Systems Engineering the U.S. Education System

Brian H. Wells, H. Alex Sanchez and Dr. Joanne M. Attridge
Raytheon Company, Waltham, MA, 02451-1219.
brian_h_wells@raytheon.com

Abstract. This paper presents the recent and on-going activities that are applying systems engineering to the U.S. education systems to identify potential improvements that will increase student proficiency and interest in Science, Technology, Engineering and Mathematics (STEM). Because applying the methods of systems engineering to a complex human system, like the U.S. education system, is somewhat novel, system dynamics modeling, which is not typically used in aerospace systems engineering projects, was required. Also, because of a lack of systems specific expertise and the need for new and diverse ideas, the project was performed as a student project with competing teams. The complexity of the U.S. education systems required an examination of the total system and then focusing on a limited portion of the system. This paper shows how the complexity was dealt with and how the particular area for detailed examination was selected. Current activities and plans are also presented.

1. Introduction

The systems engineering discipline evolved from the needs associated with the development of complex aerospace and weapon systems. Its origins can be traced to the rapid growth of technology around the time of World War II (Kossiakoff and Sweet 2003). It is proven effective when applied to unprecedented system designs and for the evolution of system improvements. More recently, systems engineering is being applied to systems of systems where most of the systems are beyond the control of the designer.

The U.S. education system is not an aerospace product, weapon system or a Department of Defense (DoD) system of systems. It is not composed of high technology products or systems. It is a complex social system that is composed primarily of policies and people. From the point of view of the number of components and numbers of people, the U.S. education system is one of the most complex systems on the planet. The largest part of the system, the elementary and secondary U.S. public education system, with more than 15,000 public school districts, 3.2 million elementary and secondary public school teachers and 49 million public school students (kindergarten to 12th grade) is so large that there is very little that compares to it in size and scope. Add to that the private elementary and secondary schools and the thousands of U.S. colleges and universities and the personnel that run these institutions and the system becomes far more complex with a total student population (public and private) in excess of 70 million and expenditures of nearly 1 trillion dollars (U.S. Dept Ed 2006).

A search of the INCOSE database indicates that examples of the application of systems engineering or systems thinking to the U.S. education system are rare and that none have been published within the past several years. While system dynamics modeling has been applied to education systems world wide (Mehmood 2005, Rodrigues et al. 2004 and Gorbbelaar et al. 2006) none of the examples found include dynamic modeling of the U.S. education system.

The unique aspects of the U.S. education system require tailoring of the systems engineering process and the addition of research and experimentation steps that are more extensive than is typical in an aerospace product development. Opportunities for direct experimentation that introduce changes to the systems without prior knowledge of the outcome are very limited. This is due both to the difficulty of controlling the environment and due to the stigma attached to the idea of experimenting with children. However, most of the systems engineering process steps used to address the education system follow the standards and take advantage of the systems engineering best practices developed by the community over the past 50 years. The application of the process and the tailoring of the standard process will be presented to illustrate the unique aspects of addressing a complex social system.

The complexity of the education systems also demanded that the total architecture be defined and considered, but that the evaluations and modeling effort be focused on a very limited part of the total system. Narrowing the scope of the systems engineering activities by clearly defining the system and its boundaries, and then further defining the subset of the architecture that would be included in the analysis was an essential part of the project. The modeling approach, key assumptions, and initial results were presented in (Wells, et al. 2007).

The paper presents the systems engineering approach used, tying it to the standard systems engineering processes. Additional detail on how the project was carried out using systems engineering students is provided to illustrate some of the unique aspects of the work. Then the steps that led to the specific areas examined are presented. These include the definition of the system, and the many external interfaces (influences), the development of the architecture description, the research and analysis that provided the focus to the system analysis activities, the modeling approach and the results. The continuing activities are presented along with a summary of the conclusions reached as a result of this project.

2. Approach

The project was initiated by Raytheon CEO Bill Swanson who believed that the same systems engineering methods used to create complex aerospace and military systems for the U.S. government could be applied to the U.S. education system. The original purpose of the project was to address this hypothesis and to determine if it could be demonstrated to be correct.

The problem statement was derived from the Business Higher Education Forum (BHEF). BHEF was founded to “advance innovative solutions to [the] nation’s education challenges in order to enhance U.S. competitiveness.” In its Spring 2006 Forum Focus, the BHEF described a future in which, owing to a shortage of trained workers in the fields of science, technology, engineering, and mathematics (STEM), the United States is no longer a leading contributor in science and technology developments (BHEF 2006). For this project the students are viewed as the users and the BHEF was treated like the customer with the recognition that there are many stakeholders that must also be considered as part of the solutions examined and proposed.

This project is unlike the typical systems engineering effort at Raytheon in many ways. It is not the development of a government system, the work activities are not directly funded by a contract, some of the systems engineering activities being performed are unique, and the work is not supported by existing subject matter experts or an existing organization. These unique aspects required substantial learning and research, involvement of outside experts and creation of process tailoring and new methods that are not in use on our DoD programs.

