Complex Systems Approach for

Simulation & Analysis of Socio-Technical Infrastructure Systems

An Empirical Demonstration

by

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ABSTRACT

Over the past century, the world has become increasingly more complex. Modern systems (i.e blockchain, internet of things (IoT), and global supply chains) are inherently difficult to comprehend due to their high degree of connectivity. Understanding the nature of complex systems becomes an acutely more critical skill set for managing socio-technical infrastructure systems. As existing education programs and technical analysis approaches fail to teach and describe modern complexities, resulting consequences have direct impacts on real-world systems. Complex systems are characterized by exhibiting nonlinearity, interdependencies, feedback loops, and stochasticity. Since these four traits are counterintuitive, those responsible for managing complex systems may struggle in identifying these underlying relationships and decision-makers may fail to account for their implications or consequences when deliberating systematic policies or interventions.

This dissertation details the findings of a three-part study on applying complex systems modeling techniques to exemplar socio-technical infrastructure systems. In the research articles discussed hereafter, various modeling techniques are contrasted in their capacity for simulating and analyzing complex, adaptive systems. This research demonstrates the empirical value of a complex system approach as twofold: (i) the technique explains systems interactions which are often neglected or ignored and (ii) its application has the capacity for teaching systems thinking principles. These outcomes serve decision-makers by providing them with further empirical analysis and granting them a more complete understanding on which to base their decisions.

The first article examines modeling techniques, and their unique aptitudes are compared against the characteristics of complex systems to establish which methods are most qualified for complex systems analysis. Outlined in the second article is a proof of concept piece on using an interactive simulation of the Los Angeles water distribution system to teach complex systems thinking skills for the improved management of socio-technical infrastructure systems. Lastly, the third article demonstrates the empirical value of this complex systems approach for analyzing infrastructure systems through the construction of a systems dynamics model of the Arizona educational-workforce system, across years 1990 to 2040. The model explores a series of

dynamic hypotheses and allows stakeholders to compare policy interventions for improving educational and economic outcome measures.

DEDICATION

To my loving husband, who never stopped believing in me. You brought new meaning to my life, empowered me to fulfill my goals, encouraged me to triumphant over challenges, and gave me the courage to dream new dreams. Your patience and positivity got me through this.

To my family, thank you for being my constant during this trying period of my life. I am forever grateful for the refuge you provided me and for being the ones I could count on throughout this entire process.

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To those who also know the struggles of being challenged with dyslexia. Keep on persevering because the world needs more of what you have to offer.

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CHAPTER 1

INTRODUCTION

As infrastructure investments decline (Kelly, Elardo & Roth, 2015; Kendall et al., 2015), existing infrastructure decays (Cromwell et al., 2001; American Water Works Association (AWWA), 2012), and natural catastrophe losses mount (Munich RE, 2017), US federal agencies have been directed to "strengthen the security and resilience of its critical infrastructure against both physical and cyber threats" (Critical Infrastructure Security and Resilience Presidential Policy Directive (PPD-21), 2013). Though the term resilience remains ambiguous and contested among researchers (Alderson, Brown, & Carlyle, 2015; Park et al., 2013; Woods, 2015; Snell et al., 2016), there is consensus that infrastructure resilience requires utilizing a holistic, systems design approach (Thomas et al., 2017; Seager et al. 2017). To strengthen the resilience of national infrastructure systems, several federal agencies including the Department of Homeland Security, the National Science Foundation, and the National Institute for Standards and Technology, have launched a frenetic portfolio of plans, policies, and research programs focused on understanding the current and future risks that threaten infrastructure resilience (e.g., Moteff, 2012; NIPP, 2013; PPD-21, 2013; HSPD-7, 2003). Despite having access to numerous critical infrastructure risk and resilience analyses, little work has been done to improve upon the state of our national infrastructure systems.

Deteriorating US infrastructure conditions were first ranked in 1988, by the congressionally chartered National Council on Public Works Improvement. Since then, the American Society of Civil Engineers (ASCE) has assumed the responsibility of grading infrastructure sectors. Over the past two decades, ASCE has released six reports on the national downward spiral of deteriorating infrastructure systems, prolonging periods of neglecting maintenance, and widening gaps between financial appropriations and the required investments for restoration (ASCE, 1998; ASCE, 2001; ASCE, 2005; ASCE, 2009; ASCE, 2013; and ASCE, 2017; Grigg, 2015). According to the ASCE 2016 Failure to Act report, if the investment gap is not addressed throughout the nation’s infrastructure sectors by 2025, the economy is expected to lose almost $4 trillion in GDP, resulting in a loss of 2.5 million jobs by 2025 (Economic Research

Development Group, 2016). Decision-makers remain unprepared to act upon the information these, and other analyses provide, because appropriate analysis and the interpretation thereof, relies on the ability to understand the nature of complex systems.

Gravity of Understanding Complex Systems

Even before the Critical Infrastructure Security and Resilience Presidential Policy Directive (PPD-21, 2013) was signed into effect in February 2013, securing our national infrastructure was a top priority to the US government. In response to the tragic events of 9-11, the USA PATRIOT Act of 2001, was signed into law and prioritized “providing appropriate tools” for strengthening America’s critical infrastructure. Soon after, the Department of Homeland Security (DHS) established the National Infrastructure Simulation and Analysis Center (NISAC) to provide modeling, simulation, and analyses of the nation's infrastructure systems. NISAC researchers develop their simulations with an emphasis on understanding system interdependencies, learning from past systems, and disseminating the education of infrastructure systems management. Although the NISAC simulation center was established to prepare decision makers with the tools to understand the complex nature of infrastructure systems, the center does not address the root cause of the issue - that existing educational programs lag behind policy initiatives because current approaches for teaching of complex infrastructures and systems thinking skills remain inadequate and ineffective (Bosch et al., 2014; McBurnett et al., 2018; Sweeney & Meadows, 2010; Richmond, 1994). As a result, no amount of analysis will equip decision makers with the abilities needed for managing infrastructure systems.

Humans fail at managing infrastructure systems because infrastructure systems are, by nature of design, complex systems (Dörner, 1996). They consist of subsystems which are bound by interdependent relationships. These interdependencies (i.e., feedback loops) produce nonlinear and stochastic responses to system inputs. These characteristic attributes exacerbate the challenge of managing socio-technical infrastructure systems. Oftentimes, human interventions designed to address problems within a complex system backfire and produce results which are unexpected or even counterintuitive (Dörner, 1996).

Over the past half century, the world has become increasingly more complex and difficult to understand (Homer-Dixon, 2011). Modern systems (i.e. blockchain, internet of things, and global supply chains) are inherently difficult to comprehend due to their high degree of connectivity. Therefore, we need to prepare decision-makers, researchers, and students who understand the complex nature of the systems they are responsible for and who are capable of managing their increased complexities. To accomplish this, we must develop new ways of teaching complex systems thinking skills and apply these skills in infrastructure management training programs.

Simulating Socio-technical Infrastructure Systems

Since as early as the 1960's, researchers have developed simulations and games to further their understanding of both natural and man-made, socio-technical infrastructure systems. For example, Jay Forester invented the Beer Game to research the effect of systems structures on the behavior of people and their decisions. In 1970, mathematician John Conway released 'The Game of Life', a zero-player simulation game that paved the way for cellular automata – an entirely new field of mathematical research. In recent years, simulation games have been designed to expose players to a diverse range of systems applications including: environmental systems (Stave, Beck, & Galvan, 2015), governmental systems (Nishikawa & Jaeger, 2011), economic systems (Doyle, Radzicki, & Trees, 2008), and military system operations (Perla & McGrady, 2011; Sabin, 2012; Brewer & Shubik, 1979). Furthermore, modern computational technologies have evolved and now afford for the ubiquitous, recreational use of simulations and games - a large, economic industry (McGonigal, 2011).

However, despite years of experience designing and playing simulation games, their use for complex systems educational applications remains limited. Current games for engineering education (Bodnar et al., 2016), define learning objectives of technical details and system optimization. Although there are several complex systems instructional games set in ecological systems (i.e. Spierre et al., 2009; Seager et al., 2009), infrastructure games remain focused on complicated systems while neglecting complex systems (Poli, 2013). There exists a potential for simulation gaming to teach the counterintuitive nature of complex infrastructure systems management without the risks and consequences of real failures.

Objectives of Research

The aim of this dissertation is to present a complex systems approach for simulating and analyzing socio-technical infrastructure systems to understand their counterintuitive traits and discover new ways for decision-makers to intervene in these systems. Two socio-technical infrastructure systems are selected to demonstrate the complex systems approach: the Los Angeles water distribution system and the Arizona educational-workforce system. These systems were selected because they are complex systems, which provide a critical service to the public, and both systems, despite intervention attempts, have received media coverage for being in a state of disrepair.

For both selected complex infrastructure systems, modeling techniques were applied to better understand the nature of each system. As George E. P. Box, a well-regarded industrial statistician and experimental design expert, once said, “All models are wrong, but some are useful.” For a model to be useful, it must provide a value or service to either the modeler or its potential users. Some models offer profitable insights, forecast future events, or help individuals make business decisions. Other models are used to test hypotheses or try out ideas. Lastly, models can be used to explain the dynamics of a system, situation, or event. Knowing that models are designed to serve a multitude of purposes, it is important to clarify how the modeling techniques used were selected and how the developed models, discussed in the articles hereafter, are intended to be used.

In support of the research objectives, this dissertation discusses the methodology and outcomes of three distinct research studies. First, a literature review into the tools and methods currently used to model educational systems is conducted. Next, a game-based educational simulation model of the Los Angeles water distribution systems is described. The third and final study, contains the creation of a system dynamics model of the Arizona educational-workforce system. Combined, these three studies demonstrate the viability and empirical value of applying a complex system modeling approach for analyzing socio-technical infrastructure systems.

CHAPTER 2

INTERPRETING EDUCATIONAL SYSTEM ANALYSIS TECHNIQUES THROUGH A COMPLEX SYSTEMS LENS

A Comparative Analysis of Modeling Techniques used for Simulating Educational Systems

Abstract

Research has shown the usefulness of complex systems modeling for revealing the nonlinear dynamics for socio-technical systems. However, little work has been done to capture the dynamics of educational systems with complex systems modeling techniques. Apart from the application of agent-based-modeling to express school-level demographic segregation, few complex models have been applied to advance our understanding of educational systems, and fewer still have yielded actionable insights to advance educational system outcomes. This paper summarizes existing analysis methods and modeling techniques used in education research and evaluates these methods for researching the complexity of the educational system. Each method was characterized by its capacity for capturing the following aspects of complex systems: nonlinearity, interdependencies, feedback loops, and stochasticity.

Introduction

Like other socio-technical infrastructure systems, understanding complex systems is critical for managing and reforming the educational system (Levin & Jacobson 2017). However, research has shown that existing education programs and approaches fail to teach complex systems thinking skills (Bosch, Nguyen, & Ha, 2014; Sterman, 1994, McBurnett et al., 2018). Without a foundation of complex systems thinking skills, decision-makers are left ill-equipped to design and institute system-wide policies; correspondingly, even well-intended system changes can result in unintended consequences. Initiatives like the school choice movement, empowerment scholarship programs, and charter school alternatives, or variabilities in school services like transportation services or free and reduced lunch programs, can bring about negative, unintended consequences. Some examples are racial segregation, poor student performance, attainment gaps among minority groups, and inequitable school opportunities.

Despite educational researchers acknowledging the educational system as a complex system (Jacobson & Wilensky, 2006; Jacobson, 2015), few research efforts have evaluated the educational system with a complex systems approach. In this article, we argue that researchers should apply a specific complex systems framework, which characterizes complex systems as having nonlinearity, interdependencies, feedback loops, and stochasticity, to educational system research. We suggest that this will allow us to draw new and important inferences that can help inform education policy and academic changes.

Literature Review. Researchers, scholars, and educators have long investigated means to improve educational system outcomes. Unlike other more siloed disciplines, educational research has welcomed insights offered by a diverse range of scholars bringing with them their own disciplinary knowledge, skills, and traditions. For this reason, the field of education research has been shaped by disciplines including psychology, biology, medicine, cognitive science, economics, statistics, applied mathematics, and engineering. Unfortunately, diverse perspectives and interdisciplinary problem-solving tactics have proven inadequate for addressing some of the complex issues which have emerged within the educational system. Since complex systems are inherently counterintuitive, educational systems are difficult to understand. Their complex nature makes them unpredictable and complicates the impact of policy or academic interventions, which were designed and implemented to improve system outcomes.

Complex Systems Theoretical Framework. A complex systems framework was used to guide this work, as this framework helps take into account the unpredictable and emergent nature of educational systems. Complex systems are typically characterized by nonlinearity, interdependencies, feedback loops, and stochasticity (Checkland, 1999; Jolly, 2015; Meadows, 2008; Sterman, 2000), each of which is described as follows.

Nonlinearity. Linear relationships have clear cause and effect patterns of direct proportionality. Thus, in linear systems, extrapolation beyond an observed dataset results in reliable predictions, where a change in an independent variable produces a corresponding and predictable change in dependent variables. Nonlinear relationships, on the other hand, result in unreliable extrapolation, making it difficult to predict outcomes of decisions or events that lie outside historical experience. For example, if two schools each decrease their student-teacher ratio by four less students per teacher, both schools may see resulting gains in student achievement measures. However, this equivalent change might affect student achievement at one school by more than it affected the other school.

Interdependency. The subsystems which comprise a complex system are interdependent in that they are mutually reliant on one another. Thus, in addition to understanding how students, teachers, and school systems operate in isolation, we must also understand the relationships between each of these systems and the ways in which these interdependencies comprise the larger, complex system.

Feedback Loops. A feedback loop is a specific type of interdependency wherein the output of one system becomes input for another. For example, when a high school football team has a good season, the school becomes a more appealing choice to parent of incoming freshman football players. Parents may move into the school's boundaries, so their children are able to play football at that high school. Since there are limited houses available within the school's boundaries, real estate prices rise and the school's property tax revenues increase. With these additional funds, the school can budget for a more expensive football coach who leads the football team to further success.

Stochasticity. Complex systems are characterized by irregularity and random phenomena. In other words, even with a set of similar "inputs" to the system, outputs can be quite different from one another. Such stochastic events are unpredictable and cannot be foreseen in models or hypotheses. For example, two students may have attended the exact same lectures and completed the same homework assignments, however one may outperform their peer.

Modelling Educational Systems. Throughout the past few decades, researchers have detailed many ways to analyze components of educational systems. Most education research can be categorized as evaluating either an academic intervention strategy (i.e. teacher training, reading comprehension technic, etc.) or an attempt to describe/model an educational phenomenon (i.e. segregation in schools, knowledge transfer in a classroom environment, etc.). Some researchers have tried to determine the impact of external factors, such as exposure to crime or environmental hazards, by differentiating to account for neighborhood effects. The following are examples of modeling techniques used to analyze the educational system: Many models have been used to learn more about students, schools, districts, and teachers. Hierarchical linear models have been used to parse out the effects of reading and math interventions on student performance (Slavin et al, 2013; Carlson, Borman,& Robinson, 2011). Fixed-effects models have been used to compare student performance in charter schools to the surrounding traditional schools (Bifulco & Ladd, 2006). Survival models have been used to evaluate student mobility and retention (Finch, Lapsley, & Baker-Boudissa, 2009), teacher attrition (Sass et al., 2012), and charter school policy dynamics (Holyoke et al, 2009). Supply/Demand models have been used in education research to model the growth of occupational-based training and certification throughout the US (Carter, 2005). Furthermore, the supply/demand interdependent relationship has been used as the framework for a decision support system for managing educational capacity utilization (Mansmann, 2007).

Multivariate analysis using an econometric education production function has been used to determine the effects of computer availability at home and at school on student learning (Woessmann & Fuchs, 2004). Classification trees and Multivariate Adaptive Regression Splines (MARS) have been used to profile students likely to take online courses (Yu et al, 2008) and to identify predictors of university student retention from sophomore to junior year (Yu et al, 2010). Network model modeling has been used to reveal insights about distributed and centralized systems of students (Kellam, 2007). Maroulis et al. (2014) investigated school choice with an agent-based model.

In this chapter, existing methods and modeling techniques are evaluated to determine whether they account for aspects of complex systems.

Methodology

For each of the modeling approaches, we investigate the methodology, components, and assumptions which are built into the modeling technique. Next, we analyze each modeling technique to evaluate the four key components of complex systems: nonlinearity, interdependencies, feedback loops, and stochasticity. Capacity for nonlinearity is determined as whether the technique uses non-first order mathematical relationships to model the given input. Interdependencies are assessed as the presence of multiple dependencies within the function. Feedback loops are considered present if the model allows for the output of a function to become the input of the same function. Finally, stochasticity is determined if for the same specified input, the function is capable of producing multiple different outputs. For each modeling technique, the presence of these components is determined and synthesized in the results table.

Software Assistance. Two software tools were used to assist with managing and aggregating the collection of sources: ReadCube Papers online and desktop application, version 4.0.2, App v2.33.14513, Updater v2.1.0 (Copyright © 2011-2018 Digital Science & Research Solutions, Inc.), and SimpleMind desktop application, version 1.19.0 build 1321 (Copyright © 2009-2017, ModelMaker Tools BV). ReadCube was used to electronically manage sources, citations, and recorded annotations. SimpleMind was used to produce a visual compilation of the literature synopsis.

Database Selection. The literature review included the use of the Google Scholar (Google Scholar, 2004) database, as well as the ASU main library, ASU thesis and dissertation database (ASU Graduate College, 2018), and the following online databases: 2018 American Educational Research Association (AERA) Annual Meeting conference proceedings (2018), 2018 Systems and Information Engineering Design (SIEDS), IEEE Symposium (2018), 2010 IEEE International Conference on Intelligent Systems and Knowledge Engineering (ISKE) (2010), 2015 Conference for Complex Systems (2015) and the 2016 Social Simulation Conference (2016).

Search Term Iterations. Many keyword search terms were used to perform this literature review. Initially, the keyword searches started out more general (i.e. “complex systems”, “educational system models”, “system dynamics”, “discrete-event simulation”, and “agent-based simulation”). When searched in each database, these general keyword searches produced thousands of journal articles and various sources. To narrow the results and focus on relevant literature sources, combinations/variations of the following keywords were used: multilevel, multivariate, hierarchical, school(s), district(s), state(s), education(al), system(s), analysis, review, advantages, disadvantages, and data-driven.

