alternatives remain after simplifying the consequence table as much as possible, swing weighting and MATO analysis can assist with choosing among the final alternatives. These methods are also useful for conducting sensitivity analysis on full or simplified consequence tables. We conducted swing weighting and MATO analysis in the Shiny app to evaluate the full consequence table and also to explore the robustness of our results to these questions (Table 9):

1. How does cost weighting influence results?
2. How does timing of the vaccine supply influence results?
3. How does swing table weighting of objectives influence results?
4. How does expert prediction uncertainty influence results?

Table 9. Results from swing weighting and MATO analysis to explore robustness of results. *We addressed the four questions above by modifying the analysis (either during the simulation modeling or swing weighting stage) as shown in the 'Analysis modification' column. We present the preferred alternative for the modified analysis.

Referenced question	Analysis modification	Preferred alternative
1. Cost weighting	Implementation = 1, productivity = 0.25	Iso_School
	Implementation = 1, productivity = 0	Iso_School
	Implementation = 1, productivity = 1	Iso_School
2. Vaccine timing	Vaccines on typical timing	Iso_School
	Vaccines available two weeks early	School
	Vaccines available two weeks late	Iso_School

Referenced question	Analysis modification	Preferred alternative
3. Swing table weighting	Weighted cost & number infected scored much higher than other objectives	
Iso_School		
	All objectives equally weighted	Iso_School
4. Expert prediction uncertainty	Used worst plausible prediction for ISOLATE core action	Iso-School
	Used worst plausible predictions for ISOLATE and SCHOOL core actions	School
	Used worst plausible predictions for SCHOOL core action	Iso-School

Conclusions

We determined from our SDM analysis that the proposed school-focused vaccination campaign, combined with the stay-home-sick isolation campaign (Iso_School strategy) may be a very effective influenza mitigation strategy robust to uncertainties about human behavioral responses and robust to different cost and objective weighting schemes. In all cases where Iso_School is the highest ranked alternative, School is a close second. In a few cases, School outperforms Iso_School.

One notable scenario in which School FAR outperforms other alternatives is when vaccines are available two weeks earler than usual. In our simulation model of this scenario (early vaccines + School strategy), an influenza outbreak did not occur in the majority of simulation replicates. This unusual finding points out a weakness in our decision analysis—the predicted consequences for two very important fundamental objectives (economic productivity loss and infected population size) come from a single simulation model. Similar to using predictions from multiple social science epidemiology experts, we could have generated predictions from different model structured and compared or combined results. Swing weighting and MATO analysis are also well-suited for determining sensitivity of results to different model structures.

This tutorial presents results from the first-round decision sketch of our Fulton County influenza case study and points to further avenues for exploration. Specifically, a subset of highly ranked alternative strategies should now be evaluated using other simulation model structures to determine if results are robust to model choice. Results could provide important insights not only for this case study decision, but also for future application of SDM to model-based public health decisions.

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APPENDIX 1:

Estimated implementation costs

Implementation costs were estimated for three core actions (ISOLATE, SUBSIDIZE, SCHOOL) underlying the various alternative strategies considered in this case study:

(from Table 3 in main text). Alternative strategies for influenza mitigation. *The six strategies considered in this case study (columns) each implement up to two core actions for influenza mitigation (row). For example, the 'Iso_Subsidize' strategy implements the ISOLATE education campaign (stay-home-sick) and SCHOOL vaccination clinics, as described in the main text.*

	Base	Isolate	Subsidize	School	Iso_Subsidize	Iso_School
ISOLATE		X			X	X
SUBSIDIZE			X		X	
SCHOOL				X		X

For strategies (e.g., Iso_School) that combined two core actions, cost was the sum of the costs for individual actions. In a real SDM setting, budget analysts or other relevant experts would provide cost estimates.F or this tutorial, costs were determined from internet research.

Cost for ISOLATE (stay-home-sick public education campaign): $167,500

$40,000 for production of two 30-second TV commercials
$127,500 for 150 runs of commercial on local TV stations @ $850 per run

Cost for SUBSIDIZE (free vaccination for persons living below the federal poverty level): $1,127,676

$1,127,676 for subsidized vaccines. According to the U.S. Census Bureau (2010), 17.7% (N=156,622 people) of the population of Fulton County lived below the federal poverty level during 2005–2009. In our case study, social scientist epidemiologists estimated 60% of the poor in Fulton County (N=93,973 people) would take advantage of free vaccinations. The wholesale cost of the influenza vaccine is approximately $12 each. The estimated implementation cost is 93,973 subsidized vaccines X $12 per vaccine = $1,127,676

Cost for SCHOOL (vaccination clinics at 250 elementary, middle, and high schools in Fulton County and free vaccination for students living below the federal poverty level): $1,109,436

$584,268 for subsidized vaccines. Based on U.S. Census Bureau (2010) data, 26.7% (N=56,615) of school children in Fulton County lived below the federal poverty level in 2005–2009. In our case study, social scientist epidemiologists esimated 86% of these poor school children would take advantage of free vaccinations at their schools. The cost of subsidized vaccines is estimated at 48,689 vaccines X $12 per vaccine = $584,268

$525,168 for nurse salaries. In Fulton County, the median salary for a public health nurse is $75,000 per year (an hourly salary of $36). Assuming school nurses would help with logistics and administering vaccinations at their own schools and based on predicted number of students who would get vaccinated (@10 minutes per vaccination), the estimated cost of additional nurses is 14,588 nurse-hours @ $36 per hour = $525,168

Estimated economic productivity loss

Loss of economic productivity was estimated as the number of person-days of missed work due to influenza, determined from the simulation model (Appendix 3), parameterized with expert predictions about human behavior (Table 5). The person-days of missed work includes working adults who would stay home to take care of a sick child (< 15 years old) in a single parent household. The information on % of working population and % of single parent households in Fulton County came from census data (U.S. Census Bureau 2010).

The median daily wage for a working adult in Fulton County is $191. This value was used to convert person-days of missed work to a measure of economic productivity loss.

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