Teaching Policy Modeling with Simulation Software

I. David Wheat
Associate Professor of System Dynamics
University of Bergen, Norway
david.wheat@uib.no

Abstract

This paper discusses an instructional method that enables students from diverse cultural backgrounds to use system dynamics simulation modeling software as a tool for policy analysis. The method also enables students to transform and clarify their mental models of policy issues. The focus in this paper is on two courses taught by the author—The Modeling Process and Policy Design & Implementation—that are part of the core curriculum of an international graduate program in system dynamics at the University of Bergen in Norway. The primary learning objective of the modeling process course is for students to build explanatory models; i.e., models that use causal, operational variables to simulate problematic behavior that has been observed historically (e.g., trends in unemployment, a flu epidemic, emigration, pollution). In the second course, students learn to craft and test feasible policy options, compare alternatives in terms of expected costs and benefits, and create interactive simulators to aid communication of model-based policy options to public officials and staff. A simple health policy issue is used to illustrate the method.

Teaching Policy Modeling with Simulation Software

This paper is about teaching students to use quantitative modeling to simulate problematic behavior that emerges from complex social and economic systems. It is also about teaching students to transform such *explanatory* models into *policy* models that enable assessment of proposals to alleviate a problem through system intervention. I focus on two courses—*The System Dynamics Modeling Process* and *Policy Design & Implementation*—that are part of the core curriculum of an international graduate program at the University of Bergen in Norway.

The International Masters Program in System Dynamics was established within the Social Science Faculty in 1995 under the leadership of my colleague, Pål I. Davidsen. A PhD program was launched a few years later. The first master's degree was awarded in 1997 to a student from Ghana, and the first PhD was awarded in 2001 to student from Egypt. Approximately 120 master's degrees and 13 doctoral degrees have been awarded, with more than 90 percent earned by students from outside of Norway. International diversity remains a hallmark of our program; last year's class of 40 students came from 27 different countries.

The core masters curriculum consists of six courses during the first year and a thesis during the second year. During the fall semester of the first year, we teach our foundation courses in system dynamics modeling: *Principles of Dynamic Social Systems*, *Model-based Analysis and Policy Design*, and *The System Dynamics Modeling Process*. The three spring courses are *Policy Design and Implementation, Experimental Methods in Social Systems,* and *Model-based Socioeconomic Planning*. Second-year thesis topics tend to cluster around our research interests: economic development, health policy, natural resource management, energy and climate change, macroeconomics, and demographic issues such migration, fertility, mortality, and aging. Thesis work typically includes developing a simulation model of the system believed responsible for the dynamic problem under study, plus an evaluation of structural changes ("policy options") that might enable the model to generate more desirable behavior patterns.[1]

In addition, the University of Bergen is one of four partner institutions in the European Master (EM) Program in System Dynamics, (http://www.europeansystemdynamics.eu) a joint study program with European Commission scholarship funding for European and non-European students. Our partners include Radboud University Nijmegen in the Netherlands, the University of Palermo in Italy, and the New University of Lisbon in Portugal. The EM students begin their studies in Bergen, where they take our foundation courses during the fall semester. They move on to either Palermo or Lisbon in the spring, with the choice depending on their preference for public management or sustainability issues. The second fall semester reunites all EM students in Nijmegen, where they develop *group* model-building skills in issue settings that involve interaction with diverse stakeholders. During the last semester of the two-year program, EM students write their theses at one of the four universities.[2]

The rest of the paper is organized into four sections, with the first addressing the issue of teaching students to use models in policy analysis. Two sections describe my courses and

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[1] Evaluation includes feasibility considerations.

[2] The EM degree depends on the choice students make during the second semester—whether to go to Portugal or Italy. Students going to Portugal will receive a multiple degree from the New University of Lisbon, the University of Bergen, and Radboud University Nijmegen. Those choosing Italy will receive a joint degree from the University of Palermo and the University of Bergen, plus a double degree from Radboud University Nijmegen. Some legislative and institutional hurdles remain before a three-way joint degree becomes a possibility.

teaching method. Finally, a simple model of an important public health issue—flu epidemics—is used to illustrate the policy modeling approach.