Screening Criteria Evaluation. After preliminary searches yielded countless sources which comment on modeling or simulation of educational systems, screening criteria was designated to filter through sources and focus on the most relevant sources. Inclusion of a source was decided by whether or not the following statements were true of the source: (i) the source is peer-reviewed, (ii) the research question is relevant to my problem statement, (iii) the simulation (or sample size) includes more than one classroom, (iv) the study evaluates the effect of more than one factor on the system outcome variable(s). For each applicable source, the abstract, methods, and results sections were reviewed and summarized.

Results & Discussion

In this section, we summarize a series of research methods regularly used in educational research and provide results of our evaluation of each of these methods as to whether they take into account aspects of complex systems. First, we describe educational research study models, which can be summarized in five categories: 1) predictive models, 2) descriptive statistical models, 3) inferential statistical models, 4) economic models, and 5) complex system models.

Predictive models. Predictive models are used for forecasting. There are four commonly utilized categories of predictive models: statistical regression analysis, time series models, survival/duration analysis, and machine learning techniques. Statistical regression analysis includes linear regression modeling, multivariate regression, and discrete choice models. There are three predominant model types used for discrete choice modeling when the dependent variable is discrete: logistic regression, multinomial logit, and probit models. Time series models are used to understand interrelationships among economic variables represented by systems of equations using VAR (vector autoregression) and structural VAR models. Survival analysis is used for systems reliability modeling and predicting the duration of time until one or more events happen. Lastly, machine learning techniques include classification and regression trees, neural networks, multilayer perceptron (MLP), radial basis functions, support vector machines (SVM), Naïve Bayes, k-nearest neighbors, and geospatial predictive models.

Descriptive statistical models. Descriptive statistical models are used to summarize the population or dataset. Descriptive statistics include numerical descriptors, such as: counts, mean, median, and standard deviation. They can be used to describe categorical data (i.e. frequency and percentages). General statistical analysis includes analysis of variance (ANOVA), t-test, chi-squared test, and others.

Inferential statistical models. Inferential statistical models are used to draw meaningful inferences about the full population from a sample dataset. There are four main grouping of inferential statistical analysis: hypothesis testing, estimation, correlation, and regression. Hypothesis testing is used to answer yes/no questions about the data and examples include chi-squared test, Mann-Whitney U, and student's t-test. Estimation is used for approximating numerical characteristics of the data and examples are conjoint analysis, analysis of variance (ANOVA), factor analysis, and mean square weighted deviation (MSWD). Correlation is used for describing association within the data. Two examples of correlation methods are Pearson product-moment correlation coefficient and Spearman's rank correlation coefficient. Regression for statistical inference is used to model relationships within the data, examples include multilevel modeling, multivariate regression, cluster analysis, principal components analysis (PCA), and multidimensional scaling. There are many multilevel models, such as: hierarchical linear models, nested data models, mixed models, random coefficient, random-effects models, or random parameter models.

Economic models. Economic models are used to model economic datasets. Economic models can be separated into two categories: theoretical economics and econometrics. Examples of theoretical models are supply-demand models and microeconomic production functions. In education research, the microeconomic production function has been adapted to the education production function, which is often used for determining the impact of student/school level factors on student performance or other outcome measures. Econometrics are the statistical analysis of economic dataset. Regression-discontinuity is an example of an econometrics method and is used to estimate the average treatment effect in an environment in which randomization is unfeasible.

System models. System models are used to understand the operation and behavior of systems. System models include network modeling, agent-based modeling, system dynamic modeling, discrete event simulation, and geographic information systems (GIS) analysis. One example of network modeling is social network analysis. Geographic information systems can be used to perform spatial models or to generate geographically weighted regression models.

To further explore how well each of the types of models align with aspects of complex systems, we analyzed each modeling technique to assess whether they take into accounts aspects of complex systems, specifically their nonlinearity, interdependencies, feedback loops, and stochasticity. Table 1, shown below, is a synthesis of our finding from reviewing the educational modeling techniques.

Table 1

Summary of Modeling Techniques as Applicable to Complex Systems Characteristics

Analysis	**Nonlinearity**	**Inter-dependencies**	**Feedback Loops**	**Stochasticity**
linear regression	-	-	-	-
logistic regression	x	-	-	-
multinomial logistic	x	-	-	-
probit logistic	x	-	-	-
autoregressive models (AR)	-	-	-	x
moving-average (MA) models	-	-	-	x
vector autoregressive (VAR)	-	x (linear)	-	x
structural VAR models	-	x (linear)	-	x
survival models	x	-	-	-
decision tree	-	-	-	-
random forest	-	-	-	x
multivariate adaptive regression splines	x	-	-	-
nonparametric regression discontinuity	-	-	-	-
parametric regression discontinuity	x	-	-	-
cluster analysis	-	-	-	-
multilevel models (hierarchical models)	-[a]	-	-	x
fixed effects model	-	-	-	-
random effects	-	-	-	-

Analysis	Nonlinearity	Inter-dependencies	Feedback Loops	Stochasticity
mixed model	-	-	-	-
ANOVA	-	-	-	-
factor analysis	-	-	-	-
supply and demand models	x	-	-	-
production model	x	x	-	x
network modeling	x	x	x	x
agent based modeling	x	x	x	x
system dynamic modeling	x	x	x	x
discrete event simulations	x	-	-	x

[a]This modeling technique has been extended to also describe nonlinear relationships (Goldstein, 1991).

Of the 27 modeling techniques that were evaluated, 13 had aspects of nonlinearity, 6 had aspects of interdependencies (although two of these only took into account linear interdependencies), 3 had feedback loops, and 11 had stochasticity. Moreover, only three modeling techniques aligned with all of the attributes of complex systems. These included network modeling, agent-based modeling, and system dynamic modeling.

Conclusions

Complex systems modeling techniques have the potential to expand our understanding of the educational system. When complex modeling techniques are applied to educational systems, we will be able to learn about the interactions and nonlinear relationships that dictate the system outcomes.

In future work, using a model of the Arizona's educational system, we plan to show that negative, unintended consequences can arise when decision-makers fail to recognize the complex relationships which govern the educational system. We expect this analysis will demonstrate the existence of complex system characteristics (nonlinearity, interdependencies, feedback loops, and stochasticity) embedded within the Arizona school system. We intend to leverage these system models to simulate intervention strategies to improve student outcomes at a local and state level. We anticipate that this analysis will provide opportunity for further investigation and simulation of policy and academic interventions applied to the educational system. As a result, we may discover policy and academic changes for refining the educational system to better suit the needs of all our students.

CHAPTER 3

SIMULATION GAMING CAN STRENGTHEN EXPERIENTIAL EDUCATION IN COMPLEX INFRASTRUCTURE SYSTEMS

The chapter to follow is a direct reproduction of the research outcomes from a collaborative effort which resulted in a published article in the Journal of Simulations & Gaming. Authors are McBurnett, L. R., Hinrichs, M., Seager, T., and Clark, S and the journal article was published in 2018. As of February 2020, the article has been cited by three peer-reviewed journal articles.

Abstract

Background. Despite federal directives to strengthen the resilience of critical infrastructure systems, existing education programs have not kept pace with ambitious policy goals. As post-war infrastructure ages, it is increasingly necessary for graduates to master systems thinking to understand the complex and interdependent nature of infrastructure. Whereas in traditional physical science and engineering courses, learning would take place in laboratory exercises, the scale and criticality of infrastructure present obstacles to experimental and experiential learning activities.

Aim. This article describes the experience of an educational simulation game, called the *LA Water Game*, to teach management of ageing water infrastructure as a complex socio-technical system.

Method. A total of over 200 participants in 16 workshops completed an introductory lecture, experimental scenario development, experiential game play, and participated in reflective group discussion. Qualitative data was collected during game play and debriefing interviews and was used to assess participant learning outcomes.

Results. Participant feedback affirmed that simulation gaming can reinforce the experimental, experiential, and reflective phases of the Kolb Learning Cycle. Subjects displayed cognitive and affective engagement, intrinsic motivation, and often reported improved

understanding of complex systems attributes, including interdependencies, feedback loops, nonlinearity, and stochasticity.

Keywords. Critical Infrastructure, Complex Systems, Experiential Learning, *LA Water Game*, Simulation Games, and Systems Thinking.

Introduction

A diverse range of disciplines use simulation games for teaching and training, including: military system operations (Perla & McGrady, 2011; Caillois, 1961; Huizinga, 1944; Sabin, 2012; Smith, 2010), economic systems (Doyle, Radzicki, & Trees, 2008), environmental systems (Rijcken, 2012; Stave, Beck, & Galvan, 2015), governmental systems (Nishikawa & Jaeger, 2011), public policy (Mayer, 2009; Duke, 2011), disaster management (Kobes et al., 2010), water resource management (Chew, 2014; Medema et al. 2016; Savic, 2016; Rusca et al, 2012), history (Corbeil & Laveault, 2011; Hofstede et al., 2010), sociology (Greenblat, 1971) and engineering (Potier, 2016). Despite their popularity, the experiential nature of simulations and games makes learning difficult to assess (Chin et al., 2009; Wolfe & Roberts, 1986; Corbeil & Laveault, 2011). Girard et al. (2013) found that the following attributes can promote learning in serious games: a) cognitive and affective engagement, b) intrinsic motivation, c) flow state (Csikszentmihalyi, 2014), and d) stimulation without distraction from learning. Nevertheless, there exists a subset of cases involving complex systems simulation games wherein participants consistently demonstrate their belief in misconceptions that lead to failure (Dörner, 1996).

Unfortunately, when existing education programs and approaches fail to teach students complex systems thinking skills (e.g., Bosch et al., 2014), the consequences extend beyond the sanctuary of simulation games. Real complex systems are typically characterized by non-linearity, interdependencies, feedback loops, and stochasticity (Meadows, 2008; Sterman, 2000; Checkland, 1999; Jolly, 2015). Thus, effective simulation games must draw attention to these qualities. Some of the earliest examples of complex systems games include a business game (Bellman et al., 1957) developed by consultants of the Rand Corporation and Booz, Allen & Hamilton, and the Beer Game (Forrester, 2007) created by professors of the MIT Sloan School of Management. Bellman's business game represented a business firm as a whole and aimed to reveal interdependent relationships between multiple firms that are competing for a known consumer market. In the Beer Game, reinforcing feedback loops and information delays result in an amplification of order imbalances called the *bullwhip effect*. The Beer Game has stumped supply chain management students since its creation in the 1960s (Goodwin & Franklin, 1994; Sterman, 1989; Sterman, 1994). Similarly, a recent study demonstrated that college students were unable to identify complex systems traits exhibited in a non-serious game (Wasserman, 2017).

This article demonstrates the value of a simulation game as a teaching method for engineering and infrastructure students to learn and develop the systems thinking skills required to support infrastructure resilience (Seager et al., 2017). We developed a simple systems dynamics model to represent the problem of maintaining the quality of the Los Angeles water distribution infrastructure over a 75-year period. Although the technical model is not specific to Los Angeles, the frequency of water main breaks during the severe California drought of 2014 allowed the game facilitators to draw upon popular news articles and events to make game play emotionally more salient for players. The simulation model features all four components of complex systems mentioned above: 1) non-linearity is represented in the ageing of the water system over time, 2) interdependent relationships exist in the way that public opinion is impacted by water rates and water system quality, 3) feedback loops are present in the dependence of funds for maintenance on public opinion, and 4) stochasticity is present in the random occurrence and expense of water main breaks. The resulting *LA Water Game* was tested in 16 workshops and played by more than 200 individuals. Workshops were organized around the four aspects of the Kolb Learning Cycle: abstraction, experimentation, experience, and reflection (Kolb, 2014; Kolb, 2009; McKenna, 2009).

Game Development and Play

The challenge of decaying infrastructure demands a novel, innovative engineering education approach that engages all four parts of the Kolb Learning Cycle to transform students' understanding of complex systems (Vanasupa et al., 2009). Existing teaching methods that emphasize homework problem sets, lab bench experiments, and experience as classroom discussion are inadequate because the scale and critical nature of infrastructure services prohibits opportunities for students to experiment with real complex infrastructure systems. Current games for engineering education (Bodnar et al., 2016), define learning objectives on technical details and system optimization. Although there are several complex systems instructional games set in ecological systems (i.e. Spierre et al., 2009; Seager et al., 2009), infrastructure games remain focused on complicated systems while neglecting complex systems (Poli, 2013).

The *LA Water Game* creates the opportunity for groups to explore the management of an abstract infrastructure water system as a simulated game, without the risks and consequences of real failures (Figure 1). The game emphasizes infrastructure complexity in relation to public opinion, funding, and the quality of the water system in Los Angeles, California (see Table 1 for full list of game parameters). In the *LA Water Game*, the participants' objective is to manage the Los Angeles water distribution system for a 75-year period without violating financial, quality, or public approval constraints.

Figure 1. Guests from the Office of Naval Research, the Space and Naval Warfare Systems Command (SPAWAR), the Energy Systems Technology and Evaluation Program (ESTEP), and Naval Facilities visited the ASU Decision Theater and played the LA Water Game. Photo credit: Emily Herring

The simulation is programmed in Vensim© (Ventana Systems, 2016) systems dynamic modeling software that allows modelers to intervene at each time step by adjusting decision variables. The game can be facilitated within a 75-minute class period or spread out over several days. Whereas the data depicted in the simulation model is not calibrated to estimate the real maintenance needs of the Los Angeles water distribution system, the curvature of model relationships have been empirically observed. For example, the decay of water system quality proceeds from 100 percent (brand new) to zero percent in a S-shaped curve consistent with that observed in real water distribution systems (e.g., Cromwell et al., 2001; Damodaran et al., 2005; Thomson et al., 2013).

Figure 2 shows how the simulation parameters are interrelated. For example, in the absence of maintenance, infrastructure system quality decays exponentially with respect to time and is modeled with a logarithmic function. Since distribution pipes are located under the ground, the public does not observe changes in infrastructure quality and the public approval is not sensitive to quality shifts. Instead, public opinion declines as a result of increasing fees and the occurrence of emergency breaks. The frequency of water main breaks increases as infrastructure quality declines, and the emergency cost of these breaks are modeled with a beta random distribution.

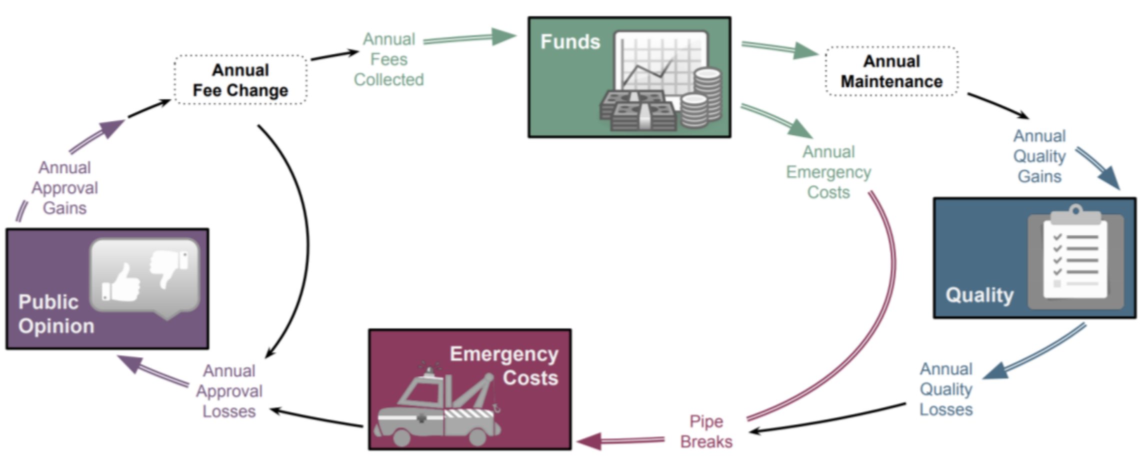

Figure 2. The influence diagram for the systems dynamic simulation model for the LA Water Game.

Each decision period, players decide on increases or decreases in the rate of fees charged to the public, and how much to spend on maintenance. As participants make decisions regarding public water fees and allocation of maintenance funds, the game facilitators enter their decisions in the Vensim© simulation to update the model. The challenge facing players is that ageing infrastructure requires more maintenance, necessitating increases in fees, and consequently damaging public opinion. Due to its complex nature, participants must learn to manage competing agendas and balance the dynamic relationships between each of game parameters described in Table 1.

Table 1

The LA Water Game Parameters

Variable	Description	Scale	Initial Value
System Quality	Overall system condition for provision of clean water and reduced frequency of pipe breaks	Range: 0% to 100%	100%
Available Funds	Sum of the annual public fees collected less the yearly preventative maintenance allocation and the total emergency repair costs	Millions of dollars	$50 Million
Public Opinion	Rating rises or falls in relation emergency repairs and fee changes	Range: 0% to 100%	100%
Annual Fees	Public fees collected and added to available funds	Millions of dollars per year	$50 Million per year
Emergency Costs	Yearly cost to repair spontaneous leaks and breaks in the water distribution system	Millions of dollars	$0 Million
Maintenance	Yearly amount allocated towards preventative maintenance and system repairs	Millions of dollars	Decision variable
Fee Changes	Percent increase or decrease to the rate of annual public fees collected, compounded annually	Range: ± 0% to 100%	Decision variable

Historical Context of the *LA Water Game.* In January 2014, the governor of California declared a state of emergency in response to a multi-year drought, placing restrictions on water usage, requirements for water use reporting, and calling for residents to reduce water consumption. Nonetheless, six months later, on the day new water restriction measures went into effect, a 90-year old water main near the University of California Los Angeles (UCLA) campus burst, releasing 20 million gallons of water and causing $13 million in damages (Gordon, 2015).

While this break was a particularly acute example, a series of prior and subsequent incidents formed an alarming trend.

Operation of the water system is provided by Los Angeles Water & Power, which budgets for its maintenance and repair. However, spontaneous breaks require immediate attention and emergency funding that may exceed available maintenance funds. Whereas the public may bristle at a steady increase in rates for water services and pipe maintenance, in the face of an emergency like the UCLA Flood, funds must be redirected for immediate use and repair. From a financial perspective it may be cheaper to fund these emergency repairs for acute pipe breaks as they arise, rather than pro-actively maintain and replace the ageing components throughout the system -- despite the unexpected service interruptions and collateral flooding damage that undermines public confidence in the infrastructure managers.

Complex Systems Thinking Skills Represented in the *LA Water Game.* The *LA Water Game* integrates four components of complex systems thinking into its design, providing a concrete experience and touchstone for engineering students to understand the complexities of decisions made regarding infrastructure, as summarized in Table 2.

