Using system dynamics to develop policies that matter: global management of poliomyelitis and beyond

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Abstract

We offer an example of modeling that influenced global health policy related to polio and we provide some insights about the modeling process. Although system dynamics lies at the heart of our modeling, we emphasize that downplaying the modeling to focus on the policy questions played a critical role in the use of the results by decision makers. Here we provide details of the system dynamics modeling that underlies our research on polio, and discuss the process we followed to bring scientific modeling of a highly complex issue to policymakers. We hope that providing a better understanding of our efforts and describing our continuing analytical journey provides useful insights for others who seek to use system dynamics to develop policies that matter. Copyright © 2009 John Wiley & Sons, Ltd.

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Introduction

In 2005, we presented a plenary talk at the society's meeting in Boston entitled "Modeling global policy for managing polioviruses: An analytical journey" (Thompson and Duintjer Tebbens, 2005). We noted the connection between polio and the beginning of system dynamics, with *Urban Dynamics* following Jay Forrester's meeting with former Boston mayor and polio victim John F. Collins, who ended up with the handicap-accessible office next door (Forrester, 1989, p. 7). Since that talk, our analytical journey continued with ever-increasing amounts of system dynamics, albeit still somewhat disguised in large, complex models.

Although the awards committee recognized one specific paper (Thompson and Duintjer Tebbens, 2007), our ability to perform the analysis in that paper built on a number of our prior studies. These include efforts to identify the policy decision options that national and international health leaders will face in the future (Sangrujee *et al.*, 2003), build a dynamic disease model for polio outbreaks (Duintjer Tebbens *et al.*, 2005), characterize the health and financial benefits of historical poliovirus vaccination in the United States (Thompson and Duintjer Tebbens, 2006), provide context related to risk management in a polio-free world (Aylward *et al.*, 2006), quantitatively characterize the risks (Duintjer Tebbens *et al.*, 2006a) and costs (Duintjer Tebbens *et al.*, 2006b) associated with the future options, model the trade-offs associated with

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various outbreak response options (Thompson *et al.*, 2006a), measure the costs and value of global poliovirus surveillance (de Gourville *et al.*, 2006), evaluate the risks, costs, and benefits of global policies for managing polio after eradication (Thompson *et al.*, 2008) and the associated uncertainties and sensitivities related to global post-eradication policies (Duintjer Tebbens *et al.*, 2008a, 2008b), make the case for global cooperation on a vaccine stockpile and coordinated OPV cessation (Thompson and Duintjer Tebbens, 2008), and reflect on the lessons learned during this collaborative project (as of December 2006) (Thompson, 2006; Thompson *et al.*, 2006b).

System dynamics lies at the heart of our modeling and helped us frame the problem and identify key dynamics in the debate about eradication. The paper (Thompson and Duintjer Tebbens, 2007) and its published technical appendix provide full details about the model (i.e., equations and inputs), so we focus here on the system dynamics concepts and show the underlying system dynamics model in ways familiar to the system dynamics community. The next sections provide context about polio eradication and our motivation for the paper, a description of the system dynamics model, a reflection on the impact of this work, and our insights about how system dynamics can play a significant role in global policy debates.

Context

On the heels of successful eradication of smallpox and impressive progress in the elimination of polio in the Americas, in 1988 the World Health Assembly committed to global eradication of wild polioviruses by the year 2000 (World Health Assembly, 1988). At the time, an estimated 350,000 global cases of paralytic polio occurred annually, many with onset of symptoms during early childhood and subsequent permanent paralysis. By 2000, the Global Polio Eradication Initiative (GPEI) had significantly reduced the global circulation of wild polioviruses, with reported paralytic polio cases globally of the order of 1,000 cases per year, and had successfully eradicated one of three wild poliovirus serotypes (i.e., type 2). This remarkable achievement occurred in spite of the reality that some countries and regions started coordinated polio vaccination campaigns as late as 2001 (Aylward *et al.*, 2003).

The anticipation of imminent success in achieving eradication of all wild polioviruses sustained the GPEI. However, in 2002–3, faced with insufficient funding to continue intense vaccination everywhere, the GPEI focused its vaccination efforts on the then endemic countries. At the time, wild polioviruses continued to circulate in six countries (Nigeria, India, Pakistan, Niger, Afghanistan, and Egypt), but many other countries remained vulnerable to importation. Political and logistical challenges led to outbreaks and exportations, and between 2004 and 2006 wild polioviruses appeared again in previously polio-free African and Asian countries. The outbreaks resulting from these

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reintroductions showed the ability of polioviruses to rapidly spread in susceptible populations, and ultimately the GPEI spent over $400 million to regain the lost ground (Thompson and Duintjer Tebbens, 2007).