Models in Policy Analysis

The most common type of model is what cognitive psychologists call a *mental* model. One way or another, everyone relies on mental models every day, usually without much self-awareness. Rouse and Morris (1986, p.351) describe mental models as “the mechanisms whereby humans are able to generate descriptions of system purpose and form, explanations of system functioning and observed system states, and predictions of future system states.” Johnson-Laird (1983) associates the origin of the mental model concept with Craik’s (1943) suggestion that the human mind can construct “small-scale models” of reality for the purpose of understanding, explaining, or anticipating events in the real world.

The power of entrenched mental models to influence policy analysis was a central point in Allison’s (1969, 1971) study of the Cuban missile crisis, although he preferred labels like “conceptual model” or “conceptual lens” to describe the mechanisms whereby foreign policy analysts describe, explain and predict.

> What each analyst sees and judges to be important is a function not only of the evidence about what happened but also of the "conceptual lenses" through which he looks at the evidence. … Analysts think about problems of foreign and military policy in terms of largely implicit conceptual models that have significant consequences for the content of their thought. … Explanations produced by particular analysts display quite regular, predictable features. This predictability suggests a substructure. … The first proposition is that clusters of such related assumptions constitute basic frames of reference or conceptual models in terms of which analysts both ask and answer the questions: What happened? Why did the event happen? What will happen? (Allison, 1969, pp. 689-690)

Of course, mental models are imperfect approximations of perceptions of reality; and the perceptual errors are most serious in the context of dynamic systems. Research on misperception of feedback (Sterman 1989 and Moxnes 1998) underscores the difficulty encountered by people who rely exclusively on mental simulation to anticipate the behavior of even simple dynamic systems. The findings suggest the need for more formal models and lend support to Bardach's (2005, p. 17) assertion that policy analysts will find a "good causal model ... especially [useful] … when the problem is embedded in a complex system of interacting forces, incentives, and constraints—which is usually the case."

Our instructional challenge is to help students (aka, future policy analysts) achieve greater congruence between their mental models and the corresponding real-world *dynamic* processes. Our goal is to equip students with tools that enable conscious and effective renovation of mental models-in-use. We want students to be aware of their preconceived mental models and have tools for deliberate reconstruction and—hopefully—improvement in their habits of mind. We contend that a method that analyzes dynamic problems while improving mental models is a useful addition to the policy analyst's toolkit. To that end, we offer simulation modeling—in particular, the system dynamics method of explanatory and policy modeling—as a learning tool as well as a tool for analysis.

The pedagogical potential of system dynamics modeling was suggested by Forrester's (1994) assertion that system dynamics is a "framework into which facts can be placed [so that] learning becomes more relevant and meaningful." That echoes Bruner's (1960) emphasis on the pedagogical significance of placing details into a "structured pattern" lest they be forgotten or their meaning slip away. In addition, claims about the learning value of the system dynamics framework are supported by results from controlled experiments involving macroeconomics students (Wheat 2007 and 2010b).

Modeling Process Course

The System Dynamics Modeling Process is the third foundation course offered during the fall semester at Bergen. Course meetings include 36 lecture hours and 18 hours of computer lab assistance over a six-week period (two lectures and one lab per week) from the end of October until early December. Mandatory assignments include a modeling project (a written report, a simulation model, an interactive learning environment, and a presentation) and a 4-hour written exam. To earn credit for the course, passing grades must be attained on both the project and the exam.

In this course, students apply, reinforce, and extend the insights and skills gained in the earlier courses. Particularly important is that they bring to this course an understanding of how certain stock-and-flow structures can generate familiar modes of behavior (growth, decay, oscillation, overshoot, and collapse), an understanding of how nonlinear feedback effects can shift driving forces within a model and change behavior modes endogenously, and an understanding of consequences of delays within a system. Before the *Modeling Process* course, students should also become well acquainted with the simulation software and proficient in the formulation of commonly-used model equations.[3] The primary learning outcomes in this course can be grouped into a few categories:

Expressing knowledge and understanding. Students should be able to
- describe in detail the system dynamics modeling process;
- explain how to use the software for designing, formulating, & explaining models.