The systems engineering process tasks as defined in the INCOSE SE Handbook, Section 4 (INCOSE 2004) along with the modified and additional steps used are shown in Table 1 below. The steps that are different, compared to typical DoD programs, are highlighted in italics.

Table 1 Systems engineering process steps applied and results.

Systems Engineering Process Steps (INCOSE 2004)	**Results or Approach**
[Define the system and the system boundaries]	Typically customer defined. See Figure 1
Define the System Objectives (User's Needs)	From (BHEF 2006): American Leadership in STEM, Increased numbers of U.S. citizen STEM graduates.
Establish the Functionality (Functional Analysis)	
[Research characteristics of the current education system]	*Development of expertise was required.* See Architecture Description Section
Establish Performance Requirements (Requirements Analysis)	Double the number of STEM BS graduates in ten years.
[Identify the existing systems architecture]	*Research and literature searches to develop an architecture description.* See Figures 2 and 3.
[Determine the influences that affect student capabilities and interests]	*Creation of influence diagrams, similar to interface diagrams.* See Figures 4 and 5.
Evolve Design and Operations Concepts (Architecture Synthesis)	*Literature searches to find proposed system changes and supporting data.*
Select a Baseline (Cost/Benefit Analysis)	Based on description of the current U.S. education system. See Modeling Section
Verify that the Baseline Meets Requirements (User's Needs)	
[*System Dynamics* Modeling and simulation]	*System Dynamics Model.* See Modeling Section.
[Experimentation using system dynamics models]	*Modeling substituted for prototypes.* See Results Section.
Validate that the Baseline Satisfies the User (User's Needs)	*Consultation with education experts.* Actual validation activities to be performed in the future.
Iterate the Process through Lower Level Analysis (Decomposition)	In-progress work activities. See Plans Section

The work started with defining the system and the system boundaries. The results and some of the variations considered are presented below. This is complicated by the fact that there are many possible ways to draw the boundaries of the system and that clear definition of the system and its boundaries is necessary for generation of the model. Unlike DoD systems, there are few physical interfaces such as cables, communication links, or mechanical connections within the U.S. education system that can be used to establish the boundaries. Almost all education systems boundaries consist of human interactions.

Research was another essential task. Expertise needed to be developed, and the proposed solutions of researchers using other techniques, such as economic analysis, need to be understood and considered. Unlike DoD programs the subject matter experts for the education system are not engineers, they are typically educators, economists and government policy makers.

Modeling of the education system required that identification of the existing system architecture as opposed to performing architecture synthesis. Modeling and simulation was substituted for prototyping of the actual system. System dynamics models based on the work of Jay Forester in the 1950's (Forrester 1961) were developed to model the human interactions and decisions, in contrast to aerospace models that are typically physics based.

These unique aspects of the project meant that the experienced engineers who are subject matter experts in typical DoD systems were not the best candidates for performing the project. Younger, less experienced engineers that are more adaptable and eager to learn were judged to be better candidates. This conclusion led to the most significant difference between this project and the typical DoD program, the use of systems engineering student teams to perform the work.

3. Systems Engineering Technical Development Program

Raytheon is a producer of systems for defense and government electronics, space, information technology, technical services, and business and special mission aircraft. The company applies systems engineering skills to areas such as Missile Defense; Precision Engagement; Intelligence, Surveillance and Reconnaissance; and Homeland Security. To develop lead systems engineers and chief engineers Raytheon provides a 6 week Systems Engineering Technical Development Program (SEtdp) that exposes the students to the many aspects of the company business and to all aspects of systems engineering. To successfully complete the class student must complete a systems engineering project. The projects are performed by teams of 5 or 6 students. The 25 to 30 students within each class form 4 to 5 teams that complete for a monetary prize awarded based on the assessment of a panel of systems engineering experts that represent businesses from across the company.

SEtdp projects are ten months in duration with each team participant spending about 200 hours working on the project over the ten months. Two in-process reviews are held where the teams present their approach and receive advice from the expert reviewers. In addition, a final report and a final presentation are required. These items are reviewed by a panel of experts and judged to determine the winning team.

Four teams competed to see which could create the best model of students’ progression through the educational system. The models created examine the flow rate of the students. They include some of the many influences that affect young people as they progress from kindergarten through college graduation and entry into the workforce. Based on architecture work and analysis performed prior to the project, the Raytheon SEtdp students were asked to focus on factors that influence the STEM graduation rate from college.

For the initial competition the teams were all provided with the same assignment and they competed head to head. The goal was to get a diverse set of ideas and methods applied early in the project to be sure that at least one of the teams would generate an effective approach to solving this challenging and unfamiliar problem. While this parallel approach was successful, in that two of the four teams successfully created models that met the project requirements, it did create other problems. The competing teams did not share any information. Only the SEtdp leaders directing the project teams saw the full scope of the work performed by the teams. This made it necessary to create an additional model that integrated the best data and methods from all of the teams. The integrated model is the one presented herein.

