Modeling Student Interest in Science, Technology, Engineering and Mathematics

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Abstract **- This paper presents preliminary results of a Raytheon project that uses systems engineering techniques to understand the intricacies of the U.S. educational system and to assist in the evaluation of proposed system changes with a goal of doubling the numbers of science, technology, engineering and mathematics (STEM) college graduates by 2015. Specifically, a system dynamics model has been developed, the initial version of which targets increasing the number of students both capable and interested in pursuing careers in STEM disciplines. To examine student interest and capabilities in STEM, the flow of students through the education system and the workforce are modeled. Separate flows delineate students that are interested and uninterested in STEM. Of those interested, the model further separates the students into those interested in teaching STEM, and those who are interested in STEM careers in industry. A few scenarios have been analyzed that examine changes for improving student capabilities. These scenarios investigate how teacher competency affects student interest and capability in STEM. Variations in teachers' capabilities caused by changes in teacher salary, class size, and tenure and retention policies are examined. The structure of the model allows it to be easily adapted to test new scenarios. For example, it is possible to separate out the career paths of specific groups, such as engineers, rather than looking at all STEM disciplines at once. Initial results provide insight into the value and viability of a few proposed changes and indicate that with continued research, model development, and analysis it will be possible to further assess proposed improvements in the U.S education system. Once effective improvements are identified, a roadmap can be created to provide policy makers with direction for future action. The ultimate goal of this project is to make the model available as an open source for use by a broad community of researchers. While much remains to be done, the systems engineering techniques and system dynamics model presented here provide a starting point for understanding the U.S. education system.**

I. INTRODUCTION

The Business-Higher Education Forum (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 [1]. Though there has been debate over the nature, scale, and to a degree the existence, of this problem, most experts seem in agreement that the problem is real and increasing with time [2; 3]. To remain competitive in the global economy, the American education system must provide an ever expanding and highly talented pool of STEM workers. The downward trend in U.S. science and engineering degree attainment could significantly affect the size and composition of the workforce available to industry. From 1980 to 2000, growth in U.S. science and engineering degree production lagged growth in science and engineering jobs. The dearth of U.S. job candidates was mitigated by an influx of foreign-born workers and low retirement rates for scientists and engineers [4]. In projecting forward from 2002 to 2012, the Bureau of Labor Statistics (BLS) estimates the need for science and technology workers will increase by 26% compared to 15% for all occupations. They predict the need for computer/mathematical scientists will increase by 39% and the need for post-secondary teachers will increase by 37% [5]. Without qualified teachers, the U.S. will have a very difficult time training future generations of American-born STEM workers.

To address this problem, the BHEF launched a multi-year initiative, "Securing America's Leadership in Science, Technology, Engineering, and Mathematics," to develop a strategy to double the number of the U.S. STEM college graduates by the year 2015. This initiative investigates a variety of problems that exist in today's education system, such as low student participation, declining achievement in STEM subjects relative to other countries, the shortage of qualified STEM teachers, and the lack of participation by women and minorities in STEM disciplines.

Raytheon Company Chairman and CEO Bill Swanson, who is co-chair of BHEF's STEM initiative, conceived of the idea of applying systems engineering to the U.S. education system as a way to organize the problem and help to determine the effectiveness of proposed solutions so that priorities could be set and guidance could be provided to policy makers. This innovative application of systems engineering skills is part of the company's multi-pronged approach to improving science and math education.

Though the complexity of the U.S. education system makes it very difficult to isolate problems for independent analysis, experts in a number of fields, especially the social sciences, have produced a vast supply of studies and publications addressing a variety of issues. Economists have looked at the role of incentives, such as teacher pay, in producing both well-trained STEM teachers, and in attracting students to STEM fields [6; 7; 8; 9]. The charged political debates in the U.S. over merit pay and student testing demonstrate the controversies generated by certain economic approaches to this problem. Educational theorists have debated just how to define and assess teaching quality, a debate that ties very closely to economic arguments over teacher pay [10; 11; 12]. Initiatives aimed at improving student capabilities, such as reducing class size, have been proposed and implemented with little supporting research. Subsequent research has indicated that class size changes had limited effectiveness and had unintended consequences such as creating a shortage of qualified teachers [13; 14].

Previous work has been done that applies systems engineering principles to the examination of the education system. Of particular value have been the critical path analysis studies produced by the California Council on Science and Technology (CCST) [15; 16]. This method uses a static approach to examine the structure and effectiveness of the California education system. In [16] the CCST researchers conclude; "Perhaps eventually, a more truly dynamic interactive model may be achieved, one that would enable policymakers to understand and respond to the functioning of the overall system on an ongoing basis." The CCST critical path analysis determined that a shortage of mathematics and science teachers persists within California schools, especially low-performing schools. CCST recommended the first step should be legislation to collect teacher workforce data necessary for fully understanding and analyzing the current situation and trends. These data will support initiatives aimed at improving teacher recruiting, professional development and retention.

The analyses in this paper have drawn on the work of these experts – economists, educators, political scientists, and leaders of industry. The majority of the existing research and analyses are limited by being static and too narrowly focused; they investigate one part of the over-arching problem and attempt to expand their conclusions from there. Many changes, when applied, have been successful only in limited applications and others have not produced the expected results. Often the experts and the analysis produce contradictory results, due to the scope limitations of their particular research studies. None of the previous studies found provide a complete description of the system and the problems that confront the U.S. when it comes to the production of STEM graduates. These approaches have been unable to describe how effects, impacts, and changes in one part of the U.S. educational system flow through and impact the other parts of the system or how changes propagate through time.

A dynamic systems engineering based tool that provides a means of examining the intricacies of the entire U.S. education system is necessary to overcome the limitations of past research and analysis. Such a tool will assist in evaluating the effectiveness of proposed solutions, so that priorities can be set and guidance provided to policy makers. In addition, the process of creating this systems engineering tool provides a means of identifying potential solutions and an organized approach for assessing them.