Toward the end of 2005, debate began about abandoning the goal of eradication. How could the world continue to justify the significant use of resources (both financial and human) on polio, particularly with the number of cases globally already so low and so many other disease control and health services programs in need of resources? In 2006, a prominent editorial questioned whether polio eradication is "realistic" and expressed concern that "international assistance for polio could have negative effects on other public health efforts" (Arita *et al.*, 2006, p. 853). The editorial suggested that "the time has come for the global strategy for polio to be shifted from 'eradication' to 'effective control' " (Arita *et al.*, 2006, p. 853). Although the authors did not define "effective control", the editorial stated that: "As soon as the annual global number of cases is less than 500 and the number of nations with polio less than 10, all polio eradication elements should . . . [shift to control]. This strategy would sustain the benefits so far gained . . ." (Arita *et al.*, 2006, p. 853). As discussed in more detail below, for those who work on major projects the theme of "late and over budget" should sound familiar. Remarkably, although the editorial emphasized that "it has cost $4 billion in international assistance and it has been estimated that eradication (including 3 years of follow up) could cost another $1.2 billion" (Arita *et al.*, 2006, p. 852), it provided no quantitative estimates of the benefits of the investments or the costs of the suggested alternative. By suggesting a switch to control, the editorial seemed to imply that a control strategy would save money while maintaining a low number of cases every year. Motivated by curiosity about how this might work, we set out to assess the economic implications and disease burden of a change in policy from eradication to control.

Model

Given our then current work on assessing the risks, costs, and benefits of post-eradication policies (Thompson *et al.*, 2008) we could use many of the components we previously developed to model a shift from eradication to control. Notably, our dynamic disease outbreak model for polio (Duintjer Tebbens *et al.*, 2005) allowed us to estimate potential numbers of cases. The dynamic disease outbreak model represents a more complicated version of the standard SIR model used in a popular system dynamics textbook (Sterman, 2000) shown in Figure 1. In the case of polio, as shown in Figure 2, we must deal with different types of imperfect immunity (i.e., from historic or recent exposure to polioviruses (including the oral poliovirus vaccine and/or vaccination with the inactivated poliovirus vaccine) as well as a latent period and routine or supplemental immunization rates). Modifying and expanding our

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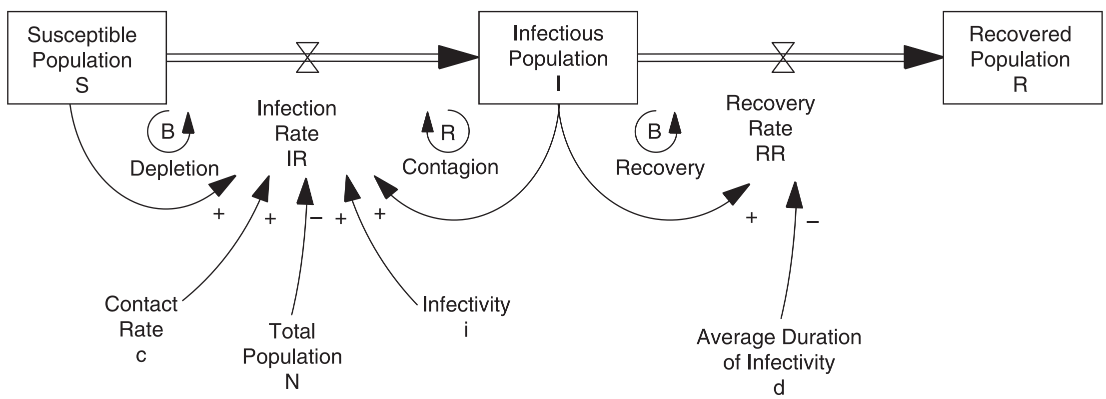

Fig. 1. Schematic of a simple SIR model (Sterman, 2000, Figure 9-5, reprinted with permission)

existing model allowed us to determine that it was not possible to "effectively control" (i.e., achieve low cases) at low cost. This means that control either implies high costs and low cases, or low costs and high cases, but not low costs and low cases. Economic studies also showed that "high control" is never optimal if eradication is feasible (Geoffard and Philipson, 1997; Barrett and Hoel, 2007), which provided further support for this insight.