The use of student project teams was effective in generating a large research database that included a broad range of data and proposed system improvements. Each of the teams uncovered unique aspects of the system and produced models that examined the factors in different ways. This broad spectrum of information and ideas enabled a rapid evolution of knowledge and identification of many potential solution sets. Without this competitive approach and the multiple teams’ parallel efforts, it is doubtful that the model would have matured adequately in the short period of time available.

4. Requirements Definition

There has been a great deal of debate about the requirements for the U.S. education system. This debate has included whether or not there is or will be a shortage of STEM workers (RAND 2007). Across all of this debate it has become clear that the U.S. is losing its leadership position in the world economy and that this is due in part to other countries better educating their children (NSB 2006A and NAS 2006B). For this project the many viewpoints generated by this debate were reviewed and the BHEF's version of the goals and requirements was adopted.

BHEF in its Forum Focus, Spring 2006 (BHEF 2006), identify the goals as:

1) Maintain American leadership in the world economy and
2) Maintain leadership in science and technology.

These goals are clearly associated with a system that includes the entire nation. Within this broad national system the requirements and system redesign would need to be applied to all aspects of the U.S. economy. Because the focus of the project is the education system a flow down of the requirements was necessary.

The BHEF publication continues by stating that there are low student participation and achievement in mathematics and science, specifically among women and minorities and a shortage of highly qualified teachers. These were translated into the following requirements:

1) Increase student participation in mathematics and science, and
2) Increase the numbers and capabilities of STEM teachers.

These lower level requirements directly support the higher level goals for the entire U.S. economy by improving the education of its citizens which is directly linked to economic leadership and leadership in science and technology.

The first requirement was further definitized by changing it to: double the number of STEM graduates receiving bachelor's degrees within ten years. Prediction of the need for STEM workers vary, with (NSB, 2006B) for example showing a 25% increase in all science and technology fields in ten years (2002 – 2012) and as high as a 37% increase in computer science and mathematics. Data shows that only half of the people trained in STEM are employed as STEM workers, so the 25% overall and 37% for computer science and mathematics could produce requirements for STEM graduates that are as high as 50% and 74%, respectively, in ten years. So while doubling may be a greater increase than is supported by the current data, achieving this requirement should provide margin.

5. System Definition

There are many possible systems and system boundaries that can be established and used as the basis for the modeling and system analyses related to the education system. The initial BHEF statement of goals covered much more than the education system. However, the only way to make the challenge tractable is to limit the extent of the system and the scope of the analysis.

At the highest level the system is defined as the educational system that produces the trained workers necessary for satisfying the demands of U.S. business, government and academic organizations. The input is children and the output is educated college graduates ready to be hired into the workforce. Figure 1 shows the context diagram for the education system and the external systems that influence it. The government (federal, state and local), parents, society (including the media), industry and donors are considered external to the education system.

During one portion of the analysis it was necessary to consider industry as part of the model because there is competition between teaching and industry in the recruiting and hiring of STEM interested students. This variation is discussed in (Wells, et al. 2007).

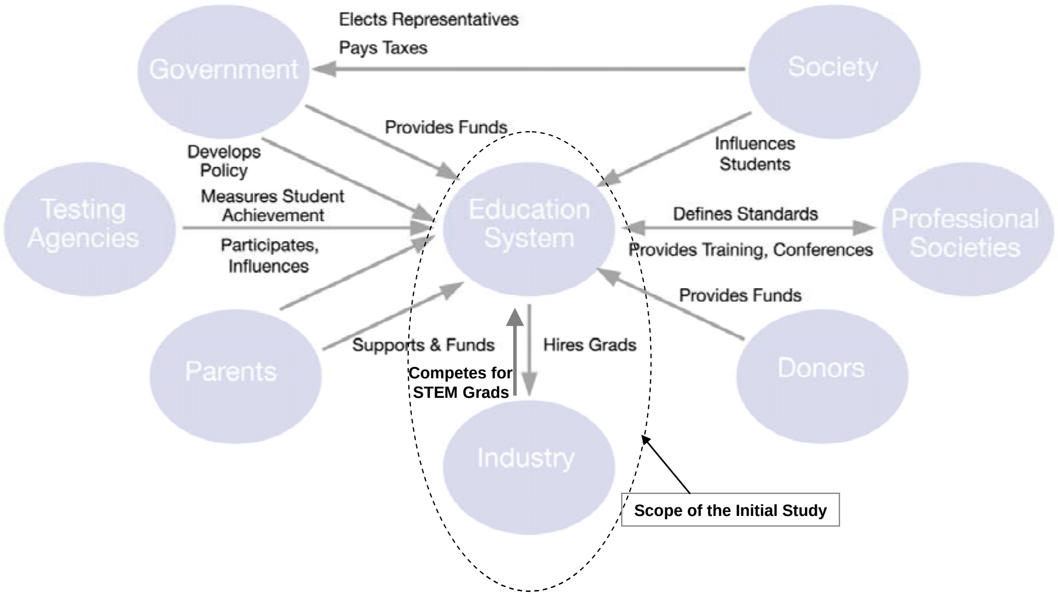

Figure 1 – Context Diagram for the Education System

6. Architecture Identification

The U.S. education system is comprised of elementary and secondary schools, 90% public and 10% private. It also includes the numerous accredited colleges and universities that grant associates, bachelors and advanced degrees. Figure 2 shows the first level of the architecture and indicates the portion that is considered in this study. Given the requirements, the scope of the study was limited to the portion of the system that produces students with a bachelor's degree. In addition, the study was limited to public K-12 schools only due to the unique nature of most private K-12 schools and the many differences in how private schools are operated.