The next section presents identified problems that exist within the U.S. education system, and indicates some potential areas for change. This discussion is followed by a brief introduction to systems engineering, and then system dynamics modeling. These introductions lead into a presentation of the system dynamics model of the U.S. education system, and the results of three case studies. Two of the cases examined were judged to be unacceptable in the current political environment. The third alternative provided the desired increase in STEM students and appears to be within the realm of political acceptability. The results are summarized and plans for future work, including on-going research and analysis, and development of an open source implementation of the model, are provided.

II. THE UNITED STATES EDUCATION SYSTEM

STEM education within the United States constitutes a very complex system that includes public and private institutions starting at pre-school levels and continuing through colleges and universities that offer graduate degrees. For this examination the model was limited to public elementary and secondary schools, and colleges and universities that offer bachelor's degrees in a STEM discipline or a related teaching discipline. Within the U.S., the public elementary and secondary schools contain 90% of the student population. Figure 1 shows the context diagram for the study. Many external organizations influence the education system and student performance. Parents and society have powerful influences on student achievement, but are considered exogenous in this study.

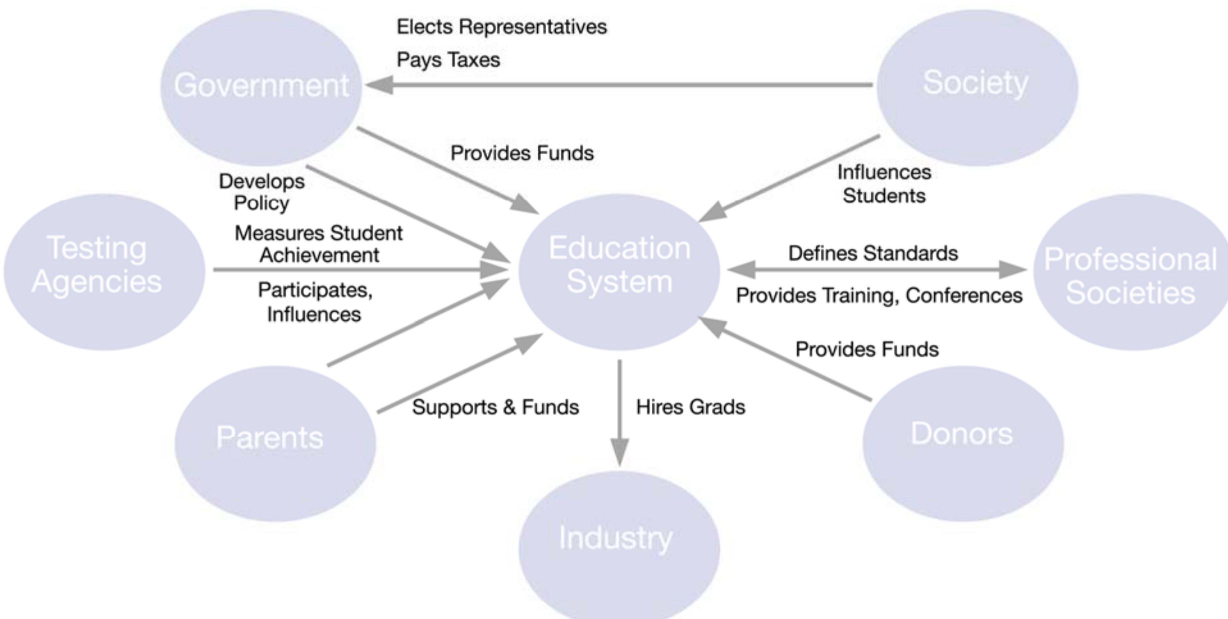

Figure 1. Context diagram defines what is included within the education system model.

The U.S. public education system teaches approximately 3.6 million students in each grade level, from first to eighth grade (see Figure 2). After eighth grade, students begin to drop out of the school system and many do not graduate with their 12^{th} grade class. Of the students that do not graduate within four years, about half never get a degree, while the other half eventually get a degree or a graduate equivalency degree. About 2.5 million students graduate high school each year and most attend college at either a two year or four year institution. Only 23% of the students enrolled in college (15% of the total 3.6 million population) choose to major in a STEM discipline in college and about 40% of those that elect STEM majors freshman year receive a STEM degree within six years (about 6% of the total 3.6 million student population) [17].

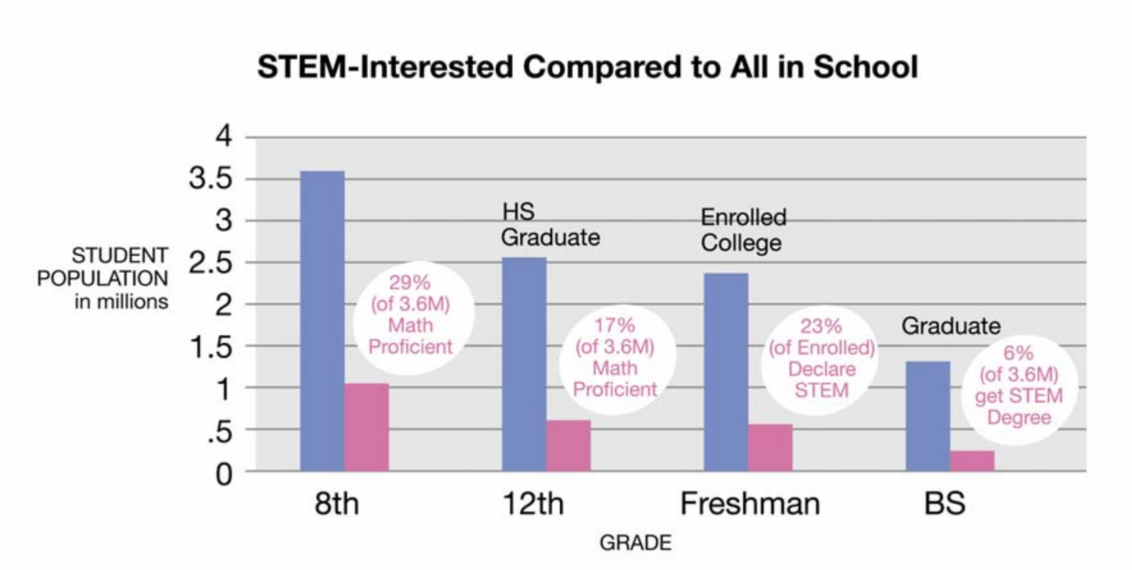

Figure 2. Attrition among students (total), and STEM proficient and interested students.