Applying knowledge and understanding. Students should be able to
- quantify and interpret the dynamics of a problem;

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[3] The primary instructional software is *iThink*, a product of isee systems inc. (www.iseesystems.com). Students also gain exposure to *Vensim* (www.vensim.com) and *Powersim* (www.powersim.com).

- formulate a model as a hypothesis that could explain problematic dynamic behavior;
- analyze and test a model to improve its reliability and usefulness;
- analyze a model's structure to discover the endogenous sources of dynamic behavior;
- identify and evaluate potential leverage points for improving model behavior;
- demonstrate software proficiency in designing, formulating, & explaining models;
- research a real-world dynamic problem with a six-week empirical and theoretical investigation, culminating in an explanatory model containing exploratory policy analysis, presented orally and in a written report.

Making Judgments. Students should be able to

- use a client's perspective to evaluate the definition of a problem, the boundary of a model, and the model's reliability and usefulness;
- establish and evaluate criteria for evaluating how well a model structure contributes to the explanation of an observed or hypothesized dynamic behavior;
- assess data requirements in light of a model's sensitivity to parameter estimates;
- anticipate and recognize policy implementation obstacles for a particular policy option;
- specify the limitations of a particular model.

Communicating. Students should be able to

- organize a written discussion of a modeling project in a way that highlights the research problem or question, the hypothesis, the method of analyzing and testing the hypothesis, and the policy implications of the investigation;
- make oral presentations of their work;
- design and present models in a way that facilitates communication and understanding;
- translate technical information into language that clients understand.

Modeling Project. The overarching objective in the *Modeling Process* course is that students learn to build models of real-world problems; i.e., models that use causal, operational variables to simulate problematic behavior patterns that have been observed during an historical time period (e.g., trends in unemployment, a flu epidemic, emigration, pollution). In this course, a semi-independent modeling project is the vehicle for development of student skills, as well as the primary means of assessment of student modeling skill and proficiency.

Students work in pairs. Each pair submits a joint paper and model, and makes a joint presentation during the last week of the course. An external examiner evaluates the project, and the grade counts as fifty percent of the course grade. Successful project completion is a prerequisite for taking the written exam.

Students are expected to follow a structured process for modeling dynamic problems by engaging in an iterative process that includes four activities:

- Defining a problem in terms of dynamic behavior patterns.
- Developing a model-based explanation of the problematic behavior.
- Formulating, testing, analyzing, and revising the model.
- Conducting exploratory policy analysis.[4]

Recent topics include

- unemployment in Spain
- stray dogs in Taiwan
- debt crisis in Greece
- coffee prices in Colombia
- doctor shortage in Malawi
- emigration from Lithuania
- adolescent obesity in Mexico
- herring fishing in Norway
- cocaine in Portugal
- bribery in Russian universities
- auto pollution in Zimbabwe
- wolf population in Norway
- urban transportation in China
- AIDS epidemic in Tanzania
- population aging in China
- traffic congestion in Jakarta
- deforestation in Pakistan
- malaria in Ghana
- fertility rates in Uganda
- pension program in Germany

An additional requirement is that the research problem must be similar to one that has been previously studied with a different methodology (e.g., agent-based modeling or econometrics), so students will have a basis for comparing system dynamics with an alternative approach.

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[4] The method is described in textbooks such as Randers (1980), Richardson and Pugh (1989), Coyle (1996), Sterman (2000), and Ford (2010).

Twenty projects (40 students working in pairs) require extensive supervision by the instructor, even with the help of two teaching assistants. Drafts of each report and model are reviewed weekly and consultations are sometimes necessary. It is also an intense period for the students because the six-week project is essentially a compressed version of a thesis. In the end, successful completion of the report, proud explanation and demonstration of the model, and a jargon-free slide presentation combine to produce a considerable sense of accomplishment.

Policy Design and Implementation Course

Policy Design and Implementation is offered during the spring semester at Bergen. The schedule structure of this course is identical to the *Modeling Process* course—six weeks in length, with two lectures and one lab per week. There is also a major project and a written exam, each of which must be passed to earn course credit.