Further examination also showed that the influence on the student interest in STEM is greatest after fourth grade. As a result the analysis of changes in student interest was limited to students in 5th to 12th grades, where the influences have the greatest effect. So the elementary education system was further decomposed into kindergarten to fourth grade, and 5th/6th grades.

The undergraduate portion of the system includes colleges and universities that grant 2 year associates degrees and that grant 4 year bachelor's degrees. Within this study the analysis and modeling has been limited to institutions that grant 4 year bachelor's degrees because this level of degree is required for teaching and for most STEM jobs in industry.

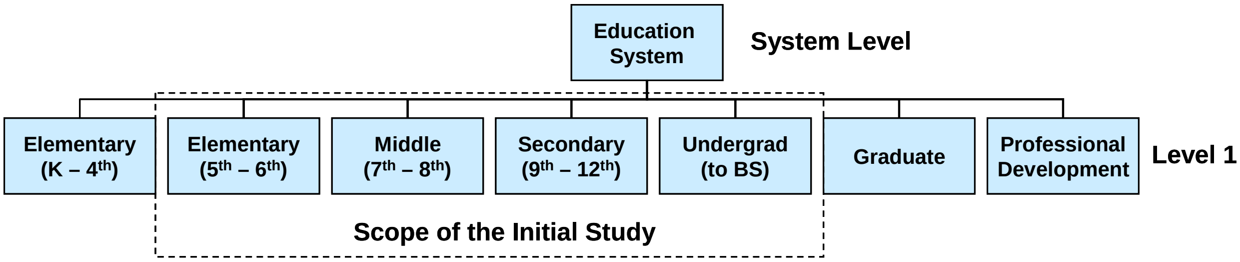

Figure 2 –Level 1 of the education system architecture decomposed by grade levels.

As shown in Figure 3 each of these subsystems includes facilities, teachers, administrators, guidance counselors, and support staff. While all of these influence the students, the teachers provide the greatest influence (Hanushek 2002), so the initial studies focused on teachers. This focus is supported by the research and the literature that provides substantial data on teachers and their influence on students. Similar data for the other level 2 elements could not be found.

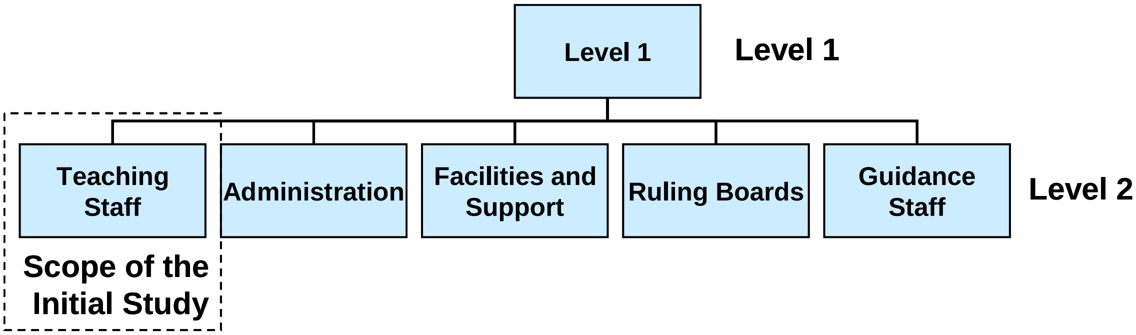

Figure 3 – Level 2 of education systems architecture decomposed by function.

Early activities aimed at determining what influences student interest and capabilities created spreadsheets that were the equivalent of N-squared diagrams. The data from these was then converted into influence diagrams, such as Figure 4. The influences come from elements both within the U.S. education system and from elements external to the system. The factors that influence students' capabilities and interest in STEM the most are external to the U.S. education systems. These influences come from the student's socio-economic background, parents, peers, and society. The objective of the study was to examine changes and improvements to the U.S. education system, so the exogenous influence factors shown in Figure 4 were not included in the analysis or the model. The student factors that related to homework, tutoring and attention in class were also deferred to later studies.

The initial studies concentrated on how teachers influenced student capabilities and interest. Research into teacher qualifications and enthusiasm quickly revealed that these two parameters were not well quantified and that there was little data to support the implementation of these variables within the model. This resulted in the definition of a new variable; STEM-capable. Analytical support for this as the measure of teacher capability was derived from (Gordon, et al. 2006) who showed that teachers ability to improve their students math scores, relative to the total population of students, has a normal distribution that has a slightly negative mean. This led to a definition of STEM-capable teachers as those that improve their students' average math score relative to the total population and not-STEM-capable as teachers who reduce their students' average math scores relative to the total population. The impact of teacher training could not be substantiated by the existing research data, nor could the affect of teacher recognition. The available data shows little correlation between most of the common forms of teacher training, such as obtaining a masters degree, and student performance. Because no positive correlation could be established for these parameters, they are not included in the initial version of the model.