Students are assessed regularly throughout their education to determine progress in mathematics. For the purpose of this study we selected student capability in math as the indicator of STEM interest. While it is understood that some students are proficient in math but not interested in STEM, there may also be some that are interested in STEM but who have marginal proficiency in mathematics. Math assessments divide the students into the categories of below-basic, basic, proficient and advanced. Proficient and advanced students were equated with STEM interested students, and the assumption was made that this equation is viable from an analytical point of view, even though many exceptions will exist. This assumption is supported by the fact that the numbers of students that are proficient or advanced in math at the 12th grade level are approximately equal to the number that declare their intent to pursue a STEM major freshman year in college [18] and by survey data collected as part of Raytheon's MathMovesU program. The MathMovesU survey data indicate that only 1/3 of middle school (6th to 8th grade) students like math a great deal, and that by eighth grade 45% are turned off to math describing it as "boring" [19].

The students who are proficient or advanced in mathematics represent 36% of their class in 4th grade (see Figure 3). This percentage gradually decreases at about 1.5% per year in elementary and middle school and by about 3% per year in high school as the students progress through the education system. By 12th grade only 17% of the student population is proficient or advanced in math [17]. This flow of students from interested to uninterested, as represented by their capabilities in math and their stated degree major in their freshman year is represented in the model.

Among the many factors within the education system that influence student achievement and interest in mathematics and science, research indicates that the quality of a student's teacher is the most important factor. Statistical analysis indicates that teachers account for about 8.5% of student variation in performance during elementary and high school [11]. Moving a student from an average teacher to one in the 85th percentile increases the student's rank by 7% [11]. Additional data from Gordon, Kane and Staiger provide an analytical basis for modeling teacher influence on student performance and interest as a normal distribution [20]. Some teachers will advance student rank, while others will reduce student rank. For the purposes of the model, teachers that improve the average student's rank were defined as "STEM-capable" and the remainder of the teachers as "not-STEM capable" (see Figure 4).

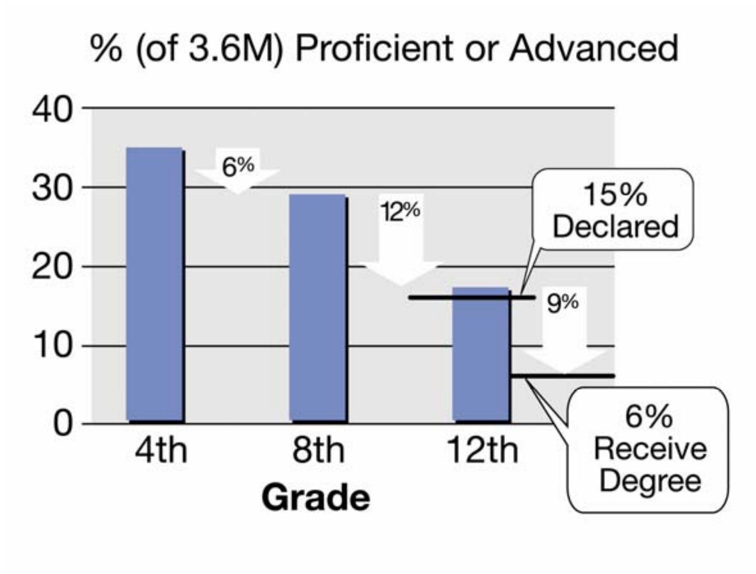

Figure 3. STEM proficiency declines in middle school (grades 4-8) and high school (grades 9-12).

Distribution data from [20] show a slight skew such that there are fewer STEM-capable teachers than not-STEM-capable. The general form of these data appears to correlate with the gradual decline in student proficiency as students progress through the grades. This apparent correlation led to a model of student change in capability (and interest) based on the relative size of the STEM-capable and not-STEM-capable teacher populations. Shifting the distribution changes the number of teachers who are STEM-capable and the proficiency of the students. A mean of zero, corresponding to equal numbers of STEM-capable and not-STEM capable, for instance, produces no change in the numbers of math proficient students from one grade to the next.