Table 2

Complex Systems Dynamics in the LA Water Game

Dynamic	Manifestation
Interdependency	Physical components of infrastructure (water pipes) are interdependent with social systems (public opinion) and economic systems (fee rates and availability of funding).
Feedback Loops	Water system quality output becomes input for public approval rating; public approval rating affects fee change; fee change affects availability of funds; funds affect system quality (Marlow et al., 2013).
Stochasticity	If the water system quality decreases, the system experiences semi-random emergency breaks to varying degree of damage.
Nonlinearity	System quality is nonlinear over time; the increase or decrease in system quality over five-year increments does not produce linear, predictable changes in public approval or fees.

In the process of making decisions within the game, participants test hypotheses to understand how the system components are related. Since participants have only two variables to manipulate, they can test all the combinations of their decision variables early on. For example, in the beginning of the game first generation participants often realize that they must test how much money is enough to maintain the quality of water service. Since many participants have no prior experience, first generation participants often decide upon an arbitrary amount to assign to maintenance (e.g., one half the annual fees collected, thus 25 million per year) and their selection of the amount to spend on annual maintenance has a relatively low weighted impact on the other parameters (public opinions and system quality). However, as the game continues and the system ages, later generations must formulate and test additional hypotheses to determine how much investment is required to mitigate rapid declines in quality.

Game Play Sequence and Objectives. Facilitators must be well-versed in the historical context and story of California's drought and water system problems, as well as the relationships between the parameters described in Table 1. Facilitators control the environment and are tasked with narrating the game, engaging participants, maintaining attention and participation, and integrating additional components of infrastructure complexity into cohort discussions and debate. Gamification relies upon the facilitators' artful ability to elevate participants' experience such that they feel emotionally invested in and affected by the outcome and are motivated to achieve success in the form of sustaining public opinion through stable maintenance fees, availability of funds for repair, and acceptable quality levels of the water system.

To begin, facilitators divide the participants into three groups. The three groups represent the first, second, and third generations to inherit the LA water distribution system. Starting with the first generation, each group plays the role of the LA water manager for five sequential turns before passing the role to the next generation. Each turn represents a length of five years in the real world where the managing group is responsible for selecting how much to spend on annual system maintenance, as well as decide whether or not to increase the LA residents' water fees. The first generation begins the game with a new water distribution system outfitted with clean pipes. They must decide how to set maintenance fee rates, accrue or spend available funds, and maintain the quality of the water system during their tenure. Since the game moves in intervals of five years, each generation has a maximum of five consecutive decision-making opportunities.

After 25 simulated years, the first generation retires, and the second generation assumes control for the next 25 years, and the third generation for the remaining 25 years.

If any of the three performance constraints are violated, the generation managing the system is dismissed – i.e., no longer permitted to make game decisions. Facilitators then have the option of promoting the next generation early or recalling a prior generation from retirement. Thus, participants who desire to complete all 25 years of their generation's service must avoid low public approval ratings, maintain a minimum quality condition, and avoid bankruptcy.
Since the game is analogous to the LA system, facilitators have access to a portfolio of real newspaper articles and videos which they may choose to interject at pivotal moments of the game. For example, when a generation raises ratepayer fees, facilitators can evoke an emotional response by pulling up a LA Times article on local billing complaints (Lopez, 2015), while implying that the complaints described in the article are the result of the decision to increase fees. When small emergencies occur in the game, news stories about minor pipe breaks in LA county (Mejia, 2015) and a NBC Los Angeles article on a water main break that sent asphalt chunks flying (Arambulo & Arvin, 2015) are available. Additional articles feature more severe events, such as the UCLA flood covered by USA Today, NBC News, and other sources (Moloshok, 2014; Woodyard, 2014; Loyd & Guinyard, 2014; Gordon, 2015) or complaints from 60,000 overcharged customers (Ezzeddine & Vara, 2014). Although game variables will not correspond to the details of these articles, by including stories and vivid images of the real LA county failures throughout the game, the students' emotional experience may correspond to the real predicament faced by LAWPD water managers.

The *LA Water Game* teaches participants about a specific kind of feedback loop that is often a cause for poor decision-making – a time lag. Because participants learn the mechanics of the system as they play, they must become responsible for operation constraints in real time, learning on the job how sensitive their system is to the decisions they make. Participants, particularly those in the first generation, do not have all the required information when asked to make their initial decisions, and yet they must decide on maintenance fund allocation and public fee amounts. In addition, the system is not nearly as sensitive to changes in the beginning of the games as it becomes at later points in the game, for the second and third generations. Thus, participants confront a time lag feedback loop because they often learn how the infrastructure system responds to changes after the system is already failing. By that time, it is often too late for the present generation to recover from poor management decisions, which are inherited by future generations.

Workshop Debriefing and Assessment Methodology. The *LA Water Game* was facilitated in 16 workshops for over 200 participants. Each workshop contained between 7 and 27 participants. Participants consisted of heterogeneous groups of undergraduate and graduate students, faculty, and active-duty military personnel. Students' backgrounds represented a diverse range of disciplines, including engineering and non-engineering majors such as, industrial design, data analytics, computer science, and business. During each workshop, participants completed an introductory lecture, experimental scenario development, and then were divided into three groups for experiential game play. In all 16 workshops, participants engaged in reflective debriefing, led by the game facilitator during and post-game play.

Data was gathered from participant observations (Robson et al., 2002) and debriefing interviews (Lederman et al., 2001). Upon evaluation, workshop themes emerged and were categorized by two attributes that Girard et al. (2013) identified with learning in serious games: a) cognitive and affective engagement, b) intrinsic motivation.

***Qualitative data collection*.** For assessing participants throughout game-play, Chin et al. (2009), recommends the qualitative data collection methods detailed in classic works such as *Writing Ethnographic Fieldnotes* (Emerson, Fretz, & Shaw, 1995) or *In the Field* (Smith & Kornblum, 1989). In addition to these sources, this study used qualitative methods (Tracy, 2012) for analyzing qualitative data gathered from participant observations and debriefing interviews. Participant observational data was structured by the framework proposed by Robson et al. (2002), which covers space, actors, activities, objects, acts, events, time, goals, and feelings. During debriefing interviews, participants were brought together for guided recall, reflection, and analysis.

***Debriefing*.** Historically, debriefing interviews have been used by military campaigns and war gaming activities (Lederman, 1992). Among simulation gaming methodology literature, debriefing is generally accepted for aiding the learning process (Crookall, 2010; Lederman, 1992) and facilitating reflection (Thiagarajan, 1992). Interim and post-game debriefing sessions were incorporated in the LA Water Game to assist participants to relate their experiences from the game to those of real-life situations. Debriefing conversations were held at two phases of the game. Intermediate debriefing was conducted when a generation passed on the LA water manager role to the sequential generation. During intermediate debriefing, the facilitator asked the earlier generation to reflect on the decisions they made while they were the LA manager and to self-evaluate their job performance. After the game, the facilitator led a post-game joint debriefing session in which all participants were asked to analyze the evolution of the game and to relate their performance to a real-life situation. Participants then reflected on the differing perspectives offered by the three generations. The facilitator prompted participants to discuss alternative courses of action and asked participants to hypothesize the potential consequences of these options.

Open-ended questions were designed to induce reflection and analysis of the events and processes in the simulation game, their contributions to these processes, and to develop their systems thinking skills relevant to other real-life situations. These questions were based off of Thiagarajan's (1992) 7-point debriefing sequence, including recollection of what happened and their feelings, hypothesize cause-effect relationships, and determine real-world relevance or further applications of principles learned during game play. In accordance with Peters & Vissers (2004) exploratory/development debriefing classification, the LA Water simulation game provides a context for exploration and experimentation while the facilitator guides participants to use the opportunities provided by the simulation game to explore boundary conditions, and a chance to change these conditions if necessary.

Findings from the LA Water Game Pilot Workshops

The game was evaluated as a tool for teaching complex systems thinking skills with particular focus on two assertions that effective educational games: 1) foster cognitive and affective engagement, and 2) increase intrinsic motivation that allows for longer training periods. For each finding highlighted, we provide examples from qualitative participant observations gathered during game play or debriefing interviews. Table 3 describes the diverse set of student and researcher teams with whom we have tested the *LA Water Game* in 2016 and 2017.

Table 3

The LA Water Game Piloted Workshops

ID	Workshop	Location	Date
1	Systems Engineering Class	ASU campus, Tempe, AZ	04/26/2016
2	Naval Postgraduate School (NPS)	NPS campus, Monterey, CA	05/09 - 05/11/2016
3	Thunderbird Executive Education Crisis Management Instruction & Decision Theater team	ASU campus, Tempe, AZ	06/01/2016
4	Navy Enterprise Partnership Teaming with Universities for National Excellence Veteran student	Decision Theater, Tempe, AZ	07/15/2016
5	Resilient Infrastructure Graduate Research Seminar	ASU campus, Tempe, AZ	09/06/2016
6	Water Sustainability Climate Research Team	Decision Theater, Tempe, AZ	09/09/2016
7	ASU Luminosity Lab	Decision Theater, Tempe, AZ	10/21/2016
8	Decision Theater Coding Team	Decision Theater, Tempe, AZ	11/23/2016
9	Systems Engineering Class (subset)	ASU campus, Tempe, AZ	01/09/2017
10	Office of Naval Research, SPWAR, ESTEP, and NAVFAC visitors	Decision Theater, Tempe, AZ	01/11/2017
11	Systems Engineering Class (full class)	ASU campus, Tempe, AZ	03/02/2017
12	ASU Spirit of Service Scholars Workshop	Decision Theater, Tempe, AZ	03/25/2017
13	Infrastructure Socio-Eco-Tech Seminar	Decision Theater, Tempe, AZ	03/27/2017
14	Infrastructure Grad. and Undergraduate Students	Purdue, West Lafayette, IN	04/19/2017
15	Frontiers of Resilience Workshop	George Mason University	05/11/2017
16	Naval Postgraduate School (NPS)	NPS campus, Monterey, CA	06/01 - 06/03/2017

Couple Cognitive Engagement with Affective Engagement and Motivation. Annetta et al. (2010) suggested that cognitive engagement in training, coupled with affective engagement and motivation (Baker et al., 2010; Knight et al., 2010; Sitzmann, 2011) is correlated with learning in serious games. During game workshops, we observed the following signs of cognitive engagement among players: paying attention, experimenting, deliberating, and negotiating. All participant names have been changed to protect their privacy.

Paying attention. Prior to the start of every game, facilitators opened the room for questions. Participants asked questions about the game rules and how to interpret the game progress metrics and graphs. We observed participants visually track game progress and dynamics on the projected screen. Participants demonstrated alert behaviors, learning forward in their chairs, pointing at the screen graphics as they changed, and directly incorporating reported data into their conversations. Figure 3 shows how each generation grew more engaged during their turn as the LA water manager in workshop 11. During the first generation's turns (Figure 3A), participants from the second and third generations listened attentively to the first generation as they deliberated, repeating spoken words, phrases, and numerical figures amongst their own groups. As facilitators shared news articles and game updates, participants asked clarifying questions and nodded along with facilitators' directions.

Experimenting. Participants attempted various combinations of maintenance investment and public service fees to maintain public opinion over the course of the game. When given access to the single-player version of the *LA Water Game*, participants from the second and third generations tracked the game progress with their personal computing devices and simulated multiple future scenarios to anticipate future events and test the efficacy of different response strategies for when their turn arose.

Deliberating. Participants engaged in conversations, debates, and problem solving with their own generation and other generations. First generation participants often spent the most time to plan out their decisions, attempting to forecast anticipated effects of a given fee amount or maintenance investment. By the third generation's turn, the system was often in a state of disrepair, the public approval rating was below 25 percent and the city budget was in debt. Thus, third generation participants often spent the least amount of time forecasting and calculating, given that they had less freedom to operate within their given constraints.

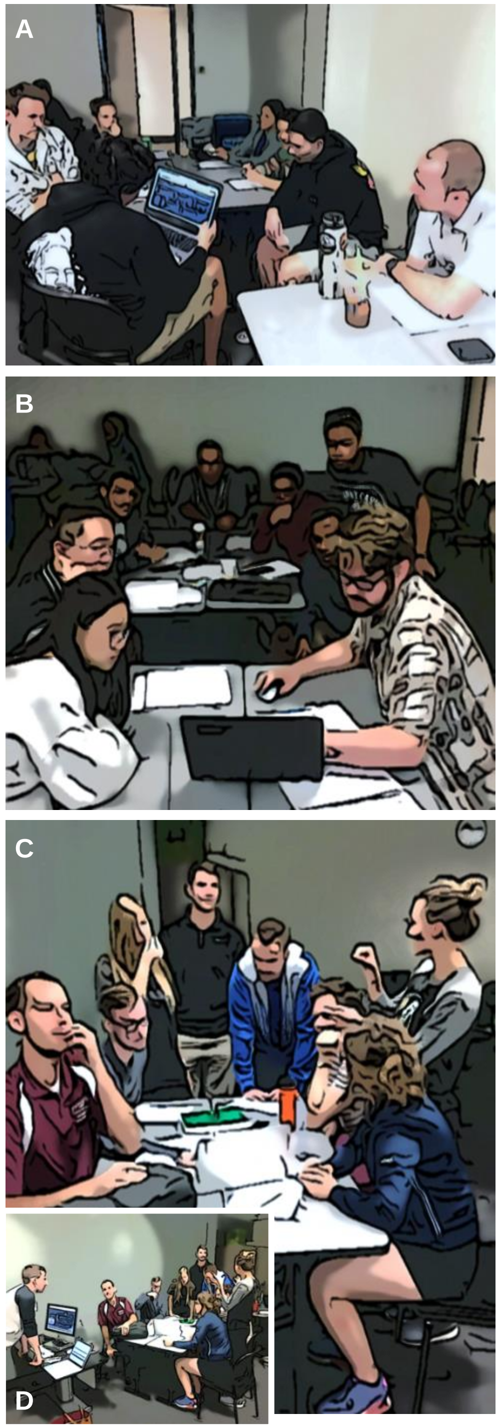

Figure 3. A, B, and C show the 1st, 2nd, and 3rd generations from workshop 11. The 1st generation (A) seated themselves across at two tables with just one student running the calculator simulation. In the 2nd generation (B), students are leaning into the discussion. By the 3rd generation's turn (C), students are standing crowded around a table immersed in heated debate.

(D) One 3rd generation student got up from the group table, stood at the facilitators' laptop for immediate access to the simulation controls, and proceeded to tab through the simulation graphs.

Negotiating. Participants who inherited a broken system often negotiated with game facilitators. In workshop 10, a second-generation participant, declared that the second generation would not accept the role of the LA water manager unless facilitators guaranteed they would be given at least 30 years without fear of being fired. By the end of the 30 years, this group was able to raise water fee rates, invest in the infrastructure, and eventually public approval (which remained below the 25 percent threshold) began to increase. While this interaction might appear to bend the game's rules, the player's negotiation was acceptable since this interaction helped the group explore the boundaries and constraints of the system – a skill critical to understanding complexity.

In addition to the listed indicators of cognitive engagement, participants also exhibited signs of affective engagement and motivation. Starting each workshop, participants were optimistic and confident in their ability to accomplish the game requirements. They laughed, smiled, and sat leaning forward, expectant and ready to participate. By the time the second generation inherited the manager position, participants began to demonstrate physical indications of stress. They sat with their arms folded, brows furrowed, and their chins rested on their hand while contemplating the data on the screen. Participants expressed anxiety after the sudden emergency costs and by the non-linear decays in system quality, often letting out strained laughs and using common expressions to convey resigned, emotional responses to decisions made both by their own and other generations.

Below is a workshop excerpt of participant observations that conveys affective engagement between two students through their dialog and physical gestures. The participants' conversation highlights their learning process and their iterative approach to decision making that helps them to understand the system's underlying feedback loops.

> Tyler: Start super high (increasing the fee change by a large amount early on in the game). Everyone is going to hate you.

Zach: So… drop the maintenance? [entering the decision]

Tyler: There goes your public opinion.

Zach: Yeah. It is already gone. [laughing]

Tyler: Now, drop it by 20% every decision cycle because they (the public) already hate us. So let's just see what happens.

Zach: Exactly. Oh wait. You mean the fee (change) or maintenance?

Tyler: The–the maintenance price and then the fee change is minus 20% but the maintenance should be the same.

Zach: How about minus 10%?

Tyler: Ok. Sure. [throwing hands in concession]

Zach: Minus 0.1 [mumbling while entering the fee change decision]

Tyler: Just want to see what the results are.

Zach: This is per year, so the–that actually will make a really big impact. [hypothesizing before inputting the decision]

Tyler: Ohhhh… ok.

Zach: [clicking forward] Wow. You see like how here. [pointing at screen]

Tyler: See the public opinion goes right back up… [pointing at screen]

Zach: Yeah.

Tyler: …and you dropped the fee just a little bit. And we are still at a ridiculous amount of money. You recover just about–about half of what you lost.

Zach: Yeah. [laughing]

Tyler: Right? [laughing] But, look at our *funds*!

[grinning and laughing together]

Zach: Dude! Yeah!

Tyler: [laughing, throwing hands upwards into a V-victory position]

Zach: Look at the rate.

Tyler: What a *bank account*.

Zach: Look at the *rate*. [repeating himself in a louder voice to be heard over Tyler's excited laughing]

Zach: Oh my god.

Tyler: [pointing at screen] Do it again. Let's see what happens the next time.

The above transcription exemplifies two participants displaying signs of cognitive and affective engagement throughout game play. From the onset, Tyler and Zach experiment with a high fee change to increase annual revenue from fees. When Tyler and Zach realize they have an exorbitant amount of funds, they decided to reduce the public fees and negotiate the magnitude of the fee change. Both participants were motivated and expressed affective engagement through laughing and hand gesturing.

Intrinsic Motivation. The simulation game encouraged participants to continue practicing for longer than a traditional lecture period. After students played through three generations of the game, many participants requested to restart the simulation and play the game over again. The majority of participants expressed dissatisfaction with the first game results and some students insisted on playing the game several more times. When time allowed, facilitators agreed to the students' requests to replay the game. Of the 16 workshops, 10 of the workshops had time to play through multiple attempts. Because it took a full 75-minute class period to play one round of the game (including the time required to introduce and debrief the game), some students, such as those in workshops 2 and 16, were given the opportunity to repeat the game during a second class period. With each voluntary repetition, students devoted additional time to experimenting with the complex system components (non-linearity, stochasticity, interdependencies, and feedback loops) featured in the game.

We believe that students requested to play the game over because the game capitalized on intrinsically motivating features and allowed students to work towards a meaningful purpose, while pursuing mastery and autonomy (Pink, 2001; McGonigal, 2011; Garris et al., 2002). Students' disciplinary backgrounds may also have correlated with the purpose or goals they pursued as the LA water manager, as indicated in the following anecdote.