This course embraces a key purpose of system dynamics modeling: improving the behavior of social systems by designing feasible, cost-effective, and transparent public policies with minimal adverse unintended consequences. Students gain experience using a structured method for policy design and evaluation that reflects an informed view of institutional and cultural constraints on policy feasibility and outcomes, including costs and benefits. Students also develop skills for interacting with those for whom the modeling work is done, including elicitation of information about the dynamic problem, relevant organizational procedures, and potential obstacles to implementing new policies.

The focus is on the second stage of the modeling process—policy design—which involves restructuring an explanatory model in ways that can alleviate its problematic behavior.

The primary learning outcomes of *Policy Design and Implementation* include deeper understanding and higher proficiency with respect to the knowledge and modeling skills previously listed for the *Modeling Course*. Additional learning outcomes include:

- recognizing the political, organizational, and cultural influences on policy feasibility;
- learning the theory and method of cost-effectiveness analysis;
- assessing whether simulated policy options are cost-effective and feasible;
- evaluating implementation obstacles & modifying expected cost/effects accordingly;
- designing and evaluating an interactive learning environment to facilitate communication of policy insights and implementation requirements.

Implementation Project. Again, a modeling project is used to extend a student's capacity for learning. Students are required to select from the published literature a peer-reviewed model that contains little or no policy design. For example, the published model may be only explanatory and make no claim to policy insights. Or, perhaps analysis in the original published model is limited to parameter testing; i.e., no policy-motivated structural changes in the model have been tested. After translating the original explanatory model into *iThink* software language, replicating the original behavior, and thoroughly analyzing the model, the students complete a two-fold assignment. First, they design a policy for the original model. Second, they develop an interactive learning environment as a communications tool for explaining their revised policy model.

The next section illustrates the policy modeling process, beginning first with an explanatory model. Screen shots give some impression of the design and components of the interactive learning environment. The data and model are derived from a classroom simulation of an epidemic transmitted by human contact.

Example: Policy Model for the Epidemic Simulation Game

The first lecture of the *Modeling Process* course begins with a physical simulation game. The purpose of the game is to illustrate in one session what is meant by:

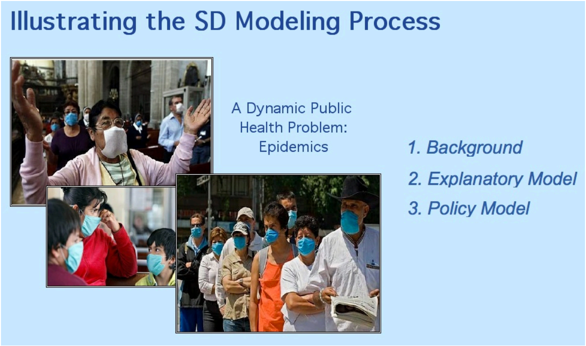
… identifying the dynamics of a problem,

… developing a dynamic hypothesis,

… formulating and simulating a model,

… testing a model,

… designing policies.

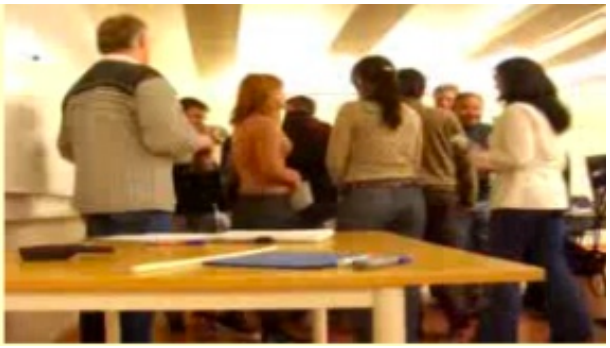


Illustrating the SD Modeling Process

A Dynamic Public Health Problem: Epidemics

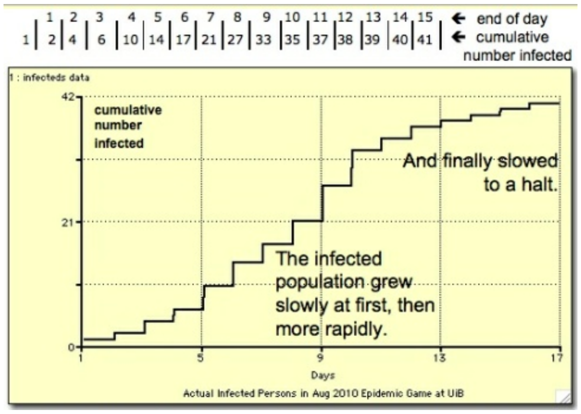
1. Background
2. Explanatory Model
3. Policy Model