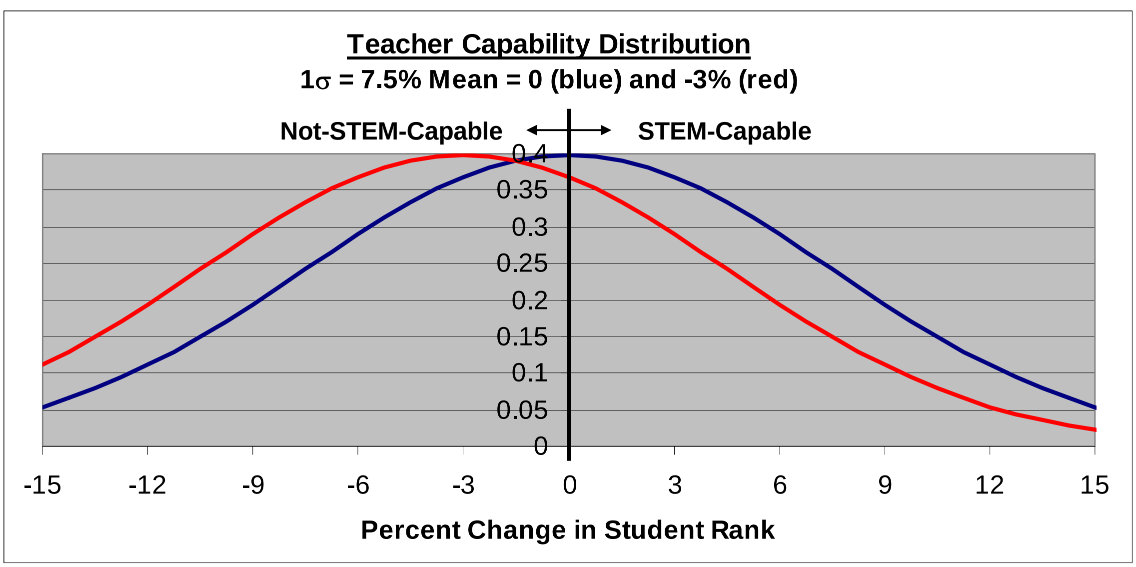

Figure 4. Teacher capabilities can be modeled by a normal distribution related to their ability to impact student performance.

Changes in policy related to the number of STEM-capable teachers can shift the distribution mean or reduce/increase the numbers of teachers in any part of the distribution. As suggested by Gordon, Kane and Staiger, one of the potential methods for improving student performance is through identification of teachers in the lowest quartile of the ranking and then reducing their numbers through denial of tenure or development programs that improve their capabilities [20]. This concept was examined using the model and it was found that its effect was dramatic and has the potential for eliminating the decline in student math proficiency as students progress through the education system from 4th to 12th grade.

In order to simplify the model, and because of a relative lack of knowledge about the exact distribution of teacher capabilities, the current version of the model computes the change in student capabilities based on the ratio of two populations: STEM-capable teachers and not-STEM-capable teachers. This simplification is approximately correct for symmetrical distributions with means near zero (i.e. a fraction of a standard deviation) and is adequate for examining the trends in student capability as changes to the ratio are made.

III. APPROACH – APPLICATION OF SYSTEMS ENGINEERING

The International Council on Systems Engineering (INCOSE) defines systems engineering to be "…an interdisciplinary approach and means to enable the realization of successful systems." Systems engineering methods integrate persons and techniques from a variety of disciplines into a problem solving team, whose goal is to provide a quality system that meets the needs of all users [21]. Systems engineering is commonly used to define the life cycle of high-tech products from their conception, through to production, operation, and disposal. Systems engineering techniques assist in organizing the problem presented and the approach to it, enabling a multi-disciplinary team solution, and providing tools for capturing data and assessing alternatives. The incorporation of modeling allows checks to be performed on the understanding and interpretation of the problem, and on the effectiveness of potential solutions.

Figure 5, derived from [22] displays a flowchart describing the systems engineering process. This process is comprised of seven steps: state the problem, investigate alternatives, model the system, integrate, launch the system, assess performance, and re-evaluate.

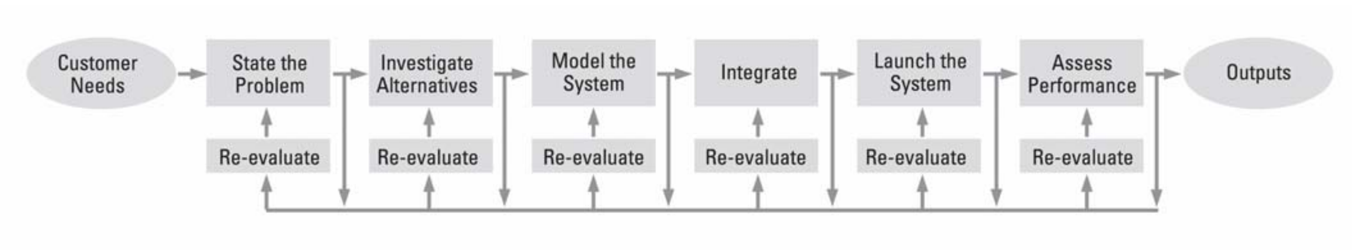

Figure 5. The systems engineering process. [22].

Though the U.S. education system is not a high-tech deliverable such as a radar or computer system, it fits the definition of a system, and can benefit from systems engineering techniques that bring a variety of disciplines together to satisfy the needs of the students and the wide variety of stakeholders including; parents, teachers, and hiring managers. Specifically, by developing a model of the education system, it is possible to break down an extraordinarily complex entity into manageable sections. Though each may be analyzed independently, the relationships and interdependencies between the individual sections are maintained by the overall model.

A simplified representation of the student flow model is shown in Figure 6. This model is based on system dynamics methods developed by J. W. Forrester beginning in the 1950's [23]. The arrows represent flow of students between the different populations. Each flow is controlled by valves that are set based on the numerous factors that relate to the population. Flows can be unidirectional or bidirectional. Single headed arrows, such as the ones leading to retirement, represent one-way flows in the direction of the arrow. Double headed arrows, such as the ones between STEM interested and un-interested boxes, represent two-way valves. The factors that set the valves and the relationships that determine these factors are not shown in this simplified representation. In direct contradiction to the static studies described earlier, the dynamic model presented here allows varying trends in the education system to be observed over time.

