STEM Pressures from Birth to Globalization: Five Related Models

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The U.S. is becoming progressively more concerned about the impact of science, technology, engineering, and math (STEM) skills on the future of U.S. prosperity. Five independent system dynamics models have been developed to test policy proposals related to this problem. The Boeing Company, as the catalyst for development of three of these five models, was requested by this conference's organizing committee to host a special session on this topic. At this special session, all five models will be presented. The purpose of this paper is to summarize and briefly compare these five models. Details on each model are provided in the respective papers and special session presentations on each model.

Introduction:

"U.S. corporate leaders worry that, as competition from other countries is becoming fierce, America is not producing an adequate number of highly trained engineers and scientists" (BHEF, 2006, p. 8). Indeed, we are becoming progressively more concerned about the impact of STEM skills on the future of U.S. prosperity (National Academy of Sciences, 2007). Although our country is having a national conversation about what to do about this question, it is usually a fractured conversation, sometimes about education, sometimes about R&D spending, sometimes about child development, sometimes about immigration, sometimes about other facets of the problem, but rarely about interactions among the various pieces of the whole system relevant to the problem. The whole system relevant to this problem is a dynamically complex nonlinear system encompassing all of these facets, a system with many feedback loops and long delays, the type of interconnected complex system for which humans are "really weak at inferring implications without the support of simulation models"[2]

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[2] From Richardson (1997): "System dynamics is the use of computer simulation for policy analysis in complex systems. Its big contribution is helping people to build progressively richer understandings of some dynamic problem, and anticipate weaknesses in policy initiatives that would develop over time. It gets a lot of its power from a 'feedback' perspective -- the realization that tough dynamic problems arise in situations with lots of pressures and perceptions that interact to form loops of circular causality, rather than simple one-way causal chains. Humans are really good at thinking up all that interconnected complexity and really weak at inferring its implications without the support of simulation models."

The purpose of this paper is to provide, in one place, an introduction to, and a brief comparison, of the five system dynamics simulation models of which we are aware, that begin to address aspects of this problem. Boeing, as the catalyst for development of three of these five models, was requested by this conference's[3] organizing committee to host a special session on this topic. At this session, individual papers on each model will be presented by their authors; this paper is an overview to provide context and a first attempt at comparison. As shorthand for this paper the five models will be referred to by the names of the organizations with which their respective developers are associated, as the Boeing, MIT, Raytheon, Sandia and SimBlox/NIH models.

Our history with, and the focus (underlined) of, each of the models:

Boeing model: As mentioned in the introduction, Boeing, along with other businesses, has experienced increasing difficulty in hiring engineers in the U.S. Being aware of the dynamic complexity of the whole system relevant to this problem, and of the difficulty of inferring the implications of that complexity without the support of simulation models, we decided to continue our exploration of the system by building a high-level very aggregate simulation model of the system that produces the STEM hiring pool. The focus of our model is understanding how U.S. overseas investment, education, immigration, and R&D investment policies, as well as the decisions of other countries and people, act through major feedbacks to cause risk to the future prosperity of the U.S. We based our model on the dynamic hypotheses we understood as represented in the National Academies' report (2007) entitled, "Rising Above the Gathering Storm: Energizing and Employing America for a Brighter Economic Future." The model is documented in Richey et al. (2008, with download link). We continue to believe that this model provides a good context and framework within which to place the other four models.

MIT model: This model has its origins in Boeing's being the client of a team of three graduate students in a Spring-2008 Brandeis University system dynamics course taught by Professor Bradley J. Morrison.[4] Dan Sturtevant, then a Master's student, and now a PhD student, in MIT's Engineering Systems Division, was one of the three student-consultant's to Boeing as part of Professor Morrison's class. Dan became so interested in the problem that he decided to make it the subject of his Master's thesis at MIT (Sturtevant, 2008a and 2008b, with download links). Dan's work explored the cause of the nearly twenty-five year decline in the percentage of U.S. born undergraduates earning degrees in engineering.

Raytheon model: We first became aware of this model during the spring of 2008. It is an outgrowth of Raytheon's involvement with the Business-Higher Education Forum's (BHEF's) multi-year initiative "Securing America's Leadership in Science, Technology, Engineering, and Mathematics" (http://bhef.com/). The purpose of this initiative is to "to develop a strategy to double the number of U.S. STEM college graduates by the year 2015" (Wells et al. 2008a, p.1).

[3] The 27th International Conference of the System Dynamics Society, Albuquerque, N.M., USA. July 26-30, 2009.
[4] Course description from Brandeis University web site: "BUS 286a - Applications of System Dynamics *Prerequisite: BUS 276a.* This course gives students the opportunity to apply the standard method of system dynamics to assist a real company or organization. The core activity in the course is to work with a client organization, using the tools of system dynamics, to develop insights into a problem the client has identified. Students experience conceptualizing and building a system dynamics model "from scratch," learn a set of standard pieces of model structure called 'molecules,' and gain an appreciation for the challenges and rewards of consulting for clients in a helping relationship."