However, our most significant insight came from exploring the dynamics of the economic investment in eradication. After watching the GPEI deal with the reintroductions of wild polioviruses in previously polio-free countries between 2004 and 2006, we recognized that reducing vaccination led the stock of susceptible individuals to build up and ultimately to outbreaks after some delay. Responding to the outbreaks requires reinvesting in intensive vaccination, which after some delay contains the outbreak and reduces or eliminates circulation of the virus. With success comes a perception that the high level of investment compared to the low incidence is no longer justified. If policymakers succumb to the resulting pressure to reduce vaccination spending, this creates a situation in which populations again become vulnerable to new outbreaks. To capture this behavior, we constructed the negative feedback loop shown in Figure 3, which we called "wavering". We incorporated this feedback loop into our dynamic disease model and tailored the model to two populous northern Indian states in which wild poliovirus still circulates. We explored two options: (1) vaccinate intensively until eradication; and (2) vaccinate intensively only if the costs per incident case remain below a certain acceptable level, but reduce the vaccination intensity otherwise (i.e., a "control" option with the possibility of wavering). Figure 4 shows the expected oscillations that occur for the second option due to the negative feedback loop with time delay structure (Figure 3). Clearly, the second option leads to both more cumulative costs and more cumulative cases over the 20-year period of time

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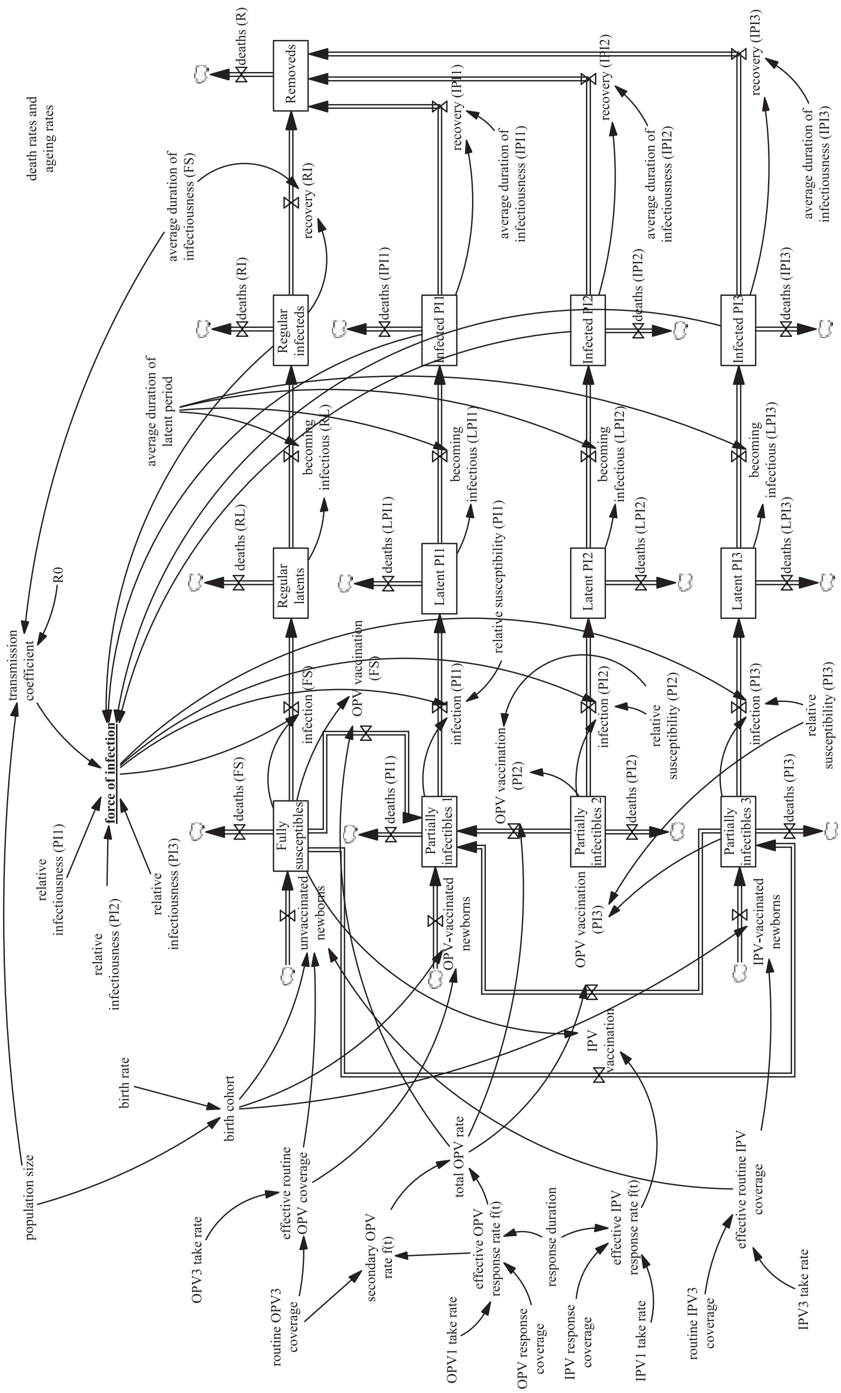