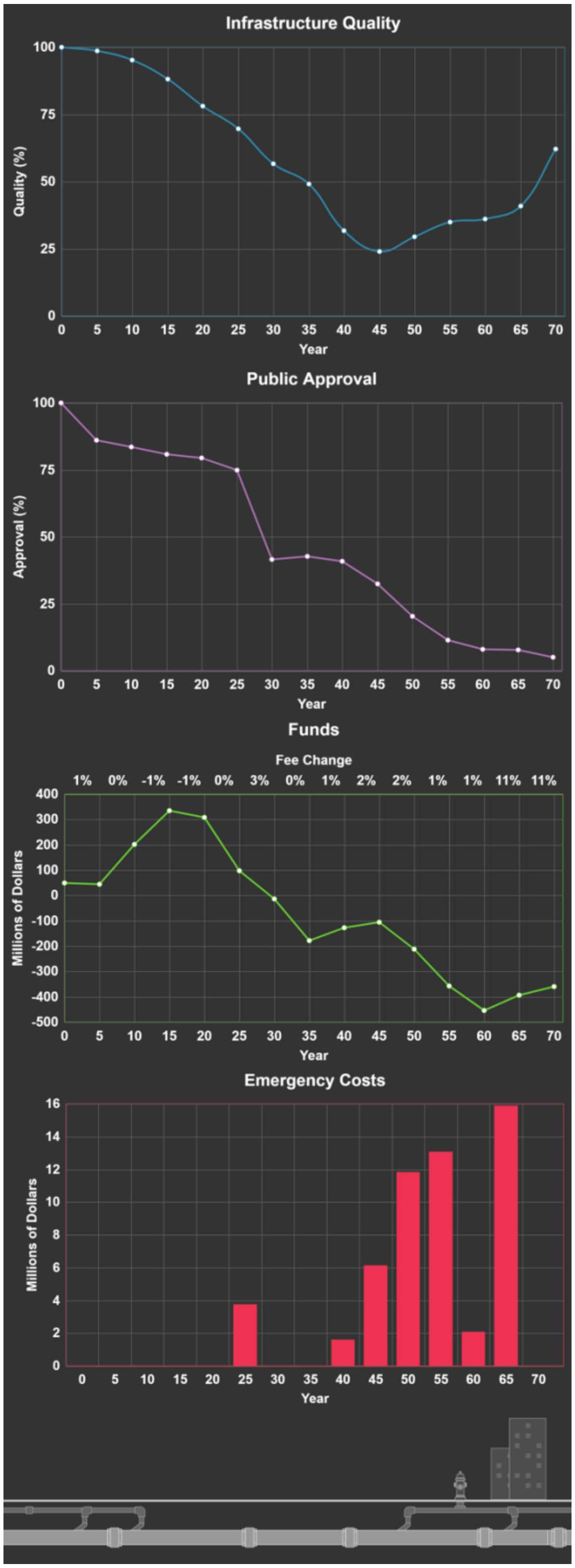

Figure 4. The LA Water Game simulation results from workshop 7. When the first generation reduced public fees, the resulting consequences of scarce funding, poor infrastructure quality,

and expansive emergency costs were passed on to later generations. The second generation made small maintenance investments and limited fee increases in an attempt to avoid getting fired. After the second generation's strategy had failed, the next generation spiked maintenance investments and fees.

In workshop 7, participants included graduate and undergraduate student researchers representing academic disciplines such as computer science, chemical and electrical engineering, accounting, industrial design, business, and data analytics. Members of the first generation, led by an industrial designer and business major, made small investments in maintenance to avoid negative public opinion toward fee changes. When the water system experienced its first stochastic break, ratings for public opinion plummeted as the system required an increased fee change to fix the break and save funds for future maintenance. The first generation invested only enough to ensure that the quality of the system was acceptable until their retirement. In their final decision, the industrial designer and business students decided to decrease the fee change and "give money back to the public", thus making the public approval rating rise, rather than stockpile for future generational maintenance.

In contrast, the second generation was led by a chemical engineering student who was eager to take on management of the LA water system. This student argued for increases in fees and maintenance spending. However, public opinion ratings declined so much that his generation was fired.

Following the game workshop, the chemical engineering student insisted on repeatedly playing the *LA Water Game* to achieve 100% quality for the full 75-year period. To accomplish this, the engineer and industrial design students played the game on a facilitator's laptop for an additional hour after the workshop ended. When asked about why the quality constraint was important, he responded, "I'm a chemical engineer. We can't have emergencies at a nuclear power plant. The public's opinions and complaints don't matter if they aren't alive." This student prioritized public safety over public opinion, which may be a result of internalizing lessons in engineering ethics learned in other courses. Nevertheless, students who requested to continue playing the game until achieving a satisfactory outcome are exhibiting mastery-based learning (Bekki et al., 2012).

Reflections. After processing qualitative data from participant observations and debriefing sessions, a common pattern was identified throughout the workshops. Prior to playing the game, participants were not aware of the reinforcing loops inherent to the system. In the first generation, participants expressed curiosity and eagerness to succeed, as was demonstrated by their questions and physical demeanor. As each generation played the role of the manager, it was only through a trial and error process that participants were able to test hypothesizes, receive feedback, and define the system's underlying complex relationships.

After each decision was made, the simulation advanced forward 5 years, and feedback was presented to the group in the form of data visualizations. Through this, participants were able to identify patterns in the system – one participant from a second generation remarked that, "the public opinion seems more affected by rate increases [fee changes] than to the actual rate [fees paid annually]."

Debriefing interview discussions showed that the players had identified the complex relationships presented in the game. Through hypothesis testing, participants were able to identify the interdependencies between game variables, the nonlinear nature of infrastructure deterioration, stochastic emergency breaks, and the reinforcing feedback loops within the game. When asked what decisions they would make if they played again, one participant suggested that, "The higher you get your rate [annual fees collected] as soon as possible, the better it is, because you just flatten it [fee change] off to zero and you keep the rate [annual fees collected], which is already high, for the rest of the game."

Two examples illustrate the eagerness of participants to go beyond the parameters of the game to realize additional layers of complexity regarding water infrastructure. During the workshop 2 debrief, NPS participants described new strategies for balancing competing complex dynamics. As a result of their experience playing the simulation game, they recommended a modification of the computational influence diagram. They requested that a new decision variable be added which would allow players to allocate funds to educating the public on water infrastructure. These participants argued that by educating the public, the public would better understand how their fees are being used to maintain the quality of the distribution system. As a result, the public upset might be less sensitive to rate increases.

A similar theme emerged in the workshop 5 debrief, in which participants in the Systems Engineering class acknowledged that they began playing the game with the assumption that the public would pay for a well-maintained system. However, through their participation in the simulation game this misconception was exposed through the relationship between public opinion, funding, and system quality. Participants shared their realization that the public often takes for granted both the existence of infrastructure systems and their successful function. Without technical expertise, the public is unaware of the maintenance requirements of the infrastructure systems which are integral to daily life. Like the NPS participants, the engineering participants considered how they might engage and educate the public in the process of maintaining infrastructure.

By highlighting the most critical elements of the system, participants were able to recognize the underlying, and sometimes counterintuitive, relationships governing system interactions. Participants commented on the transferability of feedback loops connecting public funding, public opinion, and system quality to other systems, particularly transportation and road maintenance. Participants observed non-linear relationships between allocation of funds toward maintenance and system quality in the first generation and admitted to being lulled into a false sense of correlation between these system dynamics. However, as later generations inherited the ageing system, the relationship between maintenance and system quality became nonlinear, requiring a more adaptive approach to fee changes and system maintenance all while managing public opinion. Participants described their reactions to stochastic water breaks and acknowledged the complex relationship between these spontaneous bursts, public opinion, and availability of funding for repairs.

Conclusions

Experiencing the LA Water Game gives participants, a foundational understanding of the complex nature of infrastructure management and the systems thinking approach that is required for long-term infrastructure management. By engaging all four stages of the Kolb Learning Cycle, participants learn abstract conceptualizations of complex systems, experiment with parameters that leverage changes in the socio-technical system, gain concrete experiences rooted in affective responses to goal attainment (or failure), and reflectively observe both their own actions and those of other generations. The game also demonstrates complexity around water system infrastructure. Although the simulation game itself is a cartoon-like abstraction of the real system, it provides a foundation for students to begin developing complex systems thinking skills which are critical for managing interdependent infrastructure systems.

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CHAPTER 4

COMPLEX SYSTEMS APPROACH FOR MODELING THE ARIZONA EDUCATION SYSTEM

Abstract

Since education systems are complex, there is an acute need for education policy and academic decision makers to understand the full impact that their decisions have on students, schools, population, workforce and economies at local, state, and national scales. Complex systems modeling techniques have the potential to expand our understanding of educational systems and their influence on interdependent systems, in ways that traditional statistical modeling techniques do not support. Systems dynamics modeling can be used to demonstrate the existence of complex system characteristics (nonlinearity, interdependencies, feedback loops, and stochasticity) embedded within educational systems. This study presents a system dynamics model of the Arizona educational-workforce system that allows for stakeholders to simulate policy interventions for improving student and economic outcomes at a state level. Results demonstrate the model's capability, as a sandbox tool for iterative scenario testing, through an illustrative use case example. The sample use case is focused on increasing Arizona's postsecondary degree and certificate completion rate to constitute 60% of the adult population by the year 2030.

The simulation model was constructed on the Vensim®, version 6.4 (©VENTANA Systems, Inc.) system dynamics software. Using data from several local, state, and federal education and economic empirical databases, the model tracks interactions between Arizona's population, economy, and schools over a period of 50 years, from 1990 to 2040. The model explores a series of policy interventions and allows stakeholders to test dynamic hypotheses and compare how each intervention improves state-wide educational attainment levels and economic outcomes. After testing various scenarios across multiple interventions, the combination of increasing K-12 spending, improving adult education programs, and increasing SET employment was shown to be the best scenario for increasing the percent of Arizona's population with a postsecondary degree.

Keywords. Systems Dynamics, Complex Systems, Socio-Technical Infrastructure, Education Systems, Educational-Workforce Pipeline, Public Policy, Education Reform.

Introduction

Over the past few decades, complex systems research has emerged in new ways and the principles of complexity have been introduced to many fields of research to generate new insights. Whereas many of the pure science fields have been influenced by complex systems research, human systems, such as socio-technical infrastructure systems have yet to benefit from complexity research for providing tangible, engineering solutions. Researchers have long agreed that education systems are, by nature, complex systems and as such, there are conceptual and methodological implications for education research and policy (Jacobson, Levin, & Kapur, 2019; Jacobson & Wilensky, 2006). However, apart from agent-based modeling (ABM) few studies have been conduced to glean new insights through applying complex system modeling techniques to the field of educational systems research.

Complex systems are typically characterized by exhibiting traits of nonlinearity, interdependencies, feedback loops, and stochasticity (McBurnett et al., 2018; Checkland, 1999; Jolly, 2015; Meadows, 2008; Sterman, 2000). Nonlinearity is a behavior in which a set change in the input does not equate to a proportional set change in output. Thus, the system cannot be defined by a linear relationship (Checkland, 1999). Interdependency indicates that subsystems within a complex system are mutually reliant on one another (Meadows, 2008). Feedback loops occur when the output of one system becomes the input for another, and lead to either reinforcing or balancing behavior (Jolly, 2015). Lastly, stochasticity is characterized by irregular and random phenomena - allowing for unpredictable and emergent behavior to occur within the system (Sterman, 2000).

Unintended consequences arise when decision-makers fail to recognize the elements of complex systems (non-linearity, interdependencies, feedback loops, and stochasticity) that govern the educational and economic systems. Some examples of interventions which produce unintended consequences are ESA scholarships, school choice movement/charter schools, transportation funding, free and reduced lunch price options, and variability of high school graduation requirements. Negative, unintended consequences include school racial segregation, poor student academic performance, educational attainment gaps, partial or inadequate school funding, and inequitable school opportunities.

Edward Glaeser and Jesse Shapiro (2001) note “The level of residents’ education and income are consistent predictors of urban growth.” They also acknowledge the tendency of skilled communities to experience growth “has been true for every time period going back to the late 19th century.” Enrico Moretti (2004), who looks at wages in cities with differing levels of educational attainment, finds that “a percentage point increase in the supply of college graduates raises high school dropouts’ wages by 1.9 percent, high school graduates’ wages by 1.6 percent, and college graduates wages by 0.4 percent.” This suggests that education spillovers have an indirect benefit on other labor market segments.

A college degree is one of the most important investments an individual or the state can invest in (Arizona Board of Regents, 2018). The American Community Survey (ACS) reports median wages in Arizona are $65,573 for an individual with a graduate degree, $51,197 for a bachelor’s degree holder, $35,802 for those with an associate degree or have attended some college, and $28,821 for an individual with a high school diploma alone (U.S. Census Bureau, 2018). Arizonans with an undergraduate degree earn a median wage that is $22,376 higher than their peers who do not pursue a postsecondary education (U.S. Census Bureau, 2018). Although the benefits of graduating from college are considerable for students and the state, Arizona high school students go to college at a rate far less than the national average. Consistently throughout 2013 to 2017, only 52.6 percent of Arizona’s high school graduating class enrolled in either a two- or four-year college after graduation (Arizona Board of Regents, 2018). This is nearly 18 percentage points lower than the national average immediate college enrollment rate for high school completers of 69.8 percent in 2016 (National Center for Education Statistics, 2018). Furthermore, the current rate of Arizona’s high school graduating class enrolling in college, 52.6 percent in 2017, is a decrease from 53.5 percent in 2012 (Arizona Board of Regents, 2018). Enrollment trends reflect an almost even split between two- and four-year schools with 52.1 percent enrolling in a four-year university and 47.9 percent attending a two-year college in 2017 (Arizona Board of Regents, 2018).

College enrollment rates are just part of Arizona's educational attainment problem. For the vast majority of Arizona college students, college is a more than a four year commitment. This can be a challenge financially. The college completion rates for the high school graduating class of 2005 are 22.5 percent completing a two- or four-year degree. The college completion rate has increased and has now leveled off at 27.1 and 27.3 percent of the high school graduating classes of 2010 and 2011, respectively (Arizona Board of Regents, 2018). Moreover, 32.0 percent of female high school graduates complete a degree within six years of high school graduation, as compared to 22.4 percent of male high school graduates who complete a two- or four-year degree within six years of high school graduation (Arizona Board of Regents, 2018). Female high school graduates earn a four-year degree within six years of high school graduation at a higher rate than males, 24.4 percent for females versus 16.7 percent for males (Arizona Board of Regents, 2018).

Twenty percent of Arizona high school students do not graduate high school in four years (Expect More Arizona, 2018). An additional disparity among gender is the five-year high school graduation rate for males at 81 percent versus 86 percent for females. Incorporating the high school graduation rate, only 13.5 percent of male ninth graders complete a four-year degree compared to 21 percent of ninth grade females. If educational attainment trends stay on their current trajectory, only 17.2 percent of today's ninth graders will graduate from a four-year college by 2028 (Arizona Board or Regents, 2018).

Arizona faces unique challenges that contribute to uneven educational attainment rates. Poverty is a leading indicator of reduced educational achievement and 2017 poverty rates in Arizona are among the nation's highest, ranking 12th in the nation for individuals who fell below the federal poverty threshold in the past twelve months (U.S. Census Bureau, 2018). That year, nearly a quarter of all Arizona children fell below the poverty line (Arizona Board of Regents, 2018). Approximately 25,000 children attending Arizona public schools are homeless and 57 percent of K-12 students qualify for free or reduced meals (Arizona Department of Education, 2018). Lack of educational attainment is a primary limiting factor not only on individual prosperity, but also the economy of entire communities where college enrollment and completion rates remain low.

A university education introduces students to new cultures and experiences, critical thinking skills, and fosters individuals' growth and maturation in ways that cannot be calculated or measured. There are a myriad of benefits realized through higher education, including: a stronger economy, robust workforce, greater personal success, more businesses attracted to Arizona, an increased tax base and decreased poverty. Low attainment levels result in a series of system-wide consequences including lower economic growth, fewer new jobs or businesses in the state, higher crime rates, higher dependence on social services and government assistance programs, and continuously lower projected attainment levels.

The Arizona Board of Regents goes as far as to state that "Arizona's economic fate will largely be determined by the educational attainment of our citizenry." The future prosperity of Arizona residents depends on the state's ability to improve educational attainment rates, especially among underserved geographic communities and socioeconomic groups where it is often not feasible to pursue a college or university degree. Continuing efforts to raise the educational rate of Arizona's students is crucial or Arizona's future economy will suffer.

In this study, a system dynamics model of the Arizona educational-workforce system is developed to address the following research questions: (i) How can complex systems modeling techniques be applied to improve our understanding of educational, economic, and population system interactions?, and (ii) How does Arizona's educational system relate to the state's economic performance? This model is used to: a) demonstrate the unique insights that can be garnered using a complex systems approach as opposed to traditional modeling techniques , b) demonstrate the empirical value of using a systems approach to model complex, socio-technical infrastructure systems and determine the economic value of Arizona educational systems, and c) reflect on how the system interacts when intervention levers are applied to improve the educational attainment of Arizona's population.

This research improves understanding of the impact of the educational system on the workforce and economic prosperity of the state of Arizona. It increases awareness of the complex systems traits (non-linearity, interdependencies, feedback loops, and stochasticity) that govern the educational and economic system interactions and outcomes. The model is built with the intention of allowing stakeholders from the Arizona educational-workforce system to use the model for testing several policy interventions. By interacting with policy levers and discovering the interdependent relationships between the educational and economic systems, stakeholders will be able to see how each policy affects the targeted aspect of the system, as well as how non-targeted aspects of the overall system may also be affected.

Model Development

Conceptualization. The current landscape of the Arizona education system and its supporting infrastructure was deduced through a group process (Andersen & Richardson, 1997; Andersen, 1980) where educational and economic systems stakeholders (including staff from the Arizona Board of Regents, Helios Education Foundation, Mesa Unified School District, economists, education researchers at Arizona State University, system modelers) agreed upon the following problem statement: that the state of Arizona's economic workforce and educational systems both suffer from its population's low rate of postsecondary degree attainment (Achieve60AZ, 2016).

Once this problem statement was formulated, the system stakeholders then engaged in systems dynamics modeling inquiry to better understand how the state's educational attainment affects and is affected by the economic and educational systems. To do this, the stakeholders then identified the model's causal structures by determining which factors appeared to be responsible for causing the state's low rate of bachelor's degree attainment and formulate these causal structures into information feedback loops.

With the causal structures, information feedback-loops, and reference mode in place, the stakeholders then formulated the dynamic hypothesis as a potential explanation of how the system structure is causing the observed behavior. These causal structures, feedback loops, and reference modes were the basis of the model presented in this article and the following use case.