Raytheon saw an opportunity to assist in this initiative by "applying systems engineering to the U.S. education system" (ibid. p.2). The initial focus of this model is to test proposed teaching workforce improvement policies in relation to this 2015 objective. Further enhancements of this model will test other policies' impacts. This model is the first open-source model offered by the STEM Research and Modeling Network (http://www.stemnetwork.org/).

Sandia model: In late summer 2008 Boeing initiated conversations with Sandia National Laboratories (SNL) about continuing the STEM modeling effort. After studying the Boeing, MIT, and Raytheon models and related research, SNL proposed to develop a model focused on the influences on the attractiveness of STEM careers, which had been incompletely explored in the models to date. Boeing contracted SNL to deliver this model and the current iteration reported on here was completed in December, 2008 (Kelic and Zagonel, 2008).

SimBlox/NIH model: Boeing became aware of this work sometime in the fall of 2008, but did not solicit a briefing on it until preparing for this conference. This model was developed in collaboration between SimBlox (http://www.simblox.com/) and the National Institutes of Health (NIH) under a Phase I Small Business Innovation Research (SBIR) grant. The focus of the work is a concern about the aging demographics of the Principal Investigators (PIs) funded by the NIH. It is anticipated that this model will be enhanced under a Phase II SBIR grant.

Model Comparison

For this comparison, to accompany the information in Table 1 mostly suffices.[5] With one notable exception (the MIT and Raytheon models), these five models address different aspects of the problem area.

The Boeing model tests the effects of combinations of three policies [R&D investment (public & private), education investment, and immigration] on the dynamic behavior of the prosperity of the U.S. From a system dynamics perspective, many criticisms can be leveled at this model. For example, its concepts are not operationalized, that is, it doesn't do a good job of defining what it means by the "prosperity" of a nation (is it GDP?) or of its "science and engineering enterprise" (is it the size of the science and engineering workforce?). Another criticism is that its policies are exogenous time series and should be made endogenous, that is, immigration policy should perhaps respond to the state of the "science and engineering enterprise," and investments in education and science and engineering enterprise should be functions of prosperity. Indeed, relative to this last criticism, one way to look at the other four models is as offering portions of the causal linkage from prosperity to investments in education. Despite these criticisms, this model does offer excellent global context for the other four models. Further, it is the only one of the five models that begins to go beyond education policy alone to consider both immigration policy and policies for R&D investment by both government and industry.

Of the five models, the MIT model is best grounded in historical trends and research. It knits together theories from multiple research studies to create a dynamic hypothesis that represents a

[5] For additional information the reader is encouraged to reference model sketches and other information, both in the papers for this session as well as previously published (Richey et al., 2008; Sturtevant, 2008a, 2008b; Wells et al., 2007, 2008a, 2008b; Kelic et al., 2008; and White et al., 2008).

plausible set of feedback loops that could have been responsible for creating observed declines in the percentage of U.S. born undergraduates earning degrees in engineering. It then goes on to investigate the degree to which relative degrees of STEM teacher to STEM industry worker wage increases could reverse these trends, and illustrates the possible existence of a "tipping point" at which feedback loop dominance shifts cause increases in the percentage of U.S. born undergraduates earning degrees in engineering. Although an incomplete model (for example, see Sandia model discussion below), the MIT model helps us better think about the system in light of multiple influences, e.g., the effect of an increase in women's career choices over the period 1975 to 1985.

Model	Model Focus	Sectors Included (or Feedback Loops if so noted)	Policies Tested	Time Frame; INITIAL to FINAL time	Calibrated to Historical Time Series Data?
Boeing	Represent the dynamic relationship between science/engineering enterprise and prosperity from the NAS report, "Rising Above the Gathering Storm."	US Prosperity & Science-Engineering Enterprise Reinforcing Feedback Loop	Increase fraction of national prosperity invested in STEM education	1950-2050	To anecdotal historical tendencies
		US Overseas Investment	Increase fraction of national prosperity invested in R&D		
		Overseas Prosperity & Science-Engineering Enterprise Reinforcing Feedback Loop	Encourage STEM immigration		
		Relative Attractiveness of US to foreign-born scientists, engineers & students			
MIT	Cause of the nearly twenty-five year decline in the percentage of U.S. born undergraduates earning degrees in engineering.	STEM Labor Supply/Demand Feedback Loop	Various teacher wage increases to increase teacher quality	1940-2040	To historical tendencies
		Availability of Jobs Feedback Loop			
		Teaching Quality Feedback Loop			
Raytheon	Can STEM college graduates be doubled by 2015?	K12 STEM Interested & Not	Training, mentoring, laying-off or denying tenure to the least capable teachers after 3 years	2003-2025	Not yet, but planned (Wells et al., 2008a, p14.)
		Teacher College STEM	Changing STEM Teacher Salary and Compensation		
		Industry College STEM	Changing the class size		
		Teacher Workforce STEM & Not			
		Industry STEM Workforce			
		STEM Labor Supply/Demand Feedback Loop			
		U.S. Population			
Sandia	Attractiveness of STEM Careers	K12 with degree of STEM literacy	Lift H1-B Visa Cap	1983-2033	To historical tendencies
		Undergrad & Grad School	Boost K-12 STEM literacy		
		Workers Entry Level (EL)	Curb offshoring of jobs		
		Workers Higher Level (HL)	Maintain STEM worker training		
		Imported Workers			
		Jobs EL Domestic & Offshored			
		Jobs HL Domestic			
		Continuing Education, EL			
		Continuing Education, HL			
		Labor Adequacy EL			
		Labor Adequacy HL			
		STEM Attractiveness			
SimBlox NIH	Concern about aging demographics of Principal Investigator (PI) Pool	An aging chain of Principal Investigators	Adding various numbers of new young PI's to the PI Pool	1980-2020	To historical demographic age distributions