A great deal of data exists on how teachers are affected by salary and benefits, and the affects of class size. So these were researched and included in the model as secondary influence factors.

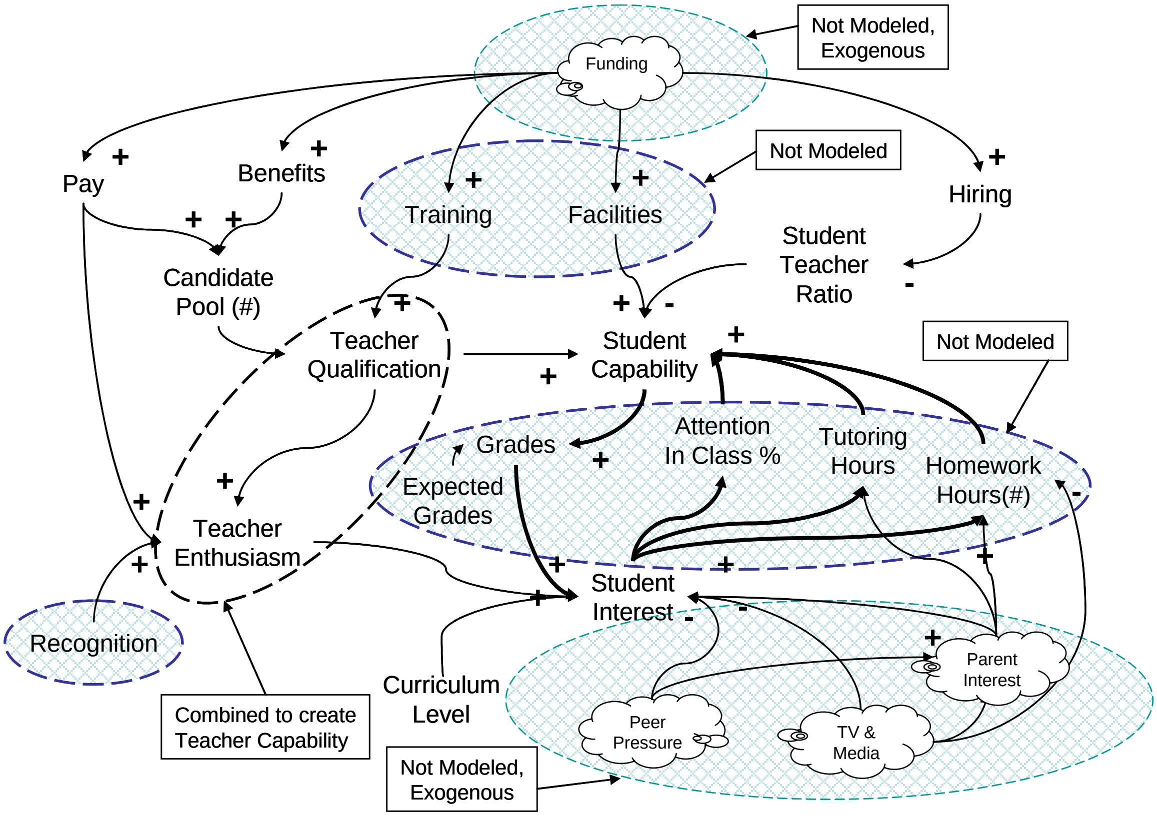

Figure 4 – Initial influence diagram with areas not modeled in initial study indicated.

7. Modeling

System Dynamics Modeling. Several modeling methods were considered and a few tried before the system dynamics modeling methods and the Vensim (Vensim is a registered trademark of Ventana Systems, Inc.) tool was selected. The modeling of human interactions can not be accomplished using physics based models that are typical within the defense industry. While other methods, appropriate for modeling humans were considered, Vensim was selected due to its low cost, easy of use and the more than four decades of experience behind the system dynamics modeling methods it employs.

Dynamic Hypothesis. Several dynamic hypotheses were considered. The first was that increasing the salary of teachers, especially STEM teachers, would attract and retain more capable teachers and improve student performance. The second hypothesis was that increasing class size would have an effect on student performance by decreasing the demand for teachers and allowing more capable teachers to be hired. The third hypothesis was that identifying the least effective teachers and denying them tenure at three years of experience will lead to attrition of these least effective teachers that will then improve student performance and interest in STEM. These three hypotheses were captured in the dynamic hypothesis, shown in Figure 5, and included in the dynamic model of the system.

In Figure 5, arrows show the causal relationship between the variables, and indicate the flow of change. A positive (+) sign on the arrow indicates positive flow, i.e. when the value of the input variable increases, the output variable also increases. A negative (-) sign on the arrow indicates negative (or opposite) flow, i.e. when the value of the input variable increases, the output variable decreases. The positive feedback loops create the significant changes that are required to improve the U.S. education system.