Data Collection. After formulating the dynamic hypothesis, the system was studied in depth in order to identify the decision-making processes and capture the flow of information into policies which could be added as levers in the system dynamics model. The dataset for initializing the Arizona education system model was collected from various local, state, and federal sources. The data was gathered to represent each of the four subsystems which pertained to the problem statement: educational data, population data, workforce data, and economic data. For each of the acquired datasets, annual data points were collected for as many years recorded as were publicly available, for the period of 1968 and 2017.

Education data sources. The Arizona Department of Education (ADE) website provided data on public school attendance, enrollment by specialty group (such as race, gender, english language learners, special education, and free or reduced lunch student), high school graduation and dropout rates, and student performance on standardized English and math assessments, for the years, 2009-2017. National Center for Educational Statistics (NCES) datacenter included data from the Common Core of Data, which pertained to school enrollment, teachers and staffing, and financial accounting for the years, 1988-2017. Civil Rights Data Collection (CRDC) contained survey data on student and school experiences for the years, 2009, 2011, 2013, and 2015. National Clearinghouse Data was used to generate the Arizona Board of Regents (ABOR) reports that track Arizona high school students and record college going and completion rates across the years 2010-2011 & 2016-2017. The National Student Loan Data System (NSLDS), College Scorecard, and Free Application for Federal Student Aid (FAFSA) 2015-2017 datasets were used to gather high school FAFSA completion percentages and student loan data.

Population data sources. The U.S. Census Bureau Decennial Census 1990 & 2000 and American Community Survey (ACS) 2009-2017, datasets were used to collect data on population counts, educational attainment, poverty, domestic and international migration flows, and median household income. U.S. Bureau of Justice Statistics FBI Uniform Crime Reporting (UCR) Program data reported crimes by policy department for the years, 1985-2014. The Center for Disease Control and Prevention (CDC) datasets established detailed population estimates including births and deaths for years, 1968-2017. Data pertaining to obesity and respiratory health was gathered through datasets on the websites of Measure of America and Institute for

Health Metrics and Evaluation 1968-2017, National Center for Health Statistics 1968-2017, and the Arizona Department of Health Services.

Workforce and economic data sources. The U.S. Bureau of Labor Statistics (BLS) 1976-2017, data contained records on employment, unemployment, wages, salaries, industries, and employers. The U.S. Bureau of Economic Analysis (BEA) 1977-2017, was sourced to collect data on state and local tax revenues and expenditures, and global domestic product (GDP). The National Science Foundation (NSF) National Science Board - Science and Engineering Indicators 2003-2016, was a source of employment in high science, engineering, and technology (SET) employment establishments as a percentage of total employment.

Listed in Table 1 are population, economic, and workforce parameters, that were selected for programming the systems dynamics simulation model. For each parameter listed, the parameter's data source is provided and the years for which annual data was collected and made publicly available are specified. The data was cultivated from several local, state, and federal education and economic empirical databases.

Table 1

Corresponding Data Sources of Model Parameters and Years of Data Availability

Parameter	Data Source	Years of Data Available
Births (per year)	Centers for Disease Control and Prevention (CDC), Arizona Department of Health Services (ADHS)	1995-2018
Deaths (per year)	Centers for Disease Control and Prevention (CDC)	1968-2016
International migration into and out of Arizona (per year)	IPUMS: NHGIS, US Census Bureau	2010-2017
Domestic migration into and out of Arizona (per year)	IPUMS: NHGIS, US Census Bureau	1970, 1980, 1990, 2000, 2005-2017
Retirements (per year)	US Census Bureau: American Community Survey (ACS) 1-year Estimates	2005-2017
K-12 population school enrollment (annual count)	National Center for Educational Statistics (NCES): Digest of Education Statistics	1980-2017
Total AZ state universities enrollment (annual count)	National Center for Educational Statistics (NCES): The Integrated Postsecondary Education Data System (IPEDS)	1984-2017
Minor population (<18 years old) (annual count)	US Census Bureau: Decennial Survey & American Community Survey (ACS) 1-year Estimates	1990-2017
Adult population (18+ years old) (annual count)	US Census Bureau: Decennial Survey & American Community Survey (ACS) 1-year Estimates	1990-2017

Parameter	Data Source	Years of Data Available
Adult population (25+ years old) (annual count)	US Census Bureau: Decennial Survey & American Community Survey (ACS) 1-year Estimates	1968-2016
Senior population (65+ year olds) (annual count)	US Census Bureau: American Community Survey (ACS) 1-year Estimates	2005-2017
High school diplomas awarded (per year)	National Center for Educational Statistics: Digest of Education Statistics	1981, 1990, 2000, 2008-2028
High school dropouts (per year)	NCES: Common Core of Data (CCD): State Nonfiscal Public Elementary/Secondary Education Survey Data	1991-1997, 2000-2009, 2010-2017
Resident 1st-time freshman college going (per year)	National Center for Educational Statistics (NCES): The Integrated Postsecondary Education Data System (IPEDS)	1986, 1988, 1992, 1994, 1996,1998, 2000-2017
Nonresident 1st-time freshman college going (per year)	National Center for Educational Statistics (NCES): The Integrated Postsecondary Education Data System (IPEDS)	1986, 1988, 1992, 1994, 1996,1998, 2000-2017
AZ adults going back to college (per year)	US Census Bureau: American Community Survey (ACS) 1-year Estimates	2005-2017
Total undergraduate enrollment (annual count)	National Center for Educational Statistics (NCES): The Integrated Postsecondary Education Data System (IPEDS)	1984-2017
Total graduate enrollment (annual count)	National Center for Educational Statistics (NCES): The Integrated Postsecondary Education Data System (IPEDS)	1984-2017
Adult (25 and over) undergraduate enrollment (annual count)	National Center for Educational Statistics (NCES): The Integrated Postsecondary Education Data System (IPEDS)	1987, 91,93,95,97,1999-2017
Adult (25 and over) graduate enrollment (annual count)	National Center for Educational Statistics (NCES): The Integrated Postsecondary Education Data System (IPEDS)	1987, 91,93,95,97,1999-2017
Associates, bachelors, masters, doctoral, and professional degrees awarded (per year)	National Center for Educational Statistics: Digest of Education Statistics	1987 to 2016
College retention rate (per year)	National Center for Educational Statistics (NCES): The Integrated Postsecondary Education Data System (IPEDS)	2003 to 2017
College graduates leave to work outside of AZ (per year)	Arizona Board of Regents (ABOR)	Average from 1990 to 2017
GDP (annual count)	U.S. Bureau of Economic Analysis (BEA)	1977 to 2017
State and Local Property Tax Revenue (per year)	U.S. Census Bureau - Annual Census of State and Local Government Finances, compiled by the Urban-Brookings Tax Policy Center	1977-2015
State and Local General Expenditures (per year)	U.S. Census Bureau - Annual Census of State and Local Government Finances, compiled by the Urban-Brookings Tax Policy Center	2004-2015
State and Local General Expenditures, Per Capita (per year)	U.S. Census Bureau - Annual Census of State and Local Government Finances, compiled by the Urban-Brookings Tax Policy Center	2004-2015
State and Local Tax Revenue, Per Capita (per year)	U.S. Census Bureau - Annual Census of State and Local Government Finances, compiled by the Urban-Brookings Tax Policy Center	1977-2015

Parameter	Data Source	Years of Data Available
Median earnings by attainment (annual count)	US Census Bureau: American Community Survey (ACS) 1-year Estimates	2005-2017
Population educational attainment (annual count)	US Census Bureau: American Community Survey (ACS) 1-year Estimates	2005-2017
SET - high tech jobs (annual count)	U.S. Bureau of Labor Statistics (BLS) Quarterly Census of Employment and Wages	1990-2017
NonSET - low tech jobs (annual count)	U.S. Bureau of Labor Statistics (BLS) Quarterly Census of Employment and Wages	1990-2017
K-12 school expenditures (instructional, support, and non-instructional) (annual count)	National Center for Educational Statistics (NCES) Common Core of Data (CCD) - School Revenues and Expenditures	1986 to 2015
K-12 school revenues (local, state, federal, and intermediate) (annual count)	National Center for Educational Statistics (NCES) Common Core of Data (CCD) - School Revenues and Expenditures	1986 to 2015

Many available data parameters collected were not incorporated in the model. The basis of this decision was made because the dataset did not have enough annual data points for calibrating the model and generating statistically significant regression models. One such example was the economic performance parameter which was not expressed using real personal income per capita (real PIPC). Despite the focus of real PIPC on income instead of jobs and its normalization to remove the effect of population changes, this parameter was not used because the data was not available until the year 2008. GDP was instead selected as the economic performance parameter in the simulation model. Another reason that certain data parameters were not included was because they were overly specific for the high-level scale of this model. Some examples of overly specific data were parameters like the number of K-12 schools, or the count of 2-year colleges and 4-year universities.

Construction. The system dynamics model was constructed with the Vensim®, version 6.4 (copyright VENTANA Systems, Inc.) system dynamics software to reveal the nonlinear relationships, interdependencies, feedback loops, and stochastic elements of the educational and economic systems. The model was built using data described in Table 1, to track interactions between Arizona’s population, economy, and schools over a period of 50 years. The model explored a series of policy interventions and allows stakeholders to test dynamic hypotheses for comparing how each intervention improves state-wide educational attainment levels and economic outcomes.

During development, the dynamic hypothesis, information feedback-loops, reference mode, and the information/decision flows were used to develop a preliminary systems dynamics model. The initial model was built with the capacity to track the interdependent relationships among variables and their dynamic behavior over time. However, this preliminary model was not calibrated to the historic data.

In its non-calibrated form, the simulation model consisted of four types of system dynamics modeling parameters: stocks, flowrates, constants, and information flows.

System Dynamics Modeling Principles. Flows expressed a temporal rate of a given quantity. Stock variables were the memory of the history of changing flows within the system at an instant in time (Meadows, 2008). Stocks were increased or decreased by changing the rates of their temporal inflows and outflows (Meadows, 2008). Feedback loops were causal connections between stocks, decisions, and actions which result in the changing of the underlying stock. Feedback loops were either balancing or reinforcing, whereas balancing loops produced a leveling-out or stabilization of the stock value, reinforcing loops were self-enhancing and lead to exponential growth (Meadows, 2008).

Influence diagrams were used to visualize the relationships between stock and flow variables. Flow rates were shown using double arrows with a value centered on the arrow. Stock variables represented with boxes. The points where flows were generated from or depart to outside of the system boundary were portrayed as clouds. Information or action links were drawn with a single arrow to express their effect on a flowrate or stock variable.

The model was constructed by creating and joining the four subsystems considered in the model: the state's (i) educational pipeline, (ii) population, (iii) workforce, and (iv) economic influencers. After the four subsystems were constructed, information flows were incorporated to adjoin the subsystems.

Subsystem (i) educational pipeline. The educational system consisted of stocks, flowrates, and constants to relate the passage of students from K-12 schools to undergraduate institutions, and then to graduate schools. At each timestep, a constant factor was applied to the school stocks to determine the flowrate of students per year which advances to the next level of academic institution. Using the same process of applying a constant factor to the school stocks, the flowrate of students per year who join the state's workforce was also calculated. The flowrate of students joining the workforce per year was allocated into stocks that describe the students' respective levels of educational attainment when they exited the educational pipeline. Flowrates were also added to incorporate the flow of students reentering the educational pipeline from the workforce stocks.

Subsystem (ii) population. The adult population was approximated as the sum of the five educational attainment population stocks: less than high school diploma, high school graduate, some college or associate's degree, bachelor's degree, and higher than bachelor's degree. This population total was developed to reflect the state's population of those who are 25 years and over. Annual population changes were considered through three mechanisms: births, deaths, and net migration. Births were added as a flowrate into K-12 schools stock. Deaths were a flowrate subtracting from each of the five educational attainment population stocks. Net migration was considered as a flowrate adding to each of the five educational attainment population stocks.

Subsystem (iii) workforce. The workforce subsystem of the simulation model was built to incorporate the educational attainment population stocks and apply a labor force participation rate constant to determine the number of adults in the workforce. Workforce jobs were created in the form of two stocks which represented the number of workers employed in industries with high employment in science, engineering, and technology (SET) occupations and those employed in other industries (nonSET). According to the NSF National Science Board, high SET employment industries were defined as those in which the proportion of employees in SET occupations is at least twice the average proportion for all industries. SET occupations included scientific, engineering, and technical occupations that employ workers who generally possess in-depth knowledge of the theories and principles of science, engineering, and mathematics at a postsecondary level. The stocks for SET and nonSET jobs were multiplied with respective SET and nonSET average median salaries.

Subsystem (iv) economic influences. The taxes, federal funds, GDP, and income portions of the model were all estimated using model parameters that were calibrated to the economic data for the state of Arizona. These economic influences played a critical role in the overall system, as they dictated the state's resources, which in turn, provided feedback into the system to affect the educational outcomes.

Adjoining Information Flows. Information flows were used to connect the model subsystems. These flows related how population's education affects the workforce, how the workforce affects the economy, and the economy affects the education system. Existing literature was used to support the causal relationships between these subsystems. Jackson, Johnson, & Persico (2016) demonstrated several relationships between school funding with educational and economic outcomes. Their models revealed that a 10% increase in per pupil spending each year for all 12 years of public school leads to 0.31 more completed years of education, about 7% higher wages, and a 3.2 percentage point reduction in the annual incidence of adult poverty (Jackson, Johnson, & Persico, 2016). These effects were more pronounced for children from low-income families. Spending increases were most effective when additional funding was allocated to reductions in student-to-teacher ratios, increases in teacher salaries, and longer school years. The following section will discuss these connecting flows and their respective regression models.

Calibration. Once the preliminary model was built, the process of adjusting the model parameters were adjusted such as to force outcome parameters to fit within the margins of the set criteria began. The criteria used, for calibrating the model, was the historical data acquired for the period of years from 1990 to 2017; this time period was selected because these years contained the most complete set of annual data points for the key factors. With the model structure in place for the four subsystems, the calibration process was carried out by applying the following strategies to fit the simulation model to the historical data:

Stock Variables. Stock variables were initialized. For example, stocks such as the number of students in the K-12, undergraduate, and graduate stocks were given initial values from 1990. This process was repeated for each of the stock parameters in the model including the total population and each of the educational attainment level population stocks.

Flowrates. Flowrates were created to connect the stocks initial known values to the historic data from 1990 to 2017. Dynamically calculated constants were applied to the stock values to allow for a percentage of the stock value to become the set flowrate at any given year. For example, the flowrate of K-12 students who graduate each year was computed as the product of the K-12 students' stock and the high school graduation rate calculated constant.

Regression Predicted Information Flows. To model the behaviors between dependent and independent variables within the systems dynamic model, stepwise regression modeling was employed. Stepwise regression helped find a linear fit model that can explain the most variance while using the fewest number of variables. With the exception of one dependent variable (poverty), final chosen models had an adjusted R_2 greater than 0.90, which indicated that at least 90% of the variability in the data was explained by the model. Adjusted R_2 was selected since R_2 is nondecreasing with the addition of new variables, while adj-R_2 decreased if additional variables didn't add to the explanatory power of the model. Additionally, assumptions of linearity, independence, normal distribution, and homoscedasticity were evaluated and met, as demonstrated in plots in the Appendix C. Because of the large number of potential variables (more than 50), smaller subsets of potentially relevant variables were used in each stepwise regression procedure. Using this approach, hundreds of models were built and analyzed to achieve the final subset of regression models which were included in the Arizona educational-workforce systems dynamic model.

Unfortunately, the relationship of poverty to the workforce parameters predicted by model, including unemployment and labor force participation, was not adequate for generating a statistically significant model. This is likely because poverty and unemployment were controlled by federal influences - factors which were external to the system boundaries of the Arizona simulation model. However, there were strong correlations between poverty and student academic performance and degree attainment rates. As a result, the poverty model, albeit a poor fit, was ultimately included in the simulation model.

Table 2

Regression Equations and R-Squared for Simulation Information Flows

Dependent Variable	Independent Variables	Equation	Adj-R^2
Births	Population 25 years and Over & GDP	74593 - 0.0256681*Population + 0.453016*GDP	0.9055
SET Jobs	Population 25 years and Over with a bachelor's degree or higher & SET Salary	-124239 + 4.82352*STEM salary - 0.0597143*(bachelors population + Greater Than bachelors population)	0.9231
NonSET Jobs	NonSET Salary, Population 25 years and Over with a bachelor's degree or higher & Population 25 years and Over	-5.18111e+06 + 0.705548*Population + 180.982*nonSTEM salary - 1.12616*(Bachelors population+Greater Than Bachelors population)	0.9597
GDP	NonSET Jobs & SET Jobs	-51820.1 + NonSET JOBS*0.08496 - SET JOBS*0.36618	0.9853
Poverty	Unemployment rate & Laborforce Participation rate	0.22476 + 0.65810*Unemployment - 0.17550*Laborforce	0.7242

Assumptions. The following assumptions were made based on historical data and form the basis of the Arizona educational-workforce simulation model:

- The ratio of bachelor's degree recipients who stayed in Arizona after graduating compared to those who left the state after graduating is assumed to be a constant of 0.7, with 0.3 being the rate of bachelor’s degree recipients assumed to leave the state.
- The ratio of master’s degree recipients who stayed in Arizona after graduating was assumed to be a constant of 0.4, with 0.6 being the rate of master’s degree recipients assumed to leave the state.
- Of undergraduate students, 4.06 percent were assumed to complete their associate degree per year, until the Adult Education intervention level is directed to manipulate this completion rate by a factor of 1.5 (to 6.09 percent) or 2 (to 8.12 percent).
- Population death rates were assumed to be a constant 1.0 percent of each population stock.

- Population stocks were divided into bins according to the population's respective highest levels of educational attainment.
- Graduate Delayed Enrollments were assumed to be 0.6 percent of the bachelor's degree population per year, which equated to being 6.0 percent of the population over 10 years.
- Graduate dropout rate was set to 7.5 percent of the graduate students per year.
- Graduate enrollment rate was assumed to be 20.0 percent of the graduating bachelor's degree class per year.
- High school dropout rate was calculated based on the high school graduation rate.
- Income taxes were calculated based on current tax brackets, with 4.0 percent of the SET Job annual salaries and 2.59 percent of NonSET Job annual salaries.
- Federal Revenue was assumed to constitute 0.45 of the total State Budget Revenues per year.
- K12 Deflation was set at a constant rate of decline by 0.3 percent of the state budget less apportioned to K12 expenditures per year. This K12 Deflation was a default constant in the model unless the deflation lever was dialed to off.
- CPI index was used to compute salaries in terms of 2012 US Dollars.
- The effect of Free and Reduced Lunch Rate on the High School Graduation Rate was estimated as 0.001*Poverty Rate.