Fig. 2. Schematic of our dynamic disease model components (indexed for 25 age groups) (Duintjer Tebbens *et al.*, 2005)

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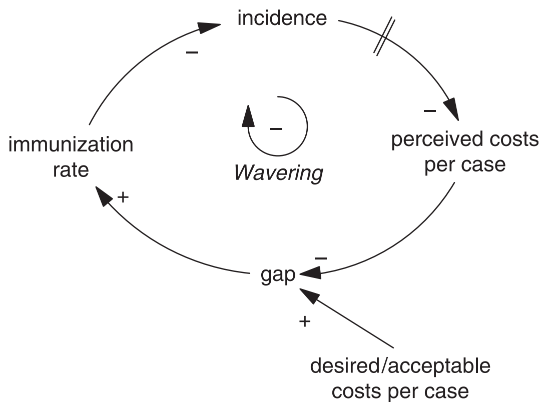

Fig. 3. Negative feedback loop with time delays used in conjunction with a dynamic disease model for wild poliovirus transmission and immunization in northern India to explore the possibility of a "wavering" commitment (used but not shown in Thompson and Duintjer Tebbens, 2007)

that we modeled. Moreover, with the wavering commitment characterized by the second option, we will pay costs to control polio forever and never achieve eradication. We used the actual experience of the prior reduction in polio vaccination from 2002–3 (analogous in effect to "wavering") to provide evidence that our model was not just hypothetical. We also found evidence of wavering with other disease eradication efforts historically (Duintjer Tebbens and Thompson, 2009).

Impact

Our analysis came at a critical time. In February 2007, the WHO Director-General, Dr Margaret Chan, convened an urgent stakeholder consultation to discuss the option of switching to control. We had the opportunity to present the preliminary results of this work at that meeting. Following publication of the paper (Thompson and Duintjer Tebbens, 2007), an article about the paper published in the same journal as the editorial mentioned above noted that our analysis provided "a nail in the coffin for the idea that there is a cheap and painless way out" (Roberts, 2006, p. 362). Showing the dynamics clearly and giving the wavering commitment a name helped key stakeholders appreciate the options quantitatively and with a much longer time horizon. Since then, efforts have continued to focus on finding the resources needed to complete eradication and on dealing with the other complex challenges that remain. National and global health leaders and financial supporters have re-committed to completing eradication, and this has led to several hundreds of millions of dollars of resources.

Remarkably, our analysis provided another additional context with respect to the goal of eradicating a disease. Given our exposure to the concepts of