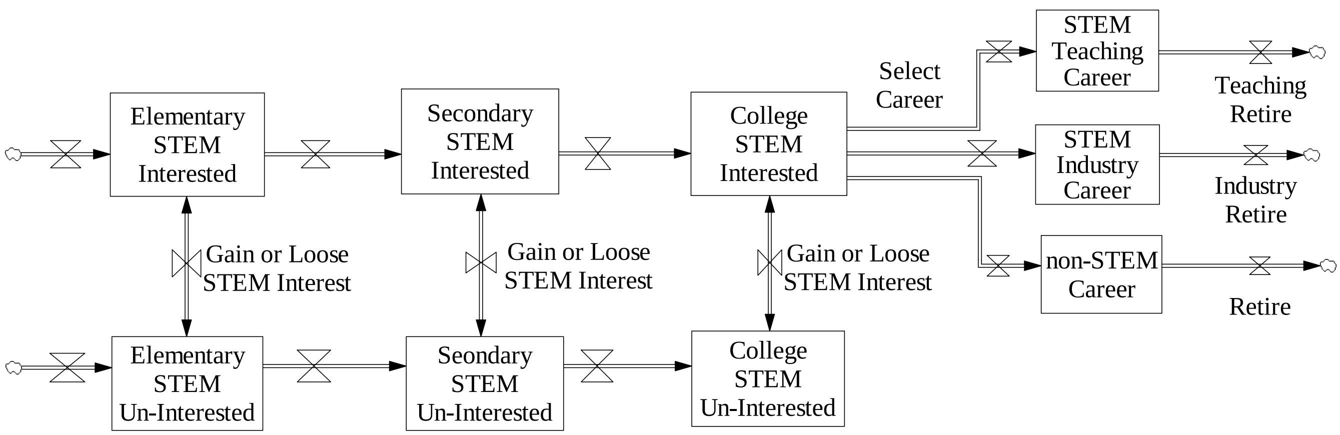

Figure 6. Simplified representation of the student flow model.

IV. SYSTEM DYNAMICS

The primary focus of system dynamics is on two things: the flow of feedback that occurs within a system and the system behaviors that result from these flows. Since its inception, system dynamics has been used to study a wide number of topics such as project management and supply chains, and to study state stability. System dynamics has also been used to evaluate the implications of success in the education system [24], to study knowledge management in engineering education [25], and to study the performance of research and development in the South African higher education sector [26]. Alan Gaynor in his book, *Analyzing Problems in Schools and School Systems*, proposes using system dynamics modeling as a method for analyzing school systems. Gaynor develops a dynamic hypothesis using methods similar to those employed in this analysis, and described in subsection B below, to support what he calls "The Effective Schooling Project." The essence of the problem posed in The Effective Schooling Project, is that in ineffective schools initial differences in children's readiness to learn at school were systematically magnified over the course of their educations [27]. Gaynor however, does not develop a mathematical model that can be simulated.

System dynamics identifies causal relationships among elements of a system and creates a holistic view of the system in which the "cause" may be affected by the "effect." System dynamics also illuminates unintended side effects caused by changes to the system.

A. Modeling Process

System dynamics modeling is based on a high level view of the problem that contains causal feedback loops existing between the elements of the system. This high level view, also referred to as a “dynamic hypothesis” is used for conceptual understanding of the system as well as to develop a dynamic stock and flow model. For the U.S. education system the stock is the students and the flow is their progression through the grades, and between STEM-interested and STEM-uninterested. The fundamental architecture of the U.S. education system provides the basis for the stock and flow model, and contains the causal relationships represented in the dynamic hypothesis. The composition of each feedback loop is examined to understand the resultant behaviors, and to determine means of making improvements. The process of forming the dynamic hypothesis, developing a stock and flow model, and investigating the behaviors of feedback loops is an iterative exercise that allows potential improvements to be analyzed for their effectiveness.

B. Dynamic Hypothesis

Several dynamic hypotheses were considered, while developing the model, and three were selected for implementation. The first was that increasing the salary of teachers, especially STEM teachers, will attract and retain more capable teachers and improve student performance. The second hypothesis was that increasing class size will increase the probability that a student will have a STEM-capable teacher. The class size increase should decrease the demand for teachers and allows more capable teachers to be hired from a relatively larger pool of candidates. Finally, the third hypothesis was that identifying and eliminating or improving teachers that are not capable will improve student performance and interest in STEM. These three dynamic hypotheses are captured in the influence diagram, shown in Figure 7, and included in the dynamic model of the system.

In Figure 7, 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.

C. 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 systems 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. 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 provided only a summary view of the complete stock and flow model developed; the full model is too complex to capture in this document.

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.