Stock and Flow Model. The stock and flow model for the U.S. education systems represents the flow of students through the system from birth to retirement. Stocks define the state of the system. They represent "things" that accumulate, for example numbers of students. Flows define the rate of change in system states, for example the rate at which students graduate from high school. Various flow paths model students that are interested in STEM and those that are not interested. Additional flows are created to model students that become teachers or go into industry. The modeling method allows for numerous alternative flows and provides a means of controlling the flow into and out of each stock (group of people) using the dynamic hypothesis as the basis. Figure 6 provides only a summary view of the complete stock and flow model developed; the full model is too complex to capture in this document.

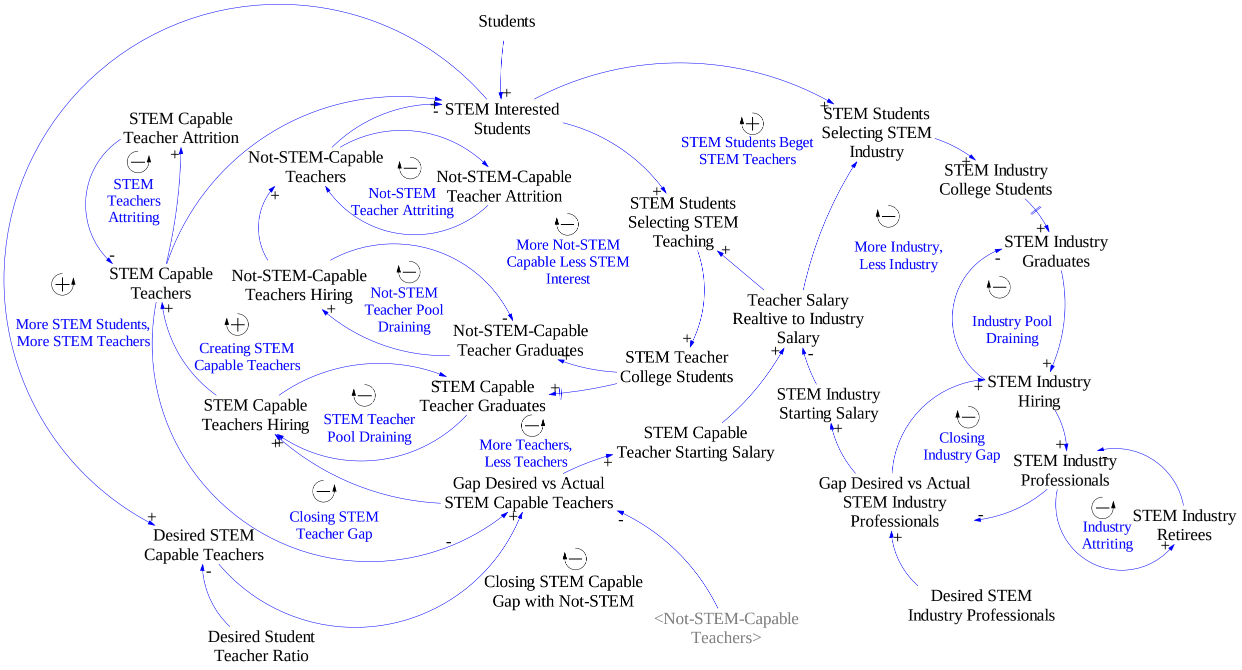

Figure 5. Influence diagram representing the dynamic hypotheses.

The complete model begins with a simple left-to-right structure. (see Figure 6) Students are born and enter the education system on the left side of the model and then progress from grade to grade, graduate from high school, attend college, get a job, gain experience, and eventually retire out the right side of the model. The flow represented by this chain of events is subdivided in the Kindergarten-12th grade years as follows: one chain tracks STEM interested students and the other tracks students who are not interested in STEM. Students who do not pursue a STEM major in college are not tracked post high school graduation. STEM interested students who graduate from high school and pursue a STEM major in college, or an education major related to STEM, are tracked, and flow into the next portion of the model.

The model includes a flow in each grade between the STEM interested students (stock) and the STEM uninterested students (also a stock). These flows represent the rates at which students become uninterested in STEM. For this study, only teacher influence and its effect on STEM interest has been considered. Teachers have the potential for moving students up or down in the rankings. STEM-capable teachers move students up relative to the average, while not-STEM-capable teachers move students down. For the model it was assumed that students that are proficient or advanced at math are interested in STEM.