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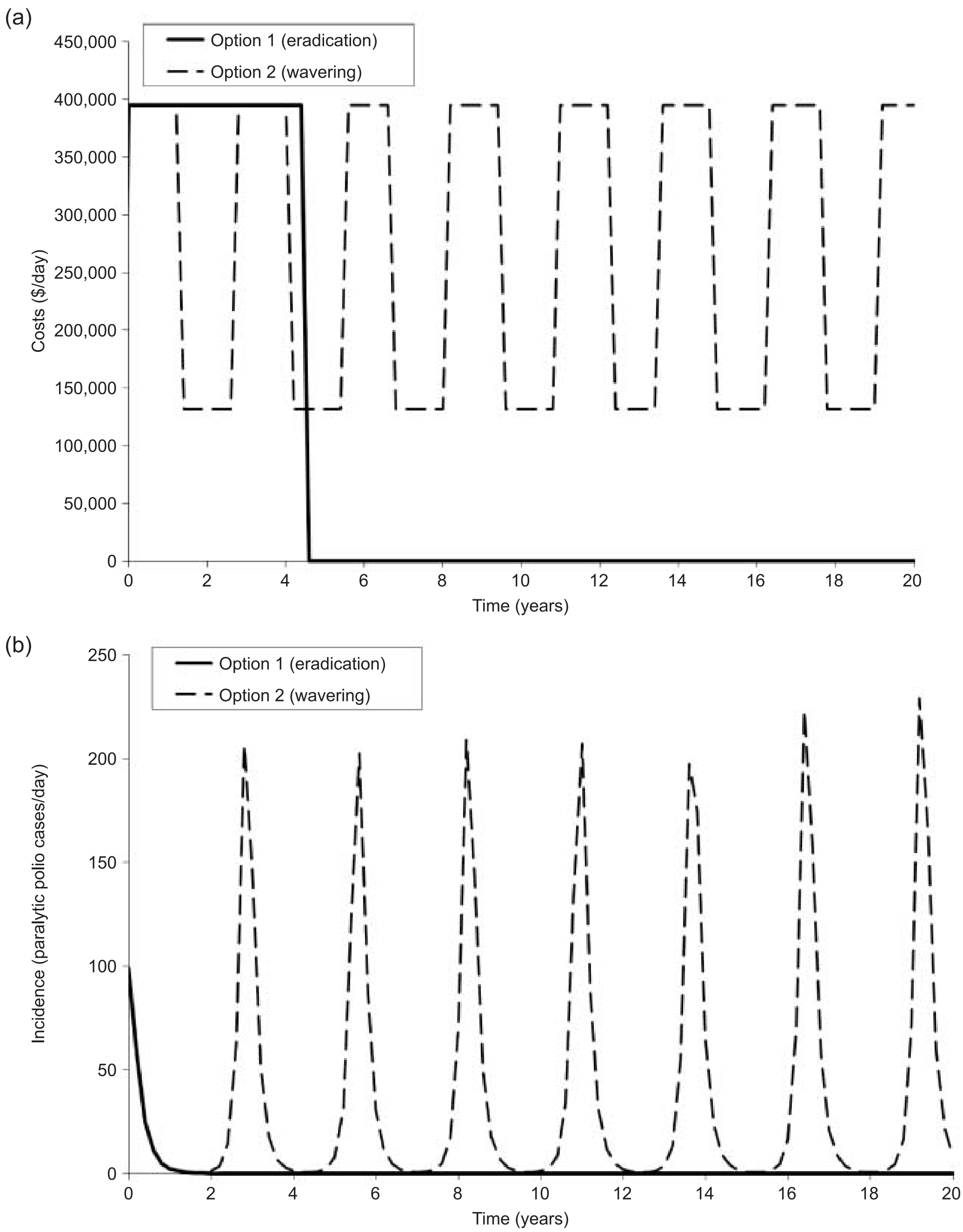

Fig. 4. Undiscounted costs (a) and paralytic cases (b) for two options: (1) vaccinate intensively until eradication; and (2) vaccinate intensively only if the costs per incident case remain below a certain acceptable level.

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modeling major projects using system dynamics (e.g., Sterman, 2000; Lyneis and Ford, 2007) and cost and schedule overruns on major projects (or "megaprojects") (e.g., Flyvbjerg *et al.*, 2003), we appreciated that national and world health leaders needed to view disease eradication as a major project. In that regard, the experience with polio appears very similar to that of other major projects, as shown in Table 1. Although projects vary, cost and schedule overruns represent a very common phenomenon, and under-appreciation of risks represents a common cause (Flyvbjerg *et al.*, 2003). Our work on polio points to systemic causes of overruns and emphasizes the importance of understanding the complex physical and social systems within which large projects operate.