Figure 1. Interactive Learning Environment



One anonymous student is infected initially. All students have one “daily” contact with each other. Some contacts are between infected and uninfected students. When an infected student and uninfected student make contact, there is a chance of a new infection, based on a coin toss. An "epidemic" occurs.

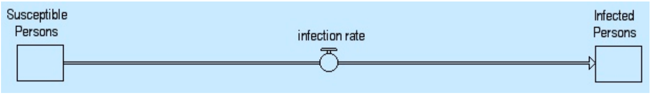
Figure 2. Epidemic Game



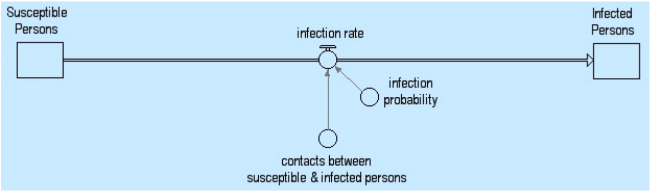
We collect, graph, and analyze the data. Here, 41 students are infected in 17 days. The number of Infected Persons grows at different rates over time: slowly during the first few days, then more rapidly, then slower, and no growth when all are infected.

Figure 3. Dynamics of the Problem

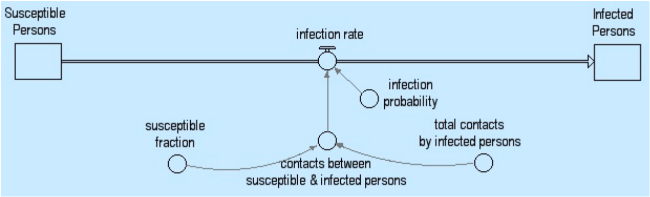
After discussing the trend in the time series graph, the students conceptualize the data in terms of stocks (persons) and flows (persons per day). We draw boxes for stocks—Infected Persons and Susceptible Persons—and connect them with a flow that resembles a pipeline. Next, we “model backwards” to investigate reasons for the flow to change. Two feedback loops emerge, and we have an endogenous hypothesis for the epidemic. See Figure 4.



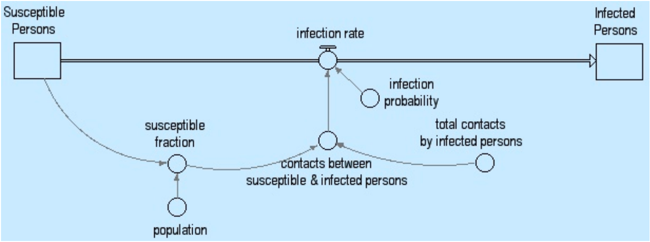
a. What causes the stocks to change?



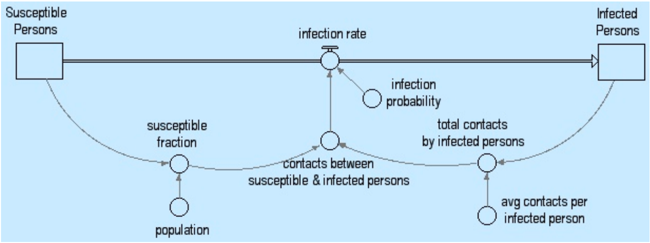
b. What causes the flow to change?



c. What causes a change in the contacts between the Susceptible and Infected persons?



d. What causes a change in the susceptible fraction?



e. What causes a change in total contacts by Infected persons?

a. In this simple epidemic model, there are two stocks: Susceptible Persons (initially 40) and Infected Persons (initially 1). People flow from the Susceptible Persons stock to the Infected Persons stock. The flow (infection rate) is the daily rate of new infections.

b. The infection rate depends on the number of daily contacts between infected and susceptible persons and the probability of an infection when a contact occurs. Assume the probability is 50/50, based on the coin toss.

c. Daily contacts with susceptible persons depends on the total daily contacts by infected persons and the fraction of the population that is susceptible.

d. The susceptible fraction depends on the number of Susceptible Persons and the total population (41).