Calibration Values. The following calibration values were established, in absence of historical data, through an iterative process of evaluating the model between the years 1990 and 2017. These calibration values were chosen to help fit the model to the historical data and were generated with a heuristics approach.

- Migration 1, the migration into the less than high school diploma population, was calibrated as 10.0 percent of the total net migration.
- Migration 2, the migration into the high school graduate or GED population, was calibrated as 10.0 percent of the total net migration.

- Migration 3, the migration into the associates or some college population, was calibrated as 38.0 percent of the total net migration.
- Migration 4, the migration into the bachelor's degree population, was calibrated as 13.0 percent of the total net migration.
- Migration 5, the migration into the greater than bachelor's degree population, was calibrated as 15.0 percent of the total net migration.
- Migration Kids, Migration Undergrads, and Migration Graduates, the migration flows into the K-12 schools, undergraduate, and graduate schools, were all calibrated as 2.0 percent of the total net migration.

Distributions. In Table 3, the model parameters which were generated using random triangular distributions are listed. Triangular distributions were programed using a minimum value, maximum value, start, peak, terminate, and seed. In the Arizona educational-workforce simulation model, three parameters were computed using random triangular distributions. Parameters were calculated using a distribution and were selected because of the high degree of stochasticity within the given parameter's dataset for the years 1990 to 2017. The three selected parameters were labor force participation rate, STEM degrees ratio, and total net migration.

Table 3

Model Parameters Calculated with Distributions

Parameter	Distribution (min, max, start, peak, terminate, streamID (or seed))
Labor Force Participation Rate	RANDOM TRIANGULAR(0.58, 0.68, 0.58, 0.61, 0.68, 0)
STEM Degrees Ratio	RANDOM TRIANGULAR(0.1, 0.2, 0.1, 0.15, 0.2, 0)
Total Net Migration	RANDOM TRIANGULAR(0, 160000, 0, 86763, 160000, 0)

Time Dependent Variables. Regression models were also used within the model to describe the three, time dependent relationships. Time dependent relationships assumed that the only factor of change was time. This was a reasonable assumption in the case of three relationships in the model (SET jobs median annual pay, the nonSET jobs median annual pay, and the salary distribution multiplier), which are shown in Table 4. Since SET jobs median annual pay and nonSET jobs median annual pay were used in the prediction of SET jobs and nonSET jobs, and they were also part of the income tax revenues calculation, these terms create the basis for the economic portions of the model. It was valid to assume that these terms were time dependent because median annual pay was based on national supply and demand forecasting, which were outside the scope of the Arizona educational-workforce system boundaries.

Table 4

Model Parameters Calculated with Time Dependent Regressions

Parameter	Time Dependent Linear Regression	R^2
SET Jobs Median Annual Pay	1055.2*Time + 66091	0.9393
NonSET Jobs Median Annual Pay	377.35*Time + 37932	0.8702
Salary Distribution Multiplier	1.89-0.0062963*Time	0.9001

Verification and Validation. The development of the model required constant and iterative validation and verification (V&V). This process of V&V occurred at both a micro and macro level. At the micro level, each regression model within the larger, systems model was verified against real-world data. For each regression model built, three random years in the dataset were withheld when building the regression model, so that they could be used as the validation set. While three years of data was smaller than ideal, this was a necessary design choice, given what little overall data the research had access to. Thus, each model was built using data from 1990 to 2017 barring three years, and then this model was used to make predictions on the missing three years of data. The fitness of the predictions between the predicted data and actual data was used to determine the overall fitness of the model, in addition to leveraging traditional statistical measures, such as adj-R^2.

At a macro level, each time a change was made to any model within the overall system dynamics model, the model was then re-run and analyzed. Given the complex nature of the model, a small change could have had large-scale changes on the overall model, and small mistakes could have been propagated out. The model was carefully reviewed with each change to ensure that the overall model produced expected results relative to the historical data.

Final Arizona Educational-Workforce Simulation Model

The computer-based simulation model demonstrated how Arizona schools contributed to the educational attainment of the state's workforce and how the education and workforce affected the state's economy. The model progressed by 1-year timesteps over a 50-year period from 1990 to 2040. At each timestep, the stakeholder decided how much of the state budget to allocate to the K-12 schools and applied public policy interventions to see their impact on various aspects of the system. Three public policy interventions were available to stakeholders. These interventions were: (i) increase the percent of the state general fund marked for K-12 spending, (ii) double the effectiveness of adult education programs, and (iii) recruit SET industries to move to Arizona and introduce new jobs. Once the stakeholder determined these input criteria, they advanced the simulation timestep by 1 year, and the model generated the projection for the over 100 parameters computed for the following year. Some of the model output included educational attainment of the population, performance metrics of the K-12 schools, and the economic status of the state in terms of GDP.

Complex Systems Attributes. The Arizona educational-workforce simulation represented the four characteristics of complex systems (nonlinearity, interdependencies, feedback loops, and stochasticity) within the selected model parameters. In Table 5, these attributes of complexity were discussed through examples from the Arizona educational-workforce system.

Table 5

Complex Systems Attributes Represented in the Educational-Workforce Model

Component of Complexity	Simulation Representation
Nonlinearity	A few of the relationships within the model were approximated with linear regressions, however the majority of outcome parameters responded to the systems interaction in nonlinear ways, where the output was nonstandard to set changes in the independent variables.
Interdependencies	Annual births depend on the size of the adult population. The population was also dependent upon birth rates.
Feedback Loops	As population increases, the workforce becomes larger and the number of jobs increase. With more jobs, GDP also experienced growth. As GDP increased, there were more births on an annual basis and, as a result, population increased.
Stochasticity	Labor force participation rate, total net migration, and STEM degrees ratio were each examples of parameters in the simulation with a high degree of unexplained variance, where the same input conditions generated different output values.

Since educational systems are complex, it was critical that these aspects of complex systems be incorporated into the model. Because the economic, population, and educational subsystems were closely related to each other, there were many overlapping connections within the systems model. In Figure 1, the full sketch view of the Vensim computerized simulation of the Arizona educational-workforce system dynamics model is shown. Because the model was complex and complicated, there were many details which are difficult to see due to the size of the illustration. The parameters which were given rectangular shapes, are stock variables. Stock variable are K-12 students, undergraduate students, graduate school students, and adults with less than high school diploma, a high school diploma or GED, an associate's degree or some college education, a bachelor's degree, or some graduate degree. Double-banded arrows were used to express flow rates among stock variables. Flow rates were expressed in people per year. For example, the flow rate between the K-12 students stock and the adults with a high school diploma or GED stock were the number of high school graduates per year. All other shapes were used to represent contestant parameters and information flows.

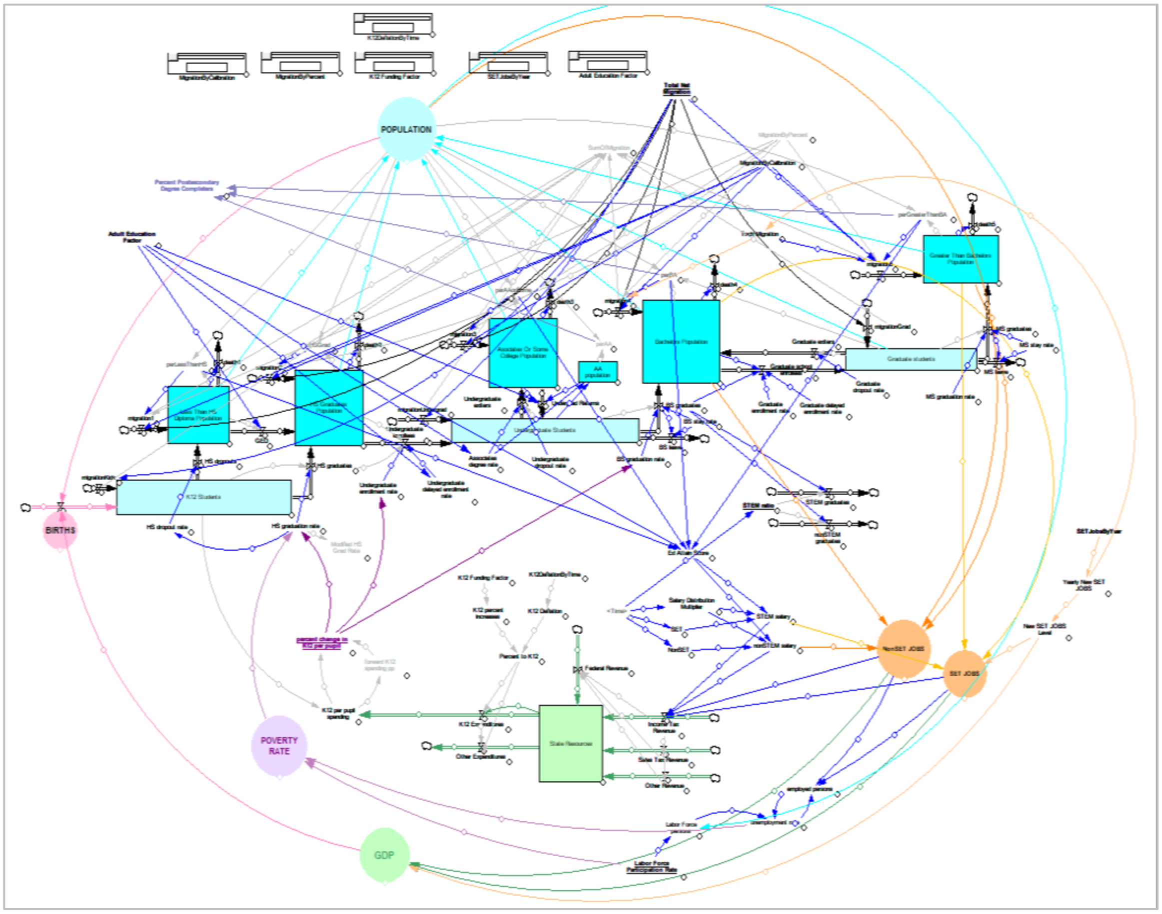

Figure 1. Illustration of the Arizona Educational-Workforce Simulation Model. The model was programmed using the Vensim Systems Dynamics modeling software.

The model was constructed with a high degree of connectivity. The sheer number of linkages diagramed in the Vensim model sketch, shown in Figure 1, makes the model's interpretation difficult. To compensate for this, Figure 2 was produced to explain the logic of the Arizona educational-workforce simulation model in a simplified, pictographic format.

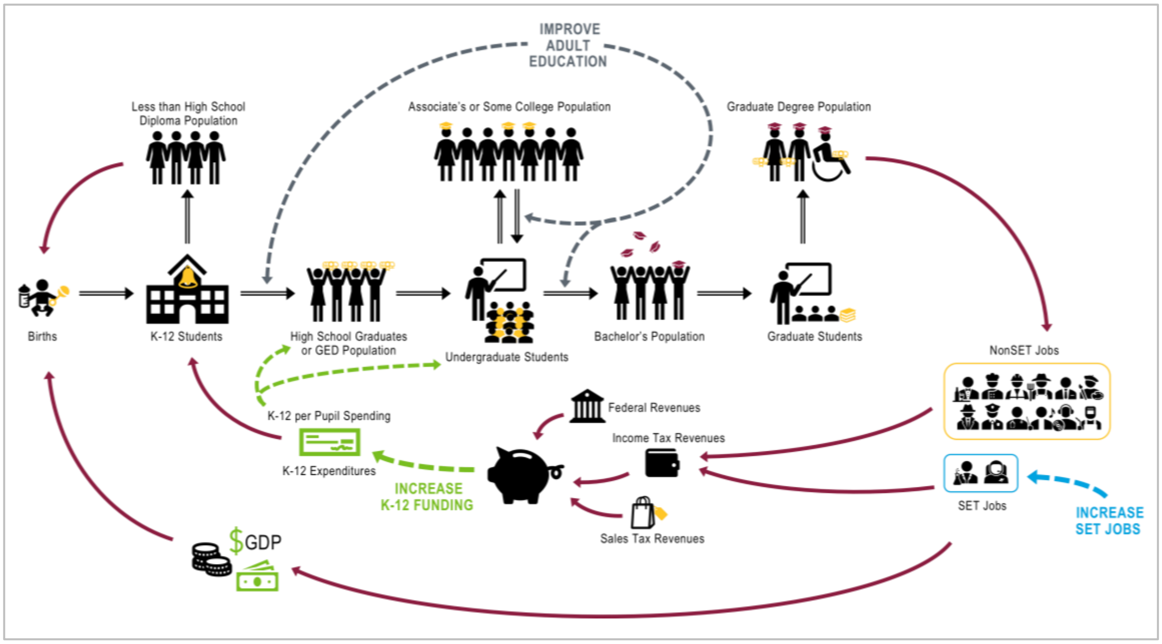

Figure 2. Cartoon Illustration of the Arizona Educational-Workforce Simulation Model.

Use Case for System Exploration

Arizona's Educational Attainment Goal. The following investigative prompt was selected as a case study example to highlight the empirical value of using this systems dynamics modeling technique for educational-economic complex systems research: (i) Can intervention strategies improve the percentage of Arizona's population with a postsecondary degree or certification to 60 percent? and (ii) How will these interventions affect the state's workforce, tax base, and GDP?

Situation Background. In recent years, many states across the country started initiative programs that set future educational attainment goals for their respective state. Currently, Arizona lags other states in the number of adults who have earned credentials or degrees past high school. Doug Ducey, governor of Arizona, introduced such a program, called Achieve60AZ (Cano, 2016). The Achieve60AZ alliance was formed in 2015 and the program was launched in 2016. Achieve60AZ is a nonprofit, nonpartisan, community-based alliance of over 150 member organizations and more than 40 municipalities that have made the postsecondary attainment goal their own. The Achieve60AZ alliance set a lofty goal that by 2030, 60 percent of Arizona adults, ages 25 to 64, will hold a postsecondary credential or degree (Achieve60AZ, 2016).

By pursuing a more highly trained and educated population, Arizona’s workforce will attract more businesses to the state, increase the tax base, and decrease poverty (Achieve60AZ, 2018). Estimates project that if Arizona meets the 60 percent attainment goal, the state will receive an additional $3.5 billion in personal income and tax revenues, and if aligned with workforce needs, will provide $7.6 billion in economic and social gains (College Success Arizona, 2018). To reach the 60 percent attainment goal and be on this path to future economic prosperity, 1 million more Arizonans must earn a postsecondary degree or credential by 2030.

Additional Use Case Details. Although the initiative launched in 2016, the year is now 2020, and the alliance remains undecided on the appropriate course of action to improve the state’s educational attainment levels. Due to the fact that little was done to change postsecondary degree completion rates in Arizona, this analysis extended the timeline of the goal for looking only until the year 2030 to looking out to the year 2040. Postsecondary education can take many forms – from earning a certificate or license to earning an associate or bachelor’s degree. Educational options were varied and include public and private options like technical institutes, apprenticeships, community colleges, and universities. In the Acheive60AZ goal, the 60 percent of the population will hold either a postsecondary credential or degree. Since data on postsecondary credentials is difficult to estimate due to data availability issues, this analysis accounted for the portion of the population with a postsecondary credential, such as a certificate, as falling between 5.0 to 8.0 percent of the population. Therefore, a total of 52 percent of the population who attained an associates, bachelors, or postbaccalaureate degree was considered as meeting the Acheive60AZ goal of 60 percent the population obtaining a postsecondary degree or certificate objective.

Experimentation Plan. To perform what-if analysis of the Arizona educational-workforce simulation model, the following experimentation plan is described. This methodology design was guided by Kleijnen, J. P. C. (1995), who performed a similar technique on other system dynamics models, explaining the principle of parsimony as a reason for assuming that only a few factors were most important to the what-if analysis of the systems model. Three initial policies were selected for the sake of understanding where in the system can interventions be introduced for maximal impact on the outcome variable, postsecondary educational attainment.

The experimental plan investigated the impact of changing each of three variables to one of two distinct levels. The factors, also referred to in the text of this article as policy interventions or model scenarios, which were tested are the following: (i) K-12 schools spending, (ii) adult education programs, and (iii) high science, engineering, and technology (SET) employment. During experimental simulation runs, each of the factors was set to one of the two levels, named "high" and "low". For all factors, the low level was set to the baseline condition (i.e. the status quo rate). A description and justification of the levels for each variable follow. The levels are also summarized in Table 6.

- By changing K-12 school spending, students may be more prepared for college and as a result, more likely to attend college. With a higher rate of college going, Arizona will have more college graduates and will increase the population's educational attainment and the percent of the population with a bachelor's degree or higher education. Since 1990, the percent of state funding for K-12 spending has been decreasing by 0.3% per year. This is the current average K-12 expenditure decline per year in the state of Arizona and is thus the baseline scenario for the simulation experiment. For the high level of the K-12 school spending scenario, instead of continuing to decrease the state contributions, starting in 2020, the state contributions towards K-12 school spending will increase by 0.3% of the state general budget per year.
- Adult education programs include: GED conversion programs, delayed undergraduate enrollment, associate degree completions, and some college re-enrollments. The baseline scenario has these programs continuing to be effective at their current rates. For the high-level test, adult education programs are given extra support and become twice as effective as it was prior to 2020. Therefore, starting in 2020, GED conversion rates go from 3% of the less than high school diploma population to 6% of the less than high school diploma population per year. Other adult education programs also double in effectiveness.

- Workforce intervention strategies include deregulation of industries and corporate tax reductions. By deregulating or reducing taxes in SET industries (where the average employee has a bachelor's degree or a postbaccalaureate education) will improve the educational attainment for the population of Arizona because these interventions will incentivize the movement of companies and startups to Arizona. With each new company or startup, employees with bachelor's degrees and graduate degrees will migrate to Arizona, improving the percentage of Arizona's population with a postsecondary degree. In the baseline scenario, the SET jobs are predicted based on the stepwise regression model. For the high level test, starting in 2020, SET industries are persuaded to move to Arizona, introducing 20,000 new SET jobs per year that are filled with 20,000 new migrants, 60% of which are assumed to have a bachelor's degree and the remaining 40% are assumed to have a graduate degree.

Use Case Scenarios. In Table 6, below, eight scenarios are outlined for the experimental plan. Each scenario represented a single or combination of relevant policy interventions which were potential approaches to meet the Acheive60AZ goal of having 60% of Arizona's adult population complete a postsecondary degree or certificates. After selecting the scenarios, each scenario was tested out in the EduSim model to elicit an understanding of whether the scenario was effective for reaching the Acheive60AZ goal, and for determining the potential implications of the interventions on the educational-economic system.