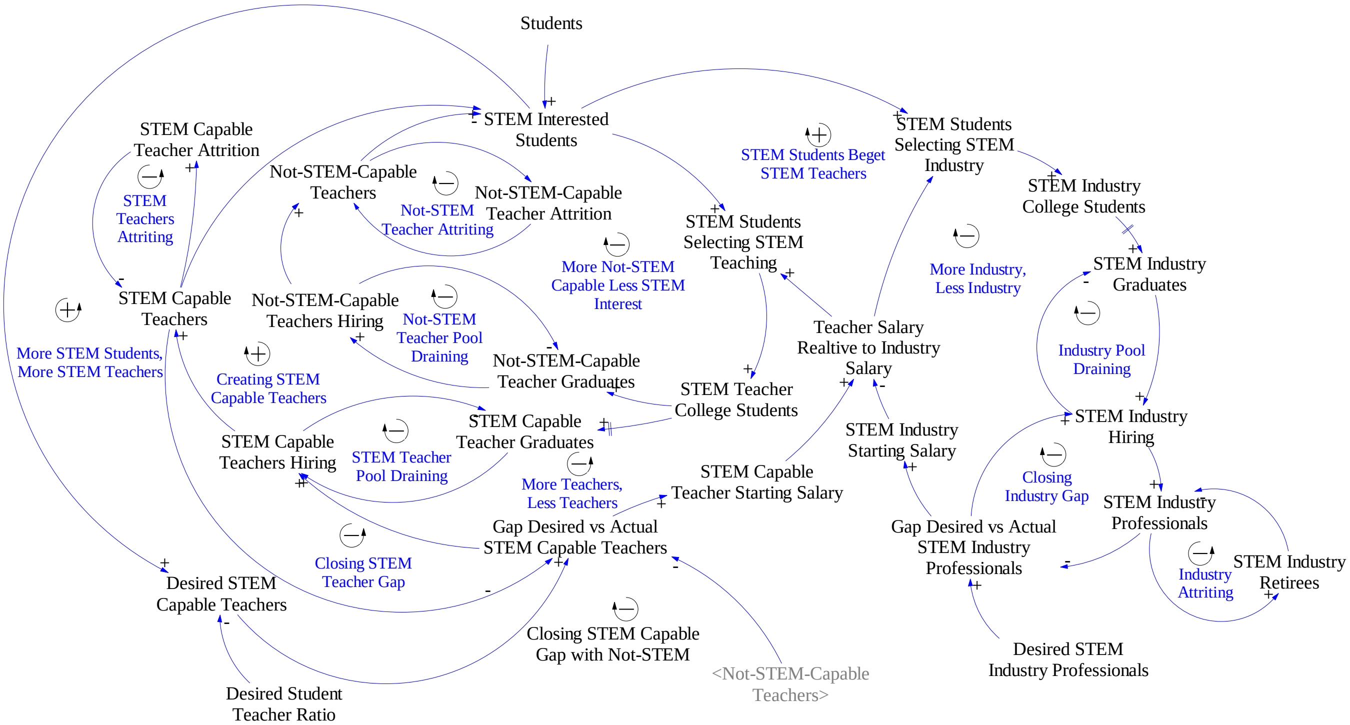

Figure 7. Influence diagram representing the dynamic hypotheses.

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.

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: 5^{th}-8^{th} grade STEM-capable teachers, 5^{th}-8^{th} grade not-STEM-capable teachers, 9^{th}-12^{th} grade STEM-capable teachers, and 9^{th}-12^{th} 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.

V. MODELING ASSUMPTIONS

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. Table 1 lists the modeling assumptions required for this evaluation due to limited data availability.

Each of these assumptions, if changed, will have 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 will 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.

Table 1. Modeling assumptions.

Modeling Assumption	**Rationale**
STEM interest is closely related to STEM proficiency.	Very little data exist on student interest in STEM. The only datum is students declaring a STEM major in college [18]. This number is very close to the number of proficient and advanced math students in 12th grade.
A STEM-capable teacher maintains STEM proficiency and interest within the class.	For the model, a STEM-capable teacher is defined as one that increases proficiency of the class on average. The model predicts average behavior.
Not-STEM-capable teachers reduce student proficiency average over a year.	This follows from the modeling definition of not-STEM-capable teachers.
Once proficiency (interest) is lost it is not recovered.	While it is possible that students can recover from a bad teacher, research indicates the effects last for years afterwards. This assumption also prevents positive runaway in the simulation that clearly would not be representative of the real world.
Administrators cannot determine which college graduates will become STEM-capable teachers.	Research that examines all teachers as a group indicates that 97% of what makes a good teacher is not quantifiable or well known. Data specific to STEM teachers are limited. The model assumes that the teachers hired match the characteristics of the pool of new candidates (i.e. no sorting occurs when hiring inexperienced teachers).
Denial of tenure will result in attrition of teachers.	There are no data that correlates attrition with denial of tenure. Tenure is rarely denied in the current system, so data collection methods will have limited success.

VI. RESULTS

During the study many factors were examined and considered for implementation in the model. After researching, evaluating and reviewing each hypothesis, three were selected for detailed examination using the model (See Table 2). Two of the hypothetical changes produced very little improvement in student interest in STEM due to the limited ability of administrators to selectively hire STEM-capable new teachers from the candidate pool of college graduates. While these changes (increased salary and class size) might have the potential for improving the system if administrators can selectively hire capable teachers, research data indicated significant issues with implementation such as rigid salary structures, union resistance, public opinion and limited school funding. The third change is the introduction of attrition through denial of tenure to teachers that have not demonstrated their capabilities within their first three years teaching. The 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.

Table 2. Summary of results.

Hypothesis	**Model Results**	**Factors**	**Conclusion**
Increasing STEM teacher salaries will increase the candidate pool and better teachers will be hired.	Assuming that administrators can differentiate capable from not-capable and that industry does not compete, then dramatic improvement is seen.	Research shows administrators cannot tell capable from not-capable coming out of college.	Increasing salary will increase the candidate pool, but more capable teachers are not hired due to the selection process.
Increasing class size will reduce the demand for teachers and allow administrators to be more selective in hiring.	Assuming administrators can differentiate capable from not-capable, improvements are seen. Natural attrition was modeled. Assumed equal attrition from capable and not-capable.	Research shows administrators cannot tell capable from not-capable coming out of college. Using the change to lay-off less capable teachers was not modeled.	The change delayed all hiring for a couple of years so no input changes occurred in that time. Improvements did not occur due to limited differentiation during hiring.
Identifying the not-STEM-capable teachers and improving their capabilities or increasing their attrition after three years will improve student capabilities.	A dramatic improvement in student capabilities is produced by implementing this policy	Data show that denial of tenure is rarely implemented [28]. Increasing attrition may result in teacher shortages.	This policy has potential for introducing improvements in student capabilities in grades 4-12.

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.