In our prior talk (Thompson and Duintjer Tebbens, 2005) we identified five requirements for success:

1. Vision, hard work, timing, and good luck
2. Recognition that process matters
3. Effective communication

Table 1. Time and cost overruns of selected completed major projects for comparison to polio eradication effort to date (last row)

	Duration (years)			Cost (2008 U.S. dollars)			
Project, year initiated	Expected	Actual	Over	Expected	Actual	Over	Note
Initial smallpox eradication program, 1959	5	20	300%	730 million	1.6 billion	120%	a
Intensified Smallpox Eradication Programme, 1966	10	13	30%	910 million	1.5 billion	65%	b
Sydney Opera House, 1959	4	14	250%	54 million	800 million	1400%	c
Channel tunnel ("Chunnel"), 1987	5	6	20%	7.3 billion	13 billion	80%	d
Boston Central Artery/Tunnel ("Big Dig"), 1991	7	15	110%	5.8 billion	22 billion	280%	e
Global polio eradication, 1988	12	>20	>67%	1.7 billion	>6 billion	>250%	f

[a] In 1959 approximately 59% of the world population lived in smallpox endemic areas. Sources: Fenner *et al.* (1988); Bureau of Labor Statistics (2008) (used to adjust to 2008 U.S. dollars).
[b] Assumes international funding represented 30% of total costs; in 1967 approximately 31% of the world population lived in smallpox endemic areas. Sources: Fenner *et al.* (1988); Bureau of Labor Statistics (2008) (includes time and costs incurred between last smallpox case in 1977 and certification in 1979).
[c] Assumes reported estimate of Australian $7 million in 1959, $102 million actual costs incurred (discounted to 1963), exchange rate approximately 1.1 U.S. dollar per Australian dollar. Sources: Flyvbjerg *et al.* (2003); Flyvbjerg (2005); Bureau of Labor Statistics (2008).
[d] Sources: Flyvbjerg *et al.* (2003); Board of Governors of the Federal Reserve System (2008); Ipsen (1993); Bureau of Labor Statistic (2008).
[e] Sources: Massachusetts Turnpike Authority (2007); Murphy (2008); Bureau of Labor Statistics (2008); Flyvbjerg (2005).
[f] Eradication not complete, shown for comparison. Cost figures include only external funding (i.e., recipient countries also significantly contributed to vaccination campaigns). In 1988 approximately 75% of the world population lived in polio endemic areas. Sources: World Health Assembly (1988); Centers for Disease Control and Prevention (1993) (expected cost based on estimate available 5 years after initiation, because to our knowledge no cost estimate was available to delegates of the World Health Assembly in 1988); World Health Organization (2008); Bureau of Labor Statistic (2008).

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4. Organization and quality
5. Good questions

These all matter, and we are delighted that modeling represents an important aspect of the global program to manage polio (GPEI, 2008). With respect to the impact of this paper (Thompson and Duintjer Tebbens, 2007), we fortunately saw the wavering commitment loop when no one else seemed to see it, and we went beyond just seeing the loop to build and use a model that provided answers to critical questions at the time the decision makers could use them (and needed them and asked us). In the presentation to the stakeholders, we showed the results to tell the dynamic story in the simplest possible way (i.e., by comparing a firm commitment to a wavering commitment showing the cumulative costs and cases). We did not focus on explaining the model itself or attempt to walk the decision makers through the equations or diagrams. Instead, we focused on communicating the key insights based on what they already knew (e.g., the 2002–3 reduction in vaccination led to big outbreaks and high costs). Similarly, we wrote the paper in a way that would work for the audience of the journal, with all of the equations and details in a technical appendix (and notably without showing the causal loop or stock and flow diagrams that system dynamics community members might expect to see).

Communicating the results in a way that ensured their consideration and use represented the highest priority, and we borrowed liberally from both system dynamics and economic modeling tools without concern about staying within (or going beyond) the bounds of any paradigm. As Jay Forrester reflected on the defensive tendency in system dynamics to ignore critics in his 1983 Presidential Address to the System Dynamics Society:

> Criticisms should be analyzed deeply to evaluate their implications. If an objection is valid, system dynamics should respond by mending its ways. If an objection arises from a misunderstanding, better explanations should be sought. If an objection reveals a fallacy in the paradigm from which the criticism arises, an opportunity is at hand for extending the system dynamics viewpoint for the benefit of both fields. (Forrester, 1983, p. 9)

We anticipated (and received) some criticism from economists who did not recognize in our paper a traditional health economic analysis, but these were relatively limited, perhaps because our paper cited and built on key theoretical economics papers (Geoffard and Philipson, 1997; Barrett and Hoel, 2007).