Table 6

Experimentation Plan for Use Case Testing of the Educational-Workforce Simulation

Run ID	K-12 Funding	Adult Education	SET Jobs	Scenario Description
1	**Low**	**Low**	**Low**	Controlled K-12 Spending
2	**High**	**Low**	**Low**	K-12 Spending Increase
3	**Low**	**High**	**Low**	Adult Education with Controlled K-12 Spending
4	**High**	**High**	**Low**	Adult Education with K-12 Spending Increase

Run ID	K-12 Funding	Adult Education	SET Jobs	Scenario Description
5	**Low**	**Low**	**High**	SET Jobs Increase with Controlled K-12 Spending
6	**High**	**Low**	**High**	SET Jobs Increase with K-12 Spending Increase
7	**Low**	**High**	**High**	Controlled K-12 Spending with Adult Education with SET Jobs Increase
8	**High**	**High**	**High**	K-12 Spending Increase with Adult Education with SET Jobs Increase

Scenario 1: Controlled K-12 Spending (Control). This was the baseline scenario. In this case, no changes were made from the final version of the model described previously. Therefore, the model was run from 2020 to 2040 with the same assumption that the apportionment of the state budget to K-12 expenditures continued to decrease at a rate of 0.3 percent per year. In the results plots, this scenario is abbreviated with the name Control.

Scenario 2: K-12 Spending Increase (K12Increase). In this scenario, K-12 funding was increased after 2020. Starting in 2020, each year, the state allocated additional 0.3 percent of the state budget to K-12 expenditures. In the results plots, this scenario is abbreviated with the name K12Increase.

Scenario 3: Adult Education with K-12 Spending Increase (AdultEd_Control). In this case, new Adult education programs were implemented (or the existing programs were given extra support). Adult education became twice as effective as it was prior to 2020. Therefore, starting in 2020, GED conversion rates went from 3.0 percent of the less than high school diploma population to 6.0 percent of the less than high school diploma population per year. Other adult education programs which doubled in effectiveness were delayed undergraduate enrollment, associate degree earners, and some college re-enrollments. In the results plots, this scenario is abbreviated with the name AdultEd_Control.

Scenario 4: Adult Education with K-12 Spending Increase (AdultEd_K12Increase). In this scenario, the effects of the K-12 funding increase intervention and the Adult education intervention were combined. In the results plots, this scenario is abbreviated with the name AdultEd_K12Increase.

Scenario 5: SET Jobs Increase with Controlled K-12 Spending (SETJobs_Control). In this case, SET industries were persuaded to move to Arizona, which introduced 20,000 new SET jobs per year that were filled with 20,000 new migrants, 60 percent of which were assumed to have a bachelor's degree and the remaining 40 percent were assumed to have a graduate degree. In the results plots, this scenario is abbreviated with the name SETJobs_Control.

Scenario 6: SET Jobs Increase with K-12 Spending Increase (SETJobs_K12Increase). In this scenario, the effects of the K-12 funding increase intervention and the SET jobs intervention were combined. In the results plots, this scenario is abbreviated with the name SETJobs_K12Increase.

Scenario 7: Controlled K-12 Spending with Adult Education with SET Jobs Increase (Control_AdultEd_SETJobs). In this scenario, the effects of Adult education intervention and the SET jobs intervention were combined. In the results plots, this scenario is abbreviated with the name Control_AdultEd_SETJobs.

Scenario 8: K-12 Spending Increase with Adult Education with SET Jobs Increase (K12Increase_AdultEd_SETJobs). In this scenario, the effects of the K-12 funding increase intervention, the Adult education intervention, and the SET jobs intervention were combined. In the results plots, this scenario is abbreviated with the name K12Increase_AdultEd_SETJobs.

Results & Discussion

Of the over 100 parameters in the simulation model, two scenarios were dominant in maximizing the majority of the outcome parameters. The scenarios responsible for maximizing the majority of outcome parameters were the combination of all three interventions (increasing K-12 spending, doubling adult education program effectiveness, and increasing SET jobs) and second most optimal scenario was the combination of the two education interventions (increasing K-12 spending and doubling adult education program effectiveness). The two scenarios which led to minimizing the outcome parameters in 2040 were the baseline scenario (no interventions applied) and the scenario with only the workforce intervention (increasing SET jobs) active.

Results were shown in two formats. First, scenario results, for selected outcome parameters, were graphed across time from 1990 to 2040. Next, three outcome parameters were focused on for a tabular comparison of the baseline scenario to the other scenarios using calculated difference and percent change.

Scenario Results Over Time. The results of this simulation run for each of the eight scenarios are shown in the following time series plots. For the purpose of interpreting the simulation results, four outcome parameters are highlighted in the results section. These outcome parameters were percentage of postsecondary degree completers, adult population, GDP, and births. For additional outcome parameter graphs, see Appendix D.

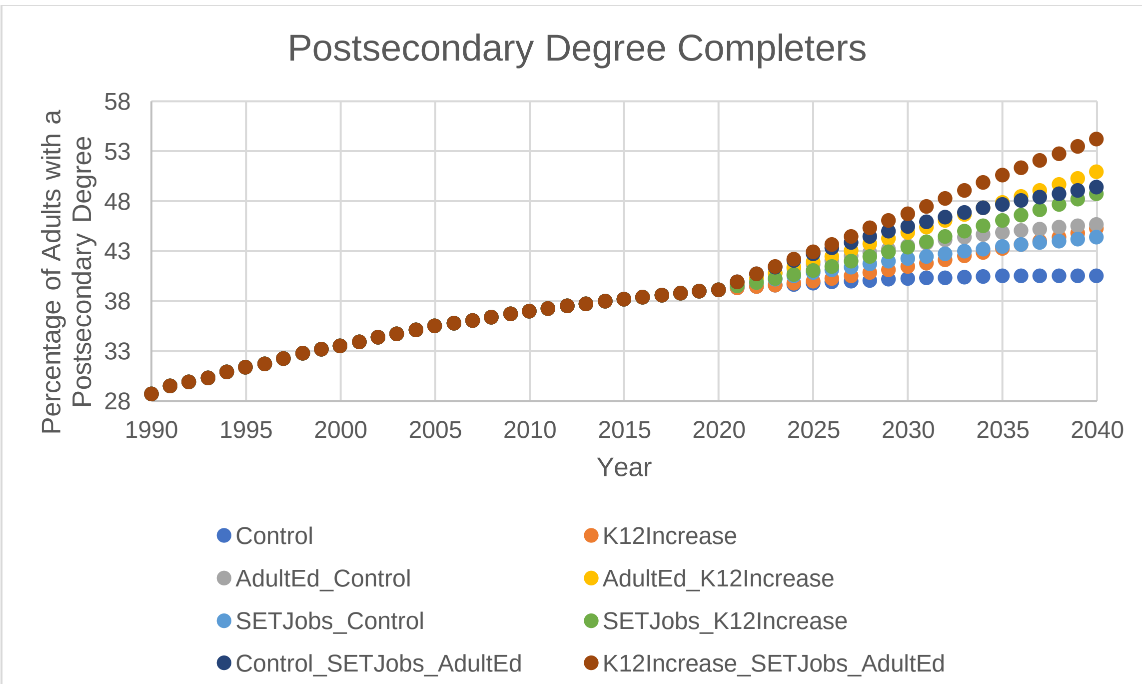

Figure 3. Postsecondary Degree Completers as a Percentage of the Adult Population, Ages 25 and Over, from 1990 to 2040. For the eight scenarios tested, the maximum population of postsecondary degree completers were 54.17 percent of adults and was the result of the K-12Increase_SETJobs_AdultEd scenario. The minimum population of postsecondary degree completers was 40.49 percent of adults and occurred under the Control scenario.

Postsecondary Degree Completers. Across the eight scenarios, the projected percentage of postsecondary completers by year 2040, varied widely. Not surprisingly, the control scenario produced the minimal number of postsecondary completers. With no interventions applied, the scenario resulted with 40.5 percent of the population, ages 25 years and over, having achieved a postsecondary degree in the year 2040. By combining all three intervention methods (increasing K-12 spending, doubling adult education program effectiveness, and incentivizing increasing the SET workforce), Arizona was able to increase the postsecondary degree completers to represent 54.2 percent of the population, ages 25 years and over, by the year 2040. The effect that all three interventions have when combined was a resulting increase of 13.7 percent difference from the control scenario. The next highest increase in the percent of postsecondary degree completers was achieved through combining the interventions of doubling adult education effectiveness and increasing K-12 spending to result in 50.9 percent of the population, ages 25 years and over, obtaining a postsecondary degree in the year 2040.

Outcome Parameters Selected for Tabular Comparison: Attainment, GDP, Population. Below are the tabular representations of each scenario result compared to the baseline scenario. Three outcome parameters were selected for tabular comparison across scenarios. The selected outcomes were percent of postsecondary degree completer, GDP, and adult population. The column labeled Control 2020 (2020_c) represents the postsecondary degree attainment percentage for the respective scenarios at present time. Control 2040 (2040_c) shows the projected attainment percentage if the control scenario is maintained throughout the 20 years of simulation. Scenario 2040 (2040_s) represents the projected attainment rate if the respective scenario is carried out through 20 years of the simulation. A difference between the 2040 control (2040c) and the 2040 scenario (2040s) is shown as Scenario Change (2040s – 2040c). The final column reflects the percentage change of the 2040 scenario from the 2040 control. This is calculated as the difference 2040 scenario and the 2040 control divided by 2040_c.

Table 7

Comparison of Postsecondary Degree Completion Rates for Intervention Scenarios

Scenario	Postsecondary Degree Attainment (%)				Scenario %Change
	2020_c	2040_c	2040_s	Scenario Change (2040_s - 2040_c)	Scenario %Change (2040_s - 2040_c)/2040_c
1. Control	39.10	40.49	40.49	0.00	0.00%
2. K12Increase	39.10	40.49	45.23	4.74	11.71%
3. AdultEd_Control	39.10	40.49	45.65	5.16	12.75%
4. AdultEd_K12Increase	39.10	40.49	50.88	10.39	25.67%
5. SETJobs_Control	39.10	40.49	44.35	3.86	9.54%
6. SETJobs_K12Increase	39.10	40.49	48.73	8.24	20.36%
7. Control_AdultEd_SETJobs	39.10	40.49	49.39	8.90	21.99%
8. K12Increase_AdultEd_SETJobs	39.10	40.49	54.17	13.69	33.80%

The results reflected in Table 7, showed that a significant lift in attainment can be achieved through the enactment of various policy changes. In particular, the system was heavily influenced by K-12 spending and adult education interventions. The largest lift in attainment was found when all three policy interventions were combined. Therefore, the simulation indicated that increasing adult education program effectiveness, K-12 spending, and SET jobs can bring the attainment to ~54%, which helped to achieve the desired 60% attainment rate that the state of Arizona aspires to. This was a 33.8% change from the baseline scenario.

Reinforcing and Balancing Feedback Loops. If this were a linear systems model, the combination of these interventions would amount to no more than the sum of the intervention effects when run in separation from each other. However, since this model was built as a complex systems model, the system was not the resultant of the sum of its parts, as the parts were also dependent on each other. Scenario 4, which combined the K-12 spending increase with the adult education intervention, was a clear example of this principal.

As is seen in Table 7, the K-12 spending increase scenario was responsible for 4.7412% in 2040 percentage of postsecondary degree completers. The adult education intervention caused a 5.1619% increase in percentage of postsecondary degree completers for 2040. When these percentages were combined, they sum to 9.9031% increase in 2040 percentage of postsecondary degree completers. However, when the interventions were combined in the scenario 4 (adult education and K-12 spending increase) and run in the simulation, the result was 10.3928% increase in percentage of postsecondary degree completers by 2040. Therefore, these interventions combined to have a greater effect on the outcome than the sum of the scenario effects when run separately.

When K-12 spending was increased, the high school graduation rate, undergraduate enrollment rate, and bachelor's degree completion rate all increased. These rate increases resulted in a greater number of students who graduate from high school and join the high school graduate population stock, additional high school students enrolling in college, and more students completing bachelor's degrees. Improved high school graduation rates also increased the number of students who enrolled in college, which increased the number of students who may go on to graduate from college with either an associate's or bachelor's degree, resulting in a greater percentage of the population with a postsecondary degree.

When the effectiveness of adult education programs (GED completion schools, delayed undergraduate enrollment rates, associate degree earners, and some college re-enrollments) improved, the population of high school graduates increased and the population of associates degree earners or adults having completed some college increased. These population increases directly increased the percent of the population with a postsecondary degree (through improvements in the associate degree completion rate) and these population shifts also created more opportunities for an increased number of adult students to re-enter undergraduate programs and complete associate's or bachelor's degrees.

The K-12 spending intervention and the adult education intervention worked together in tandem, because as these population stocks and flow rates increased, there was an exponential effect. The result was a synergistic increase of the percentage of the population having completed postsecondary degrees.

Adult Population, Ages 25 Years and Over. Population played a large role in the K-12 educational system and was a source of much of the feedback behavior in the model. As a result, population was chosen as an output parameter to track and explore. Figure 4 shows the change in population over 50 years, for each of the scenario situations.

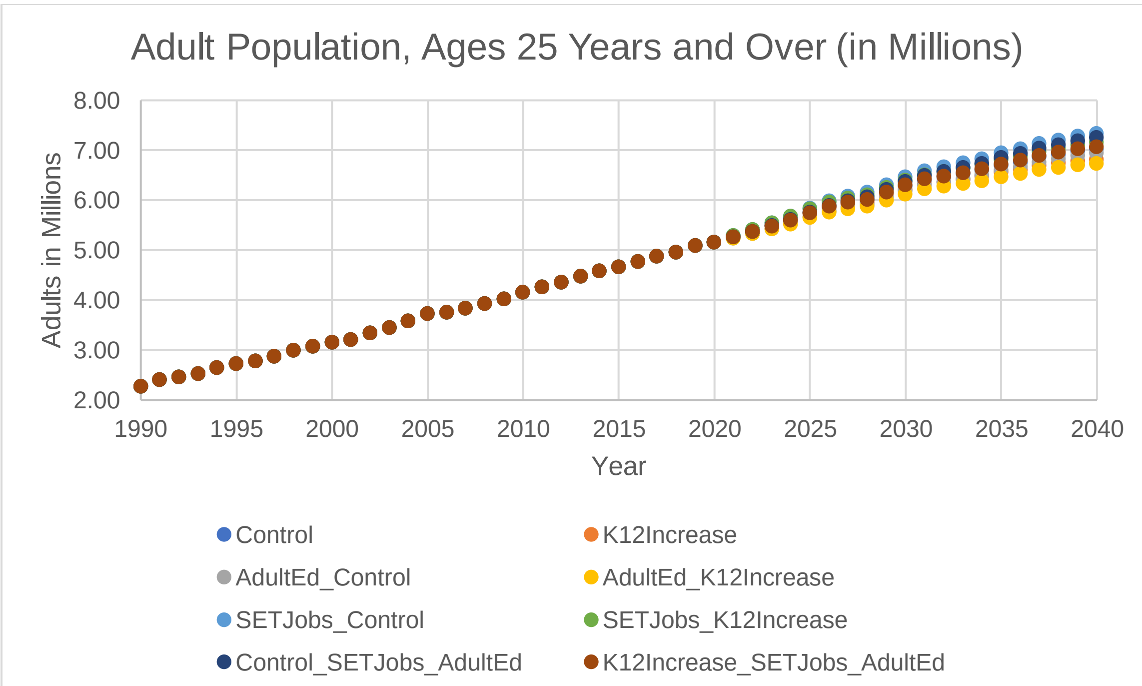

Figure 4. Adult Population, Ages 25 and Over, from 1990 to 2040. For the eight scenarios tested, by 2040, the maximum population was 7.24 million persons and is the result of the Control_SETJobs_AdultEd scenario. The minimum population was 6.73 million persons and occurred under the AdultEd_K-12Increase scenario.

Across the eight scenarios, the projected population by year 2040 varied substantially. Once again, the control scenario produced an outcome with the minimum population. With no interventions applied, the scenario results with a population of 7,030,000 adults, ages 25 years or older. When all three intervention methods (increasing K-12 spending, doubling adult education program effectiveness, and incentivizing increasing the SET workforce) were combined, Arizona was projected to see a population increase of 38,900 adults. However, unlike the postsecondary degree completers outcome, this scenario was not optimal for increasing the adult population.

As seen in Table 8, the simulation shows that the combination of doubling adult education effectiveness and increasing K-12 spending, achieved the greatest decrease in adult population, which was projected to be a 4.217**%** decrease from the 2040 baseline scenario outcome. For this outcome parameter, the most efficient way to increase the adult population was through the SET jobs increase intervention. At the end of 2040, the SET jobs increase resulted in a population of 7,330,000 people. This was a gain of 4.32% from the baseline 2040 outcome.

Table 8

Comparison of Adult Population Outcomes for Intervention Scenarios

Scenario	**Adult Population, Ages 25 and Over (in Millions)**				**Scenario %Change**
	2020_c	**2040_c**	**2040_s**	**Scenario Change (2040_s -2040_c)**	**Scenario %Change (2040_s -2040_c)/2040_c**
1. Control	5.16	7.03	7.03	0.00	0.00%
2. K12Increase	5.16	7.03	6.82	-0.21	-3.03%
3. AdultEd_Control	5.16	7.03	6.94	-0.09	-1.29%
4. AdultEd_K12Increase	5.16	7.03	6.73	-0.30	-4.22%
5. SETJobs_Control	5.16	7.03	7.33	0.30	4.32%
6. SETJobs_K12Increase	5.16	7.03	7.15	0.12	1.72%
7. Control_AdultEd_SETJobs	5.16	7.03	7.24	0.22	3.06%
8. K12Increase_AdultEd_SETJobs	5.16	7.03	7.07	0.04	0.55%

For adult population outcomes, the baseline scenario continued to grow at a continuous rate from the years prior. The educational system interventions had a negative impact on the population growth. The workforce intervention had a positive effect on the population growth. Whereas population was affected in positive and negative ways by the interventions, all the interventions had a positive effect on GDP growth.