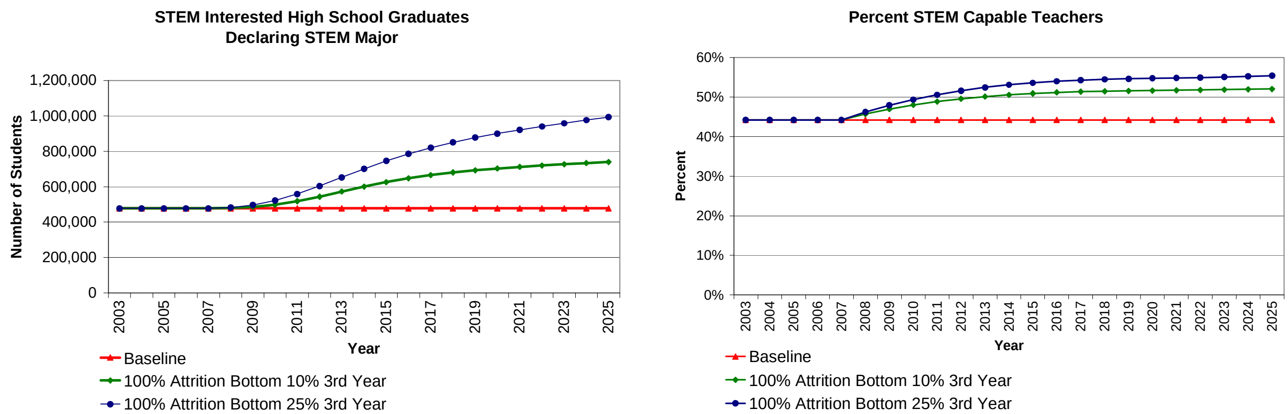

Figure 8. Baseline case (red) compared to the improvement provided by implementing the dynamic hypothesis with attrition of lowest 10% (green) and attrition of the lowest 25% (blue).

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.

The next "what if" scenario investigated was what would happen if the student-teacher ratio was increased, making each class larger. In the baseline run the desired student teacher ratio was 17:1, i.e. 17 students per class. In the "what if" scenario the student-teacher ratio was increased to 25:1.

It is seen (Figure 9) that as classroom size increases, a delay in the need for new teachers is introduced, which delays the hiring of STEM capable teachers. The delay in hiring slows down the improvement in student capabilities because improvement depends on the hiring of new teachers.

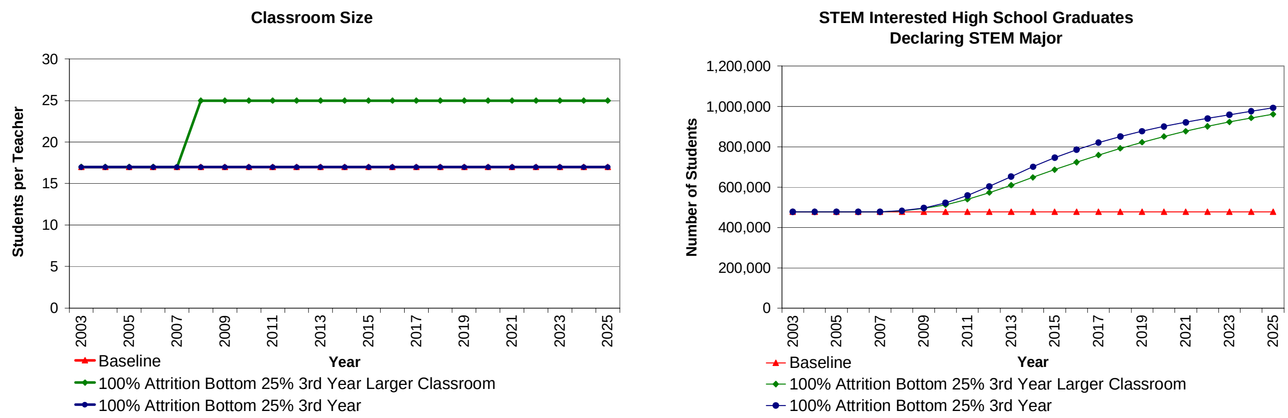

Figure 9. Baseline case (red) compared to the improvement provided by implementing attrition of lowest 25% (blue), and the larger classroom with attrition of the lowest 25% (green).

The next policy change investigated was a one time step increase in teacher salary. This change did not result in additional students being interested in STEM during their tenure in school. (see Figure 10)