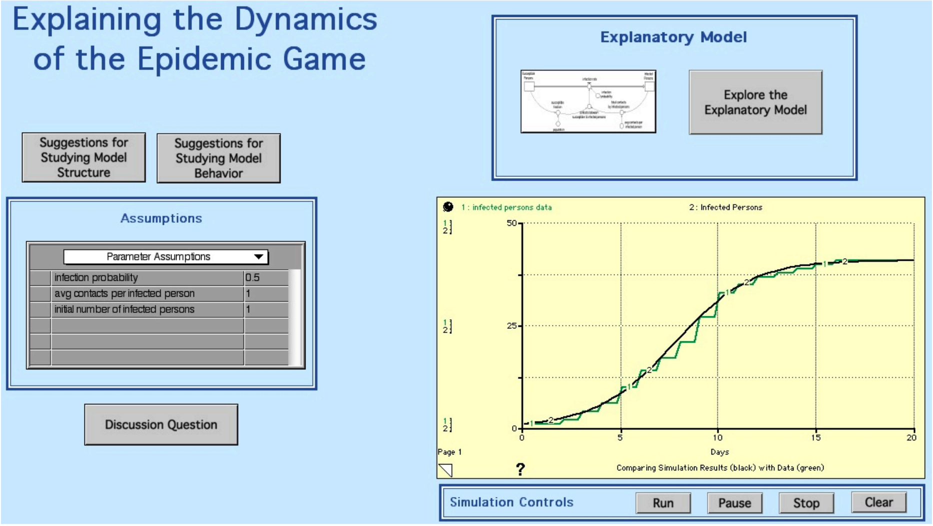
e. Total daily contacts by infected persons depends on the number of Infected Persons and the average number of daily contacts per infected person (1).

On the right, there is a positive feedback loop: the more Infected Persons, the higher the infection rate; the higher the infection rate, the more Infected Persons.

At left, there is a negative loop. The more Susceptibles, the higher the infection rate; the higher the infection rate, the fewer Susceptibles.

Figure 4. Explanatory Model

The modeler only needs to write four simple equations using basic arithmetic after specifying the three parameters based on the rules of the game. The software does the heavy lifting—using an integration algorithm to update the stocks during the simulation run. Figure 5 compares the simulation results (dark curve 2) with actual data (light curve 1) generated by student interaction during the epidemic game.

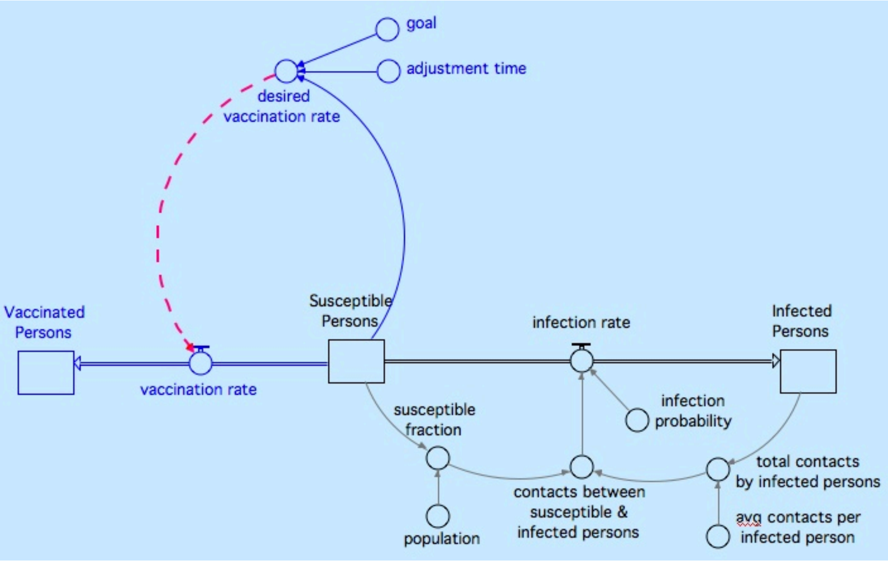


infection probability	0.5
avg contacts per infected person	1
initial number of infected persons	1