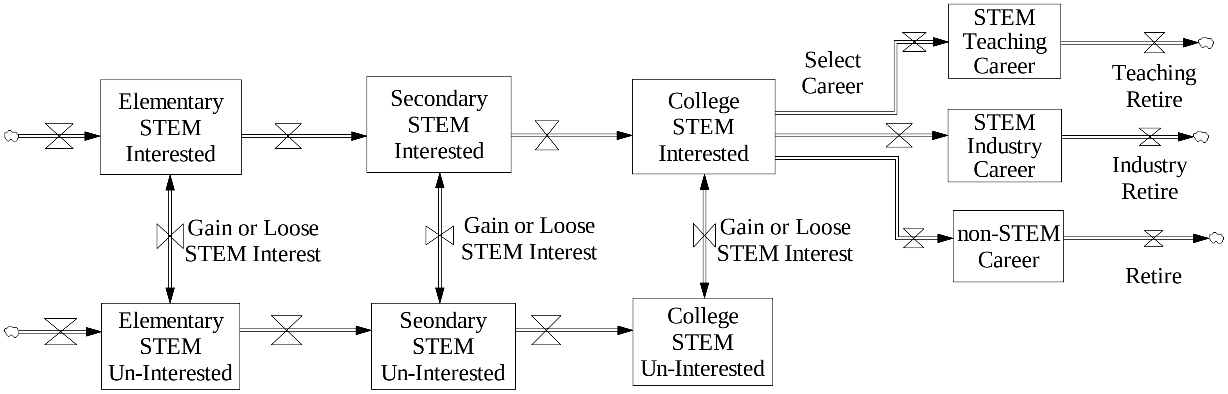

Figure 6. Simplified student flow model.

Post-college the model is divided into two major chains: STEM interested students who pursue a career in teaching STEM, and STEM interested students who pursue a career in industry. These chains each have two elements: the time spent in college, and the time spent employed in the chosen profession. The STEM interested students who pursue a career in STEM teaching are further divided into four chains: 5th-8th grade STEM-capable teachers, 5th-8th grade not-STEM-capable teachers, 9th-12th grade STEM-capable teachers, and 9th-12th grade not-STEM-capable teachers. These divisions allow examination of the dynamics of being taught by a STEM capable teacher versus a not-STEM-capable teacher.

Data related to the U.S. education system are limited and often contradictory. An essential step in the modeling process is to examine the data and determine if they are adequate for the creation of a valid model. Often the validity cannot be established from the data, and in these cases modeling assumptions must be made. The assumptions allow the modeling activity to proceed, but each assumption must be validated with further research before the model can be declared validated. (Wells, et al. 2007) lists and explains the modeling assumptions required, due to limited data availability, for the initial evaluations.

Each of these assumptions, if changed, has a significant impact on the modeling results. One of the advantages of modeling the U.S. education system is that it allows for examination of many possible assumptions to see which have a significant impact on the results. The assumptions that dramatically change the simulation results are the ones that should receive priority in future research activities.

8. Results

During the study many factors were examined and considered for implementation in the model. After researching, evaluating and reviewing each hypothesis, candidates were selected for detailed examination using the model. One of the changes provided an increase in the numbers of STEM graduates that nearly met the requirements. This policy change introduced attrition, through denial of tenure to the teachers who have not demonstrated their capabilities within their first three years teaching. This policy change can be enhanced by training, mentoring and other teacher development programs that improve performance. This approach has a dynamic hypothesis that could be implemented within the highly constrained U.S. education system, and that has significant potential for improving the system.

A baseline model was run that introduced no changes to the U.S. education system. This run used constant population statistics to avoid dynamic changes that result from population variations. Initial conditions were set to continue current education system policies, resulting in little change during the decades modeled. The level of student interest and capability in each grade remains nearly constant as expected.

The second run of the model examined the results of implementing a dynamic hypothesis that introduces attrition within the ranks of teachers having three years of experience who were rated in the lowest 10% of their peer group. A third run examined an alternate case with attrition of all teachers rated in the bottom 25% of their peer group. These runs show sensitivity to this particular change in education policy.

Figure 8 displays the comparison between the baseline and the new policies that create 10% and 25% attrition among the lowest-rated third year teachers.

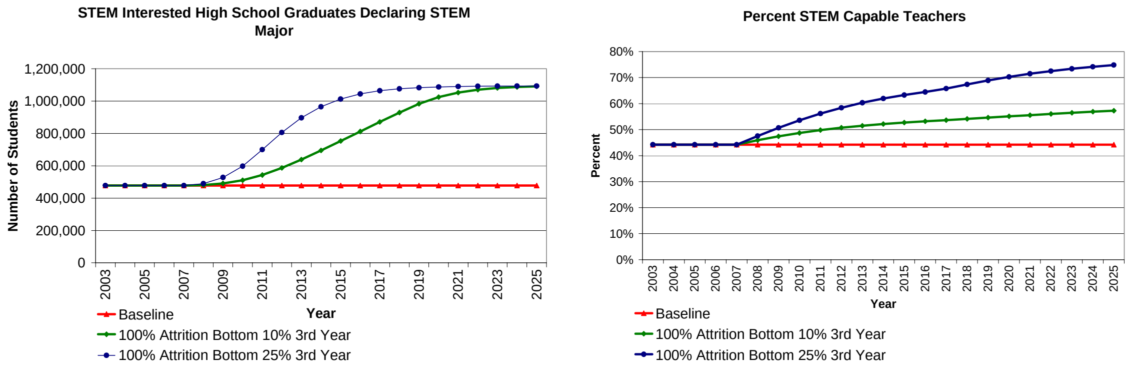

Figure 8. Baseline case (red) compared to the improvement provided by implementing the dynamic hypothesis with attrition of lowest 10% (green) and attrition of the lowest 25% (blue).