Table 1 Model Comparison

The Raytheon model is similar to the MIT model, except that its stock-flow structures are much more disaggregated; thus the Raytheon model contains much more detail. Further comparing the two models, the MIT model is much more a research model developing a plausible dynamic hypothesis for understanding past behavior, whereas the Raytheon model was born out of a desire to find and test policies to achieve a specific future behavioral goal – to double STEM college graduates by 2015. The Raytheon model was not tested to reproduce historical behavior; indeed in the "Plans" section of their paper Wells et al. (2008, p14) write that current work is aimed at "validating the model against historical data." Given the similarities between the two models, the "validation" of the Raytheon model against history could probably benefit from the MIT work in this area. Further, both models tested, to different degrees, a policy of increasing teacher salaries. Again, our thinking on the effectiveness of increasing teacher salaries could probably benefit from a detailed comparison of various degrees of implementation of this policy as they play out over time in both models.

The Sandia model focuses on STEM career attractiveness, a concept which is explicit in the MIT model and implicit in the Raytheon model. Whereas the only influences on STEM career attractiveness in the MIT model are wages, the Sandia model includes additional influences such as perceptions of 1) availability of STEM jobs, 2) offshoring of STEM jobs, 3) possibility of promotion, and 4) job tenure. Thus one begins to see the possibility that industry and government policies could endogenously affect STEM workforce availability. In addition, the Sandia model is the only model of the five to explicitly differentiate between 1) entry and higher level STEM jobs, 2) entry level and higher level continuing education, 3) entry and higher level STEM workers and demand, and 4) STEM undergraduate and graduate school and their relationships to entry and higher level STEM jobs.

The SimBlox/NIH model, at its current stage of development, is primarily a demographic simulation model that can test the age-demographic effects over time of NIH research project selection policies. Referring back to the Boeing model, this work begins to endogenize the R&D investment policy in the Boeing model.

Thoughts on Future Work

It is remarkable that BHEF and Ohio State University have stood up an organization, the STEM Research and Modeling Network (SRMN - http://www.stemnetwork.org/), that is implementing a process for releasing and maintaining open source models in this problem area, with support and guidance from the research community. The open-source availability of such models should, over time, improve our national conversation, enabling us to infer better implications as we test our various proposed policies against this dynamically complex nonlinear system of many feedback loops and long delays, helping us to avoid wasted effort and unintended consequences. In the shorter term, however, we see three broad implications of our comparison of these models.

First, the thinking underlying the current MIT, Raytheon and Sandia models should be combined to increase our individual and collective confidence that the models are useful for testing the policies we've designed the models to test, given our boundaries and other assumptions. Would our policy insights be robust if tested against a model that takes into account the thinking and research underlying all three model structures?

Second, as John Sterman (2000, p. 222) and Barry Richmond (1993, p. 132) recommend, we should "challenge the clouds." In system dynamics models the clouds mark the boundaries of the model, and our thinking. When we look into the clouds we are expanding the boundaries of our thinking. Examples in this context are looking beyond STEM education in K12 to education in general? For example, is the capacity of American children to learn at any given age undergoing slow erosion, and, if so, why? What is the system that is causing such erosion? We could look further, beyond education, as the Boeing model implies. Are our R&D investment and immigration policies contributing to, or useful, in addressing our problems?

Third, earlier we mentioned that SRMN has released the Raytheon model as their first open-source model made freely available online at http://stemnetwork.org/. This first open-source release contains an interface suitable for modelers, and perhaps some researchers who are model-savvy. But, given the complexity of the model, it is probably be unsuitable for most policy-makers themselves. Careful thought should be given to development of models and interfaces suitable for policy-makers and their immediate staff, to be included in future SRMN releases. We believe that such development is best a process of collaboration among policy-makers, modelers, model interface and communication experts, and research communities.

Finally, we thank all the people from Raytheon, Sandia National Labs, MIT, Brandeis University, SimBlox, and Boeing who have worked so hard to make this session possible. We hope that our modeling efforts together to improve our national conversation can have a meaningful impact on the future of our country.

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