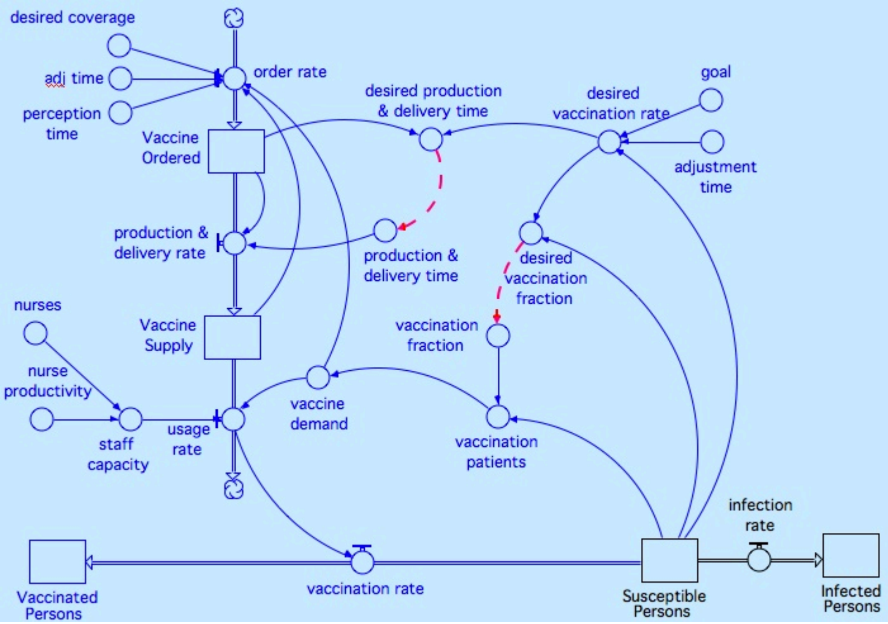
Figure 5. Data (1) Compared with Explanatory Model Simulation Results (2)

A satisfactory fit with the data has been achieved. Importantly, the model's behavior does not result from use of a preconceived mathematical function (i.e., no logistic curve equation was used). The parameters come straight from the game (e.g., probability of infection assumed to be 50/50 based on a coin toss, one contact per day by each Infected Person, etc.). And the equations are also derived from the logic of the game (e.g., infection rate = infection probability * contacts between susceptible & infected persons). The simple equations interact through the two feedback loops to produce the simulated behavior. When there are many to infect, the positive loop dominates and the growth rate increases. The growth slows—and eventually halts—when the negative loop gains dominance.

To get different behavior from the model, different structure is needed. The question is whether that can be done within real-world constraints. See Figure 6.



a. Exploratory Policy Model: a goal, desired flow, and "wishful thinking" link.



b. Implementation Policy Model: adding structure to reflect constraints. Two "wishful thinking" links await further implementation modeling.