Implementation of the policy defined in the dynamic hypothesis provided a dramatic change in the numbers of STEM-capable teachers, and in the numbers of students that are proficient or advanced in math and presumed to be interested in STEM.

9. Status of Continuing Research and Plans

This paper presents the initial version of a system dynamics model of the U.S. education system developed over the past year. Initial investigations focused on grades five through twelve and used aggregate data for the total U.S. public education system population. The available data clearly indicate the existence of distinct populations who behave differently from the average student within the U.S. education system. Among these populations are women and disadvantaged students, especially those attending inner city schools.

Current work activities are aimed at modeling the subsets of the population and validating the model against historical data. Raytheon plans on continuing the modeling effort through 2008, after which the model will be made available as an "open source" on the internet to anyone who is interested. Publication of the model and support for the model in the future is likely to be provided by the BHEF. It is hoped that additional research will be performed by a community of researchers who will enhance the model, increase its fidelity, and provide validation.

On-going modeling activities are enhancing the model to allow separate examination of the current state of men and women in regards to STEM, and to then effectively model the impact of proposed changes on each population. The populations of men and women behave differently and are influenced either by different factors or in differing amounts. This enhanced version of the model should provide a much better means of examining student interest in fields such as engineering, where men and women participate in very different numbers.

Another modeling activity is separating advantaged and disadvantaged school populations. The factors and influences that impact students in disadvantaged schools are very different from those that impact the average population. Research shows that disadvantaged schools are affected by a sorting process that results in the higher-performing students and teachers migrating to the better school districts. Combine this hollowing-out with reduced financial assets due to lower per-capita taxes, and these disadvantaged schools end up with the greatest challenges. Further modeling and examination of the affects of increased incentives to attract better teachers to disadvantaged schools is being conducted.

A third modeling activity examines attrition among college students in an effort to better understand why only 40% of first-year students who declare a STEM major graduate with a STEM degree. This examination is looking at and modeling the numerous factors that lead to attrition, and is modeling the potential improvements that result from activities such as mentoring and tutoring students. Another factor being considered is possible incentives for colleges and universities based on how many STEM graduates they produce.

10. Summary

Systems engineering and systems thinking provide a means of examining the need for more STEM capable graduates from the U.S. education system. Despite the complexity of the U.S. education system, the standard systems engineering processes enabled the decomposition of the system and the organization of the analysis such that specific factors can be examined and new policies evaluated in an effective manner.

System dynamics modeling provided an effective means of modeling this complex system that contains more analytical unknown than known parameters and relationships. While a number of critical assumptions were required to create the executable model, the assumptions are ones that can be examined using the model and checked by future research and data collection. In most cases the model was run with alternate versions of the assumptions to provide a better understanding of how these factors influence the system.

While this initial version of the U.S. education system model does not have the fidelity or the validity to provide high confidence predictions of how the system will react to policy changes, it is clear that systems engineering methods can be used to create more advanced versions of the model. With adequate research to support the model, the fidelity can be increased and the results can be validated to a point where the model will be an accurate predictor of how the U.S. education system responds to policy changes.

11. Acknowledgements

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BIOGRAPHIES

Brian Wells is the Raytheon Chief Systems Engineer and a Senior Principal Engineering Fellow within the Raytheon Corporate engineering organization. Prior to this assignment, he was the Technical Director of the Future Naval Capabilities organization and the Total Ship Systems Engineering Lead for the Navy's DDG 1000 Zumwalt program. He holds a Bachelor's degree in Electrical Engineering from Bucknell University (1975) and a Master's degree in Electrical Engineering from the University of Illinois (1976). He is a member of the International Council on Systems Engineering (INCOSE), Institute of Electrical and Electronics Engineers (IEEE), and the National Defense Industrial Association (NDIA).

H. Alex Sanchez is a Senior Principal Systems Engineer on the Mission Innovation Cross Business Team for Raytheon Integrated Defense Systems (IDS). Prior to this assignment Alex served as Program Manager for Collaborative Solutions. Prior to joining Raytheon Alex worked in the semiconductor and jet engine industries. Alex holds a Bachelor of Science in Mechanical Engineering from Boston University (1995), and a joint Master of Science in Engineering and Management in System Design and Management from the Sloan School of Management and the School of Engineering at the Massachusetts Institute of Technology (1999).

Dr. Joanne Attridge works for Raytheon Integrated Defense Systems (IDS) as a Systems Engineering Manager for the PATRIOT Radar Surveillance group. Prior to joining Raytheon three years ago, Joanne worked as a Research Scientist in Radio Astronomy at the Massachusetts Institute of Technology's Haystack Observatory. She was awarded Raytheon Technical Honors in 2006. Joanne received a Bachelors degree in Astronomy from Wellesley College in 1989, a Master's degree in Astronomy from Wesleyan University in 1992, a Masters degree in Physics from Brandeis University in 1994, and a Ph.D. in Physics from Brandeis University in 1998.