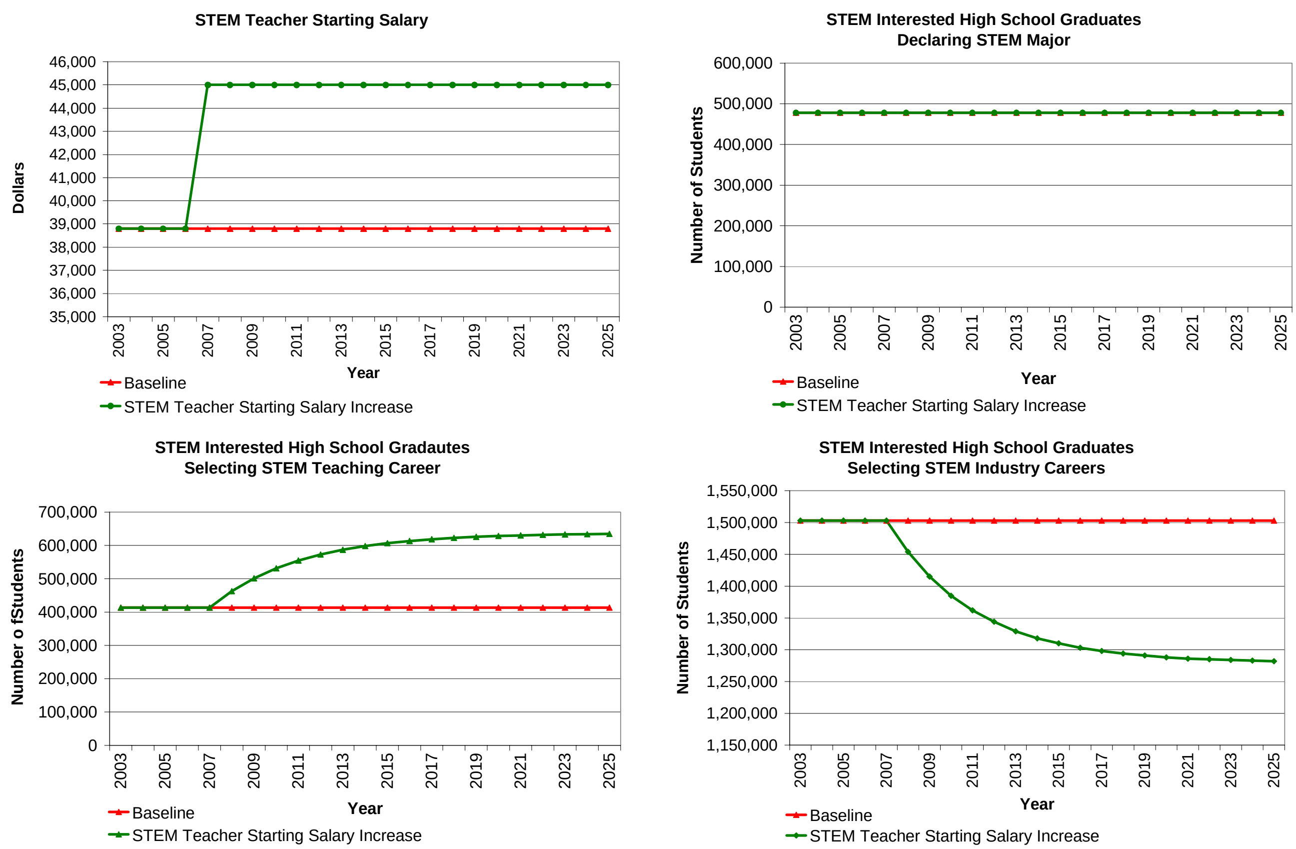

Figure 10. Baseline case (red) compared to the improvement provided by implementing the dynamic hypothesis with increased teacher salary (green).

However, it did result in an increase in the number of STEM interested students selecting STEM teaching as a profession. This was accompanied by an equal decrease in the number of students selecting to enter the STEM industry workforce as a profession. Increasing teacher pay and attracting more candidates improves the quality of the education system if the candidate mix improves substantially or if the administrators that hire the students coming out of college can selectively hire the candidates that will become STEM-capable teachers. Based on the lack of supporting research that shows administrators can select the best candidates and the research that shows there are very few indicators of what makes a good teacher [10], it was assumed that administrators cannot selectively hire capable teachers from the college graduate candidate pool.

VII. SUMMARY

Preliminary analysis and modeling of the U.S. education system indicates that reducing the numbers of teachers who are not-STEM-capable provides an effective method for improving student performance. Research shows that school administrators can determine, after three years of assessment, which teachers are STEM-capable and which are not. This knowledge can be used to deny tenure to the least capable teachers, which should lead to attrition. The system dynamics model shows a dramatic change in student performance as a result of reducing the numbers of not-STEM-capable teachers through either attrition or training. To date, there is no indication that school administrators are willing to delay or eliminate tenure for less capable teachers. There is even less likelihood that school administrators are willing to eliminate the least capable teachers through firing or lay-offs. Less than 1% of teachers leave the profession as a result of school staffing actions of all types [28]. In addition to resistance from school administrators, a change of this type will face substantial resistance from teachers unions. The results of the system dynamics modeling effort, once validated, should help to persuade policy makers, teachers and school administrators to take bolder actions to improve the quality of education.

Modeling of class size changes showed that increasing class size decreases the demand for teachers, thus allowing school administrators to be more selective in hiring from a relatively larger candidate pool. Unfortunately, research shows that 97% of what makes a good teacher is not well understood [10]. This led to the assumption that school administrators cannot select the best candidates when hiring new teachers. Obtaining an improvement in student performance through increased class size requires the ability to select the best teachers from the candidate pool, or the ability to eliminate the least-capable teachers. Neither of these options is currently available in the U.S. education system.

Increasing class size should also have the advantage of increasing the salaries of the teachers that remain, given a fixed tax base. However, data show that increasing teacher pay does not result in better teachers. The model showed that an increase in teacher pay increases the candidate pool. This would improve teacher quality if school administrators hired the more capable new teachers from the larger pool of candidates, but there is an absence of data to support a conclusion that this will happen. Increasing teacher pay shifts capable people from industry to education. When this shift of capable personnel from industry to teaching was modeled and industry was made endogenous, the model showed that such a shift resulted in a pay increase for industry candidates, which offset the teacher pay increase. The dynamic model showed the effect of teacher pay being slow to change and very inflexible, compared to industry salaries that are quick to adapt when shortages of necessary personnel occur.

Application of systems engineering methods and system dynamics modeling has achieved the study's primary objective, to provide an organized means of examining and analyzing the U. S. education system. The model was built by examining the numerous factors that influence student performance and interest and the effects of these influences. The process of creating the model looked at these influences one by one in an organized and rational fashion. Modeling activities have indicated where additional research and data are needed and have provided a means of showing the intended and unintended consequences of policies and actions.

At this time, the very limited research data available for building the current model makes it impossible to state results with high confidence. However, the model still provides a highly effective tool for understanding trends and for organizing the research process. Continuation of research efforts, especially in those areas needed to enhance the model, combined with additional model development and validation, can eventually provide an effective tool for predicting with some certainty the results of policy decisions on the U.S. education system. Achieving this goal may take time but this effort can provide tremendous benefits.

VIII. 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 Kindergarten-12 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 the middle of 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 that enhances the model, increases its fidelity, and provides validation.

Current modeling activities are aimed at validating the model in the areas related to class size and teacher hiring. In 1996, California passed legislation that reduced class size [29]. This resulted in significant hiring of teachers, which in turn depleted the pool of qualified teachers. These data are sufficient to provide validation of two key areas within the model.

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 currently 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. The attrition is particularly acute among engineering students. This examination will look at and model the numerous factors that lead to attrition, and will model 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.

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