Figure 6. Two Stages of a Policy Model

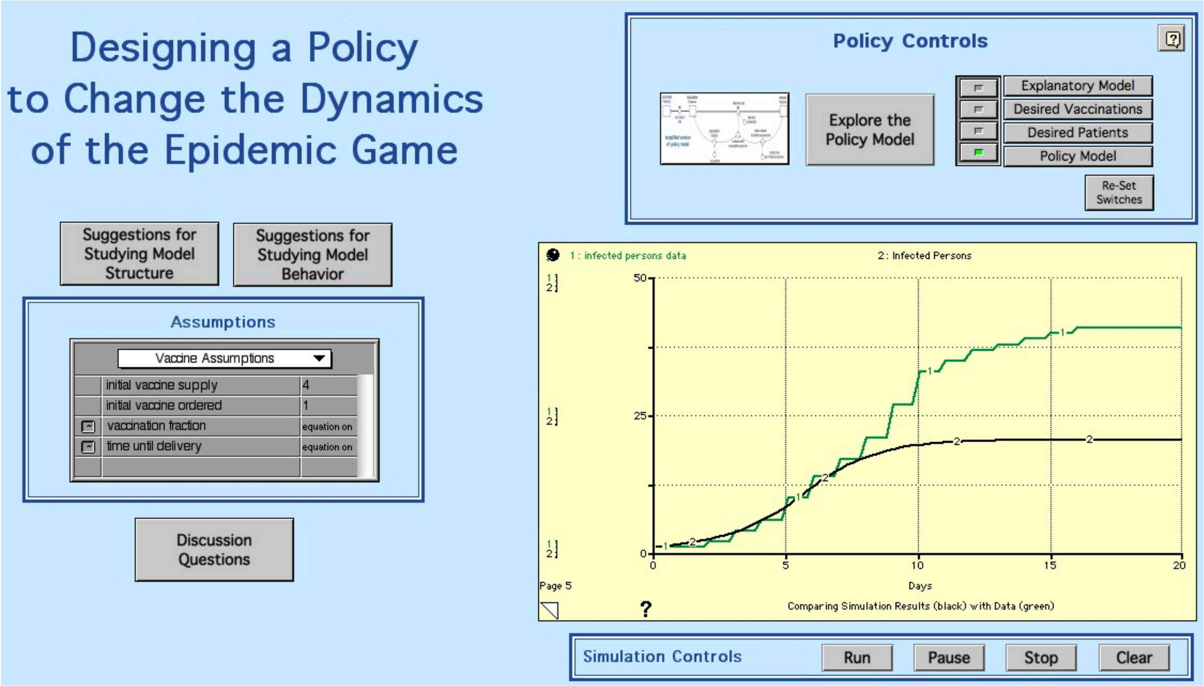
The exploratory policy model displays a vaccination strategy. However, it reflects no consideration of the implementation issues. The dashed link is a "wishful thinking" link—the vaccination rate is equal to the desired vaccination rate. Despite this limitation, the model provides a test of the logic in the strategy, and its potential impact can be simulated.

The implementation policy model reflects awareness of vaccine supply and human resource requirements.

Still, two dashed links show some remaining challenges:

- motivating people to be vaccinated, and
- assuring that vaccine is produced and delivered fast enough to be useful.

Simulating the policy model in panel (b) yields a "best case" result that is displayed in Figure 8. The dark curve (2) shows that the number of infections will be reduced by half if the vaccination policy can be carried out as desired. If a lower-than-desired number of people step up to be vaccinated or if the vaccine is not produced and delivered quickly enough to be useful, then the policy will not be as effective as the curve in Figure 8 suggests. In effect, the model says, "This is the best we can hope for; it requires that we do everything right—and be lucky."



	initial vaccine supply	4
☐	initial vaccine ordered	1
☐	vaccination fraction	equation on
☐	time until delivery	equation on

Figure 8. Best Case Result from Policy Model (dark curve 2)

Whether to continue building this model (i.e., formulating more structure that removes the two dashed links in the bottom panel of Figure 7) is a judgment call. No matter where we stop, there will always remain some "wishful thinking" links; not everything can be modeled. There is real value, however, in surfacing hidden assumptions and highlighting constraints that remain, wherever we stop. We want our students to master the skills of modeling while learning to respect the limits of feasibility.

As teachers with bounded expertise, we do not presume to anticipate all the dynamic problems our students will encounter in the complex world of policy analysis. But we try to give them a tool that will prove useful for analysis and for learning. It is often said that the best way to learn something is to teach it. We believe that the best way to learn about how a dynamic system works is to build it.

The author is an associate professor of system dynamics at the University of Bergen in Norway, a visiting professor of economics at ISM University of Management & Economics in Lithuania, and an adjunct professor of economics at Virginia Western Community College. He received his PhD in system dynamics at the University of Bergen and his master's degree in public policy at Harvard's Kennedy School. He served on the White House staff during the Nixon and Ford presidencies and managed his own consulting firm for many years before joining academia in 2005.

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