Insights

Reviewing the insights of the five prior award winners, we appreciated many of the insights that they offered as to why only some useful models get used.

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Repenning commented on his experiences and also commented on the importance of presenting models effectively:

> It . . . seems quite fantastic to believe that standard modes of model presentation would ever significantly impact academics from outside the SD community. Such an approach presumes a knowledge of dynamics that the existing experimental evidence suggests does not exist . . . (Repenning, 2003 p. 316).

He also commented on the importance of understanding other disciplines that might provide different approaches and different answers to questions:

> I now believe that my initial assumption that SD models would be easier to sell to other modeling communities may not always be correct. Practitioners of other modeling methods are certainly more equipped to understand the details of system dynamics models than those without technical training. However, membership in a modeling community (e.g., economics, operations research) also entails acceptance of the assumptions underlying that discipline. (Repenning, 2003, p. 319)

Finally, Repenning highlights four errors that he identified in his early efforts to sell his work (and system dynamics):

1. failure to ground my work in the language and literature of the field I was trying to enter;
2. developing models that were too large and too complex for the non-system dynamicist to absorb;
3. using inadequate methods to build intuition concerning the link between a model's structure and its behavior;
4. targeting scholarly communities interested in modeling rather than those interested in understanding complex social phenomena. (Repenning, 2003, p. 320)

Wolstenhome commented on the challenges of the "silo" mentality and narrow perspective often observed in organizations. He noted that:

> It is the boundary structure of an organization that mitigates for local performance measures and against systemic solutions. Boundaries bring to life the system insights that:
> - The best levers for improvement in the behavior of your own sector often lie on someone else's patch;
> - The benefits of policy change you undertake often accrue to someone else. (Wolstenhome, 2004, p. 344)

Warren provides a powerful example of the problem of perception delays in feedback loops with respect to employee training, in which we see a "wavering commitment" to training budgets. He points out that an

> intractable source of causal ambiguity does not concern flow drivers, but arises instead from the behaviour of accumulating asset stocks . . . when an accumulating

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> factor occurs between a dependent variable and some factor on which it is believed to depend, neither managerial insight nor commonly used regression methods can readily identify the nature or scale of causality. This problem becomes still more severe when there is more than one accumulating factor between independent and dependent variables. (Warren, 2005, p. 342)

Fiddaman discusses challenges that policymakers face dealing with climate change due to misperceptions of feedback. He states that:

> In the real world, their task is further complicated by a variety of institutional factors—for example, that the enabling legislation for many regulatory agencies precludes the use of the most effective policy instruments. Breaking down these kinds of barriers involves a shift in regulatory paradigms, which will not be accomplished by bigger models or more detailed answers. Instead, we need transparent models that help policymakers to appreciate the dynamics of their situation. (Fiddaman, 2007, p. 31)

Finally, Lane and Husemann emphasize the importance of building and using a simulation model to go beyond mapping out the system structure so that one can "assess the importance of reinforcing loops", "deduce resulting behaviour", and "provide a basis for interventions in a complex system" (Lane and Husemann, 2008, p. 45). They offered three very useful propositions:

> First, whether taking a drink, considering a new pay scheme or negotiating a global trade agreement, policy makers need to think about the possible existence of reinforcing feedback as well as balancing feedback. Second, finding effective interventions in complex systems is hard; we may need the help that computer simulation can offer. Third, we should never forget that these systems are human creations and are ours to influence. (Lane and Husemann, 2008, p. 58)

In addition to these insights from our recent predecessors, we suggest the following. Creating useful models requires understanding the stakeholders, which may mean the customers alone, but more likely means a much broader set of interests. Since models matter when others adopt and use them, or at least use their results and insight, modelers need to focus on working effectively with the people who need and can use the results. In our case, we recognized the importance of appropriately packaging the insights in terms that the key policymakers could use and explain to others (e.g., "wavering commitment"). Our best advice is to not underestimate the communication aspects and make sure to invest time in multi-way discussions. We needed to explain and defend the model results and insights to a wide range of audiences, including national and international policymakers, financial donors, system dynamicists and other modelers, risk and decision analysts, economists, epidemiologists, and virologists. Knowing the audiences and what they needed to understand and when was the key to our ability to have impact. We also needed to make sure that we could answer questions from any stakeholder

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and that anyone interested in the technical details could find them in the peer-reviewed, published literature.

With respect to concerns about the health of the system dynamics field, we suggest that many people (like us) are doing system dynamics, although they may use different diagrammatic conventions, and different software. We appreciate that the society has been wonderfully receptive to us and our work, and we hope that society members see the enormous potential for growth that could come from recruiting others doing system dynamics to join in. Since system dynamics does not yet seem to have a critical mass, members of the society should explore all of the options available to get more people into the system dynamics community. In this regard, doing truly interdisciplinary work requires investing time and effort in learning about what others do. We cannot expect others to invest in learning system dynamics if we do not invest in learning what they do and in combining our collective tools to achieve the greatest benefit. System dynamics offers a great deal and people need to generally understand stocks and flows and feedbacks better. However, although teaching kids is necessary and essential, it is not sufficient. Too many people do not get the basic concepts (Cronin *et al.*, 2008; Sterman, 2000, 2002, 2008; Sterman and Booth Sweeney, 2002), and we need to engage policymakers (i.e., those who make the decisions) and reporters (i.e., those who communicate the decisions to broad audiences) in active discussions to correct this. As Forrester states:

> The failure of system dynamics to penetrate governments lies directly with the system dynamics profession and not with those in government who are taking little notice of our activities. Those in system dynamics are asking the wrong questions about the sources of low influence. (Forrester, 2007, p. 3)

To further emphasize this point, those interested in impact will find no substitute for asking good questions and engaging in discussions with the decision owners and stakeholders. If we want to influence policy, then we need to ask ourselves: (1) What are the questions that policymakers need answered? (2) How can we help them understand our models and make our models to empower them? (3) How can we engage them as advocates for system dynamics and help in efforts to teach others? With respect to reporters, we similarly need to ask: how can we make connections with them and educate them about system dynamics?

While "[a]ll decisions are based on models . . . and all models are wrong" (Sterman, 2002, p. 525), "[a]ll models are wrong but some are useful" (Box, 1979, p. 202). We hope that members of the society will strive to develop truly useful models, and that they will appreciate that currently only some useful models get used, most likely because of the ways that we are (or are not) communicating with others about them.

True communication requires at least two-way discussion, and perhaps the most important opportunities will come from paying close attention to others

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and bringing them into system dynamics by showing them what system dynamics can do for them. The society is not alone in its challenge of selling its tools. Concerned about the slow adoption of some risk analysis methods, a risk analyst noted that:

> It has taken perhaps 10 years for the mainstream of the environmental risk analysis community to move from a grudging acknowledgment that uncertainty in risk is a fundamental problem to our current level of familiarity and comfort with the basic tools for actually trying to quantify and depict these uncertainties. But will it take another 10 years or more to pass over the next major hurdle in the evolution of risk management methodology and practice—namely, the routine reliance on quantitative uncertainty analysis (QUA) as the lodestar of decision-making rather than as a nicety of risk characterization or as a risk analysis appendage useful only in hindsight?
>
> However long this advance takes, part of the blame for the delay will rest on the shoulders of practitioners of QUA (including this author), who have to date concentrated on getting scientific and regulatory decisionmakers to acknowledge the magnitude of the uncertainties facing them and to understand how QUAs are conducted (that is, when we have stepped away from internecine arguments over methodological details to do so). In this, we have risked making ourselves akin to mousetrap salesmen who beleaguer the consumer with engineering details before he even understands that if the gadget works, the *result* will be a house free of mice. (Finkel, 1994, p. 751)

We hope that members of the society will appreciate that they may similarly need to do a better job explaining the benefits of their tools. We see many similarities and connections between risk and decision analysis and system dynamics, and many opportunities for mutual learning. In this sense, we also hope that system dynamicists will see the benefits in more explicitly considering variability and uncertainty (e.g., Thompson and Graham, 1996; Thompson, 2002) in their models, while risk and decision analysts will see the benefits of explicitly considering system dynamics (e.g., Duintjer Tebbens *et al.*, 2008b; Thompson and Duintjer Tebbens, 2007; Thompson *et al.*, 2008). As the fascinating story of polio continues (Oshinsky, 2005) and creates more precedents related to vaccine policy (Offit, 2005), we expect analytical modeling to play an increasing role in the global process of managing diseases, at least for those willing to engage others as partners and to truly cross boundaries.

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