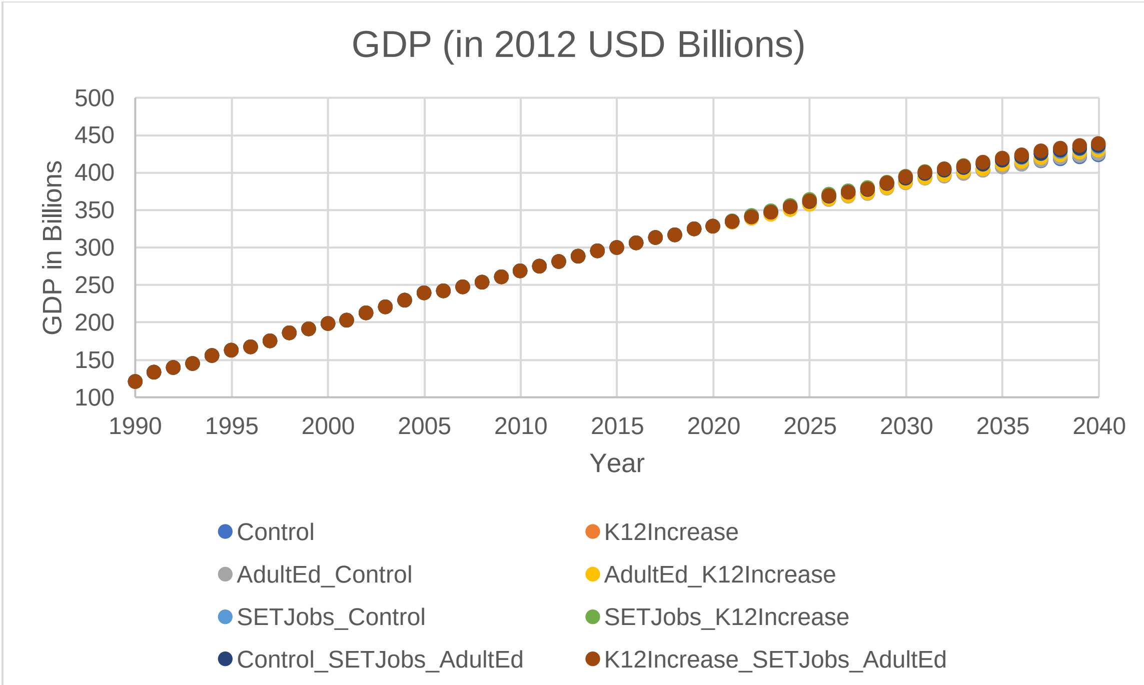

Figure 5. GDP for Arizona from 1990 to 2040. For the eight scenarios tested, by 2040, the maximum GDP was $438.727 Billion and is the result of the K-12Increase_SETJobs_AdultEd scenario. The minimum GDP is $423.345 Billion and occurred under the Control scenario.

Gross Domestic Product (GDP). In Figure 5, each of the scenarios are difficult to differentiate due to their visual overlap. In this case, the proximity was caused by the scale of the GDP axis. Since 1990, GDP had grown by two-fold. Because all the interventions were positively associated with GDP growth, it made sense that to maximize the GDP in 2040, combining all three interventions was the most optimal scenario.

Table 9

Comparison of GDP Outcomes for Intervention Scenarios

Scenario	**GDP (in 2012 USD Billions)**				**Scenario %Change**
	2020_c	**2040_c**	**2040_s**	**Scenario Change (2040_s -2040_c)**	**Scenario %Change (2040_s -2040_c)/2040_c**
1. Control	328.50	423.35	423.35	0.00	0.00%
2. K12Increase	328.50	423.35	427.64	4.29	1.01%
3. AdultEd_Control	328.50	423.35	425.22	1.878	0.44%
4. AdultEd_K12Increase	328.50	423.35	429.48	6.138	1.45%
5. SETJobs_Control	328.50	423.35	434.14	10.80	2.55%
6. SETJobs_K12Increase	328.50	423.35	437.47	14.12	3.34%
7. Control_AdultEd_SETJobs	328.50	423.35	435.64	12.29	2.90%
8. K12Increase_AdultEd_SETJobs	328.50	423.35	438.73	15.38	3.63%

As seen in Table 9, the simulation showed that the combination of doubling adult education effectiveness, increasing K-12 spending, and increasing SET employment, achieved the greatest increase in GDP, which was projected to be a 3.633% increase from the 2040 baseline scenario outcome. For this outcome parameter, this was the most efficient way to increase the GDP.

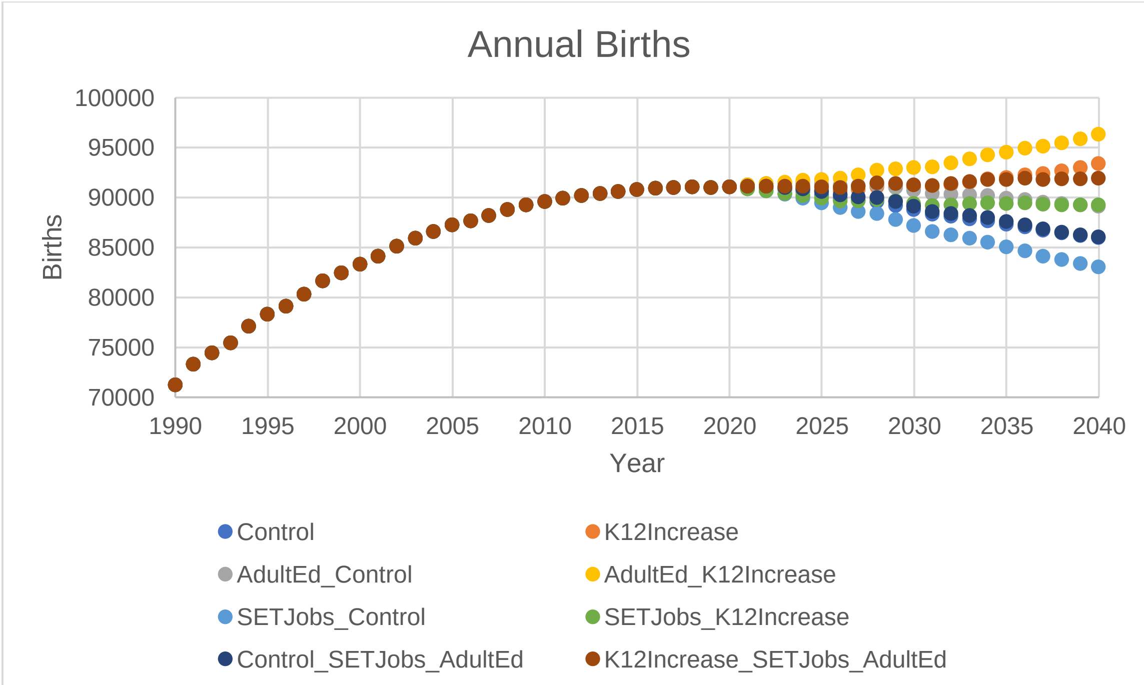

Figure 6. Arizona Annual Births from 1990 to 2040. For the eight scenarios tested, by 2040, the maximum number of annual births was 96,344 births and was the result of the AdultEd_K-12Increase scenario. The minimum number of annual births is 83,052 births and occurred under the SETJobs_Control scenario.

Annual Births. The annual birth outcome parameter was selected to showcase the nonlinearity of the Arizona educational-workforce simulation model. Although the stepwise regression model to predict births was linear with respect to its independent variables (GDP and adult population), when the model was run, each scenario produces a nonlinear curve. In this case, the combination of the three interventions seemed to level off the annual births curve at just over 90,000 births per year. The SET jobs increase intervention had the effect of decreasing the births to about 80,000 per year by 2040. On the other hand, the educational interventions of increasing K-12 spending and adult education program effectiveness improved birth rates to over 95,000 births per year.

Comparing multiple regression and systems dynamics modeling. The final subsection of this results and discussion section is provided as an opportunity to explore the contrast between the system dynamics modeling approach, which was used to build the sandbox simulation in this study, as compared with a multiple regression approach. Multiple regression is a common technique in education research.

To compare this complex system modeling approach to a standard statistical regression technique, consider the following comparison to a hypothetical multiple regression approach (where n = 100 other parameters).

$$\text{K-12Funding} \times X_1 + \text{SET Jobs} \times X_2 + \text{AdultEd} \times X_3 + \text{Parametern} \times X_n + C = \text{Attainment} \qquad (1)$$

$$\text{K-12Funding} \times X_1 + \text{SET Jobs} \times X_2 + \text{AdultEd} \times X_3 + \text{Parametern} \times X_n + C = \text{GDP} \qquad (2)$$

$$\text{K-12Funding} \times X_1 + \text{SET Jobs} \times X_2 + \text{AdultEd} \times X_3 + \text{Parametern} \times X_n + C = \text{Population} \qquad (3)$$

For the year 2040, a modeler could project/forecast into the future with linear techniques for population, etc. (some are reasonable to project this way). However, the modeler would need to do this for all the independent variables of the model. This presents several issues. First, the independent variables are dependent on each other at each time step. Furthermore, many of the parameters do not follow a linear trajectory and would need complex models to produce the estimates needed to populate the final regression model.

In essence, the complex system dynamics model, presented in this article, is a system of nonlinear differential equations and regression models, where the relationships between the various parameters are defined and allow for dynamic estimates at each time step. What makes this complex approach better than other modeling techniques, is that this approach allows for the construct of interdependencies, feedback loops (balancing and reinforcing), nonlinear equations, and stochasticity. In the section to follow, these characteristics of complex systems are explained in the context of this model.

Stochasticity Examples. Below are examples of stochasticity in the educational-workforce simulation model.

- Total Net Migration – Each year, migration is stochastically determined using a triangular distribution. This reflects migration in Arizona, since migration is a byproduct which is affected by many subjects which include public policy changes.

- Labor Force Participation Rate – Every year, labor force participation rate is stochastically determined using a triangular distribution. This reflects the actual labor force participation in Arizona because, labor force rate data varies from 0.58 to 0.68.

Feedback Loops Examples. The following are examples of feedback loops in the educational-workforce simulation model.

- Job Growth – As educational attainment rises; salaries increase and thus jobs increase. However, as attainment increases, jobs decrease since employers hire less people because the labor is more highly skilled.
- Birth Increases – As population rises; jobs increase and thus GDP increases. When GDP increases, births also increase. However, as the population increases; births decrease.

Interdependencies Examples. Each parameter relies on multiple other parameters, some parameters are reliant on a previous timestep (the previous year), such as the percent change in K-12 per pupil spending.

Nonlinear Equation Examples. Whereas many of the parameters in the model are predicted using linear coefficients, the structure of the system is defined by nonlinear differential equations, and therefore the resultant is outcomes which are nonlinear across time.

- Births – The shape of the births curve is a second order parabola.
- Population – The shape of the population curve is S-curve.
- Percent Postsecondary Completers – The shape of the postsecondary completers curve approaches an asymptote, which reflects increasing at a decreasing rate.

In summary, in order to replicate this model and these results, with the use of common statistical techniques would require the development and manual processing of data and models in a way that would no longer constitute a traditional statistical approach.

Conclusions

This model demonstrates and emphasizes the need for a complex systems approach to model education systems for the purpose of policymaking. While the results provided are only a proof of concept, they demonstrate the ability to model certain aspects of the system in a manner not available to traditional forecasting and modeling techniques. Furthermore, the model itself is shown through the Achieve60 use case, to be a useful artifact that can be used for further iteration and understanding of the system through sandbox testing. As other approaches can demonstrate the correlation between the economy, workforce, population, and educational systems, these other approaches can do no more than showcase correlations. With this complex systems approach stakeholders and decision-makers are provided with the opportunity to test out causal relationships and adjust policy interventions accordingly.

In summary, this analysis demonstrates the existence of complex system characteristics (nonlinearity, interdependencies, feedback loops, and stochasticity) embedded within the Arizona school system. This system model simulates intervention strategies to improve student outcomes at a local and state level. This analysis provides an opportunity for further investigation and simulation of policy and academic interventions applied to the educational system. As a result, the simulation may help in discovering policy and academic changes for refining the educational system to better suit the needs of all Arizona students. After testing various scenarios across multiple interventions, the K-12Increase_AdultEd_SETJobs was the best scenario for increasing the percent of Arizona's population with postsecondary degree completion.

After additional user testing and response modifications, the Arizona educational-workforce model will be transitioned into the hands of Arizona State University's Decision Center for Educational Excellence Powered by the Helios Education Foundation. There the simulation will be presented and used by groups of Arizona stakeholders and decision-makers to explore future policy initiatives.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

The complex nature of a system is significant and cannot be overlooked. For many years, numerous researchers have presented articles stating that their respective areas of research ought to be considered as complex systems. However, prior to this dissertation, these arguments included little more than incorporating this as a mere classification, and instead, left the reader lacking adequate tools and techniques to handle the complexity of educational systems. The work presented in this dissertation goes to show the value to acquiring systems thinking skills and demonstrates empirical value of utilizing a complex system modeling technique to simulate socio-technical infrastructure systems. There is more to be gained by using complex systems modeling techniques than by using standard statistical analysis techniques.

As outlined in this dissertation, socio-technical infrastructure systems are complex by nature. They are known to incorporate interdependencies, nonlinearity, feedback loops, and stochasticity. In order to maintain infrastructures systems and rebuild them with resilience, systems thinking skills are required. Since traditional technical and engineering programs lack teachings on systems thinking and complexity, new options must be introduced to allow students, teachers, and managers to experience complexity and master systems thinking skills.

In order to demonstrate the usefulness of this complex systems modeling technique, the technique was first applied to a water distribution system and was then applied to a state's educational-economic system. Both selected systems are examples of complex socio-technical infrastructure systems with counterintuitive processes. In the LA Water system model, the model was used as a game that stakeholders were able to play to discover the complex system attributes which are embedded in the management of the socio-technical infrastructure system. In the second use case, the Arizona educational-economic system model, the complex systems modeling technique was applied to demonstrate the complex system components within the system, and furthermore, to showcase the empirical benefits of the technique when compared with various other commonly utilized educational system mathematical techniques.

Conclusions 1. Complex systems modeling techniques have the potential to expand understanding of the educational systems. When complex modeling techniques are applied to educational systems, they will create opportunities for learning about the subsystem interactions and nonlinear relationships that are often not included in traditional techniques but may dictate system responses and outcomes.

Conclusions 2*.* The *LA Water Game* was evaluated as a tool for teaching complex systems thinking skills with particular focus on two assertions that effective educational games: 1) Foster cognitive and affective engagement, and 2) Increase intrinsic motivation that allows for longer training periods. For each finding highlighted, we provide examples from qualitative participant observations gathered during game play or debriefing interviews.

Experiencing the *LA Water Game* gives participants a foundational understanding of the complex nature of infrastructure management and the systems thinking approach that is required for long-term infrastructure management. By engaging all four stages of the Kolb Learning Cycle, participants learn abstract conceptualizations of complex systems, experiment with parameters that leverage changes in the socio-technical system, gain concrete experiences rooted in affective responses to goal attainment (or failure), and reflectively observe both their own actions and those of other generations. The game also demonstrates complexity around water system infrastructure. Although the simulation game itself is a cartoon-like abstraction of the real system, it provides a foundation for students to begin developing complex systems thinking skills which are critical for managing interdependent infrastructure systems.

Conclusions 3. This model of Arizona’s educational system analysis demonstrates the existence of complex system characteristics (nonlinearity, interdependencies, feedback loops, and stochasticity) embedded within the Arizona school system. This system model simulates intervention strategies to improve student outcomes at a local and state level. This analysis provides an opportunity for further investigation and simulation of policy and academic interventions applied to the educational system. As a result, the simulation may help in discovering policy and academic changes for refining the educational system to better suit the needs of all Arizona students.

After testing various scenarios across multiple interventions, the combination of increasing K-12 spending, improving adult education programs, and increasing SET employment was shown to be the best scenario for increasing the percentage of Arizona's population with a postsecondary degree.

Future Work. Now that a sandbox environment has been created, there are numerous other studies which can be performed in the future utilizing the *Arizona Educational-Workforce Simulation* tool. Further research is needed on assessing the effectiveness of using simulation and gaming for developing the systems thinking skills that are required to maintain socio-technical infrastructure systems in the 21st century.

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APPENDIX A

DATASETS USED TO DEVELOP THE ARIZONA SIMULATION MODEL

Table 1

Arizona Population, Births, Deaths, and Migration from 1990 to 2017 – U.S. Census Bureau

Year	Births	Deaths	Total Population	Migration In	Migration Out	Immigration	Emigration
1990	68814	28789	3684097	-	-	-	-
1991	68040	29548	3788576	159653	142754	-	-
1992	68675	31055	3915740	164093	130324	-	-
1993	69037	33321	4065440	175622	125265	-	-
1994	70896	34298	4245089	192511	121848	-	-
1995	72463	35342	4432499	202232	125418	-	-
1996	75322	36592	4586940	186898	127999	-	-
1997	75699	37066	4736990	187522	131875	-	-
1998	78243	38300	4883342	188441	137920	-	-
1999	81145	40050	5023823	186545	136242	-	-
2000	85273	40500	5160586	191560	141670	-	-
2001	85597	41058	5273477	189668	143187	-	-
2002	87837	42816	5396255	191551	140774	-	-
2003	90967	43392	5510364	184787	135997	-	-
2004	93663	43198	5652404	199007	134468	-	-
2005	96199	45827	5839077	288960	157459	54133	49333
2006	102429	46365	6029141	287071	193632	57082	16521
2007	102981	45554	6167681	262787	189388	62079	54365
2008	99442	45823	6280362	241357	187722	40484	35057
2009	92798	45816	6343154	225990	196439	46368	60109
2010	87477	46762	6407002	222725	176768	39068	61892
2011	85543	48381	6465488	222877	211816	43562	23020
2012	86441	49549	6544211	232457	206842	39987	27694
2013	85600	50534	6616124	236146	183178	44711	33847
2014	86887	51538	6706435	249730	203810	48864	34630
2015	85351	54299	6802262	253281	184476	47316	29972
2016	84520	56645	6908642	273257	192103	53749	38888
2017	81872	57553	7016270	261727	163214	45322	29117

Table 2

Arizona Educational Attainment for Adult Population, Ages 25 and Over – U.S. Census Bureau

Year	Population	Less than HS Diploma	HS, Associates or Some College	HS Diploma or Higher	Bachelor's or Higher	Greater than Bachelor's
1990	2283017	491080	1343224	1810097	466873	160319
1991	2368211	437570	1347255	1865430	518175	-
1992	2463327	-	-	-	-	-
1993	2565231	391069	1292976	2037931	544096	544096
1994	2704073	403216	1640936	2148784	507848	507848
1995	2826512	457368	1633088	2126632	493544	493544
1996	2931256	429000	1640600	2171000	530400	530400
1997	3041276	500250	1814125	2374750	560625	560625
1998	3119568	511144	1694400	2312856	618456	618456
1999	3192500	499564	1741084	2456436	715352	715352
2000	3249331	619547	1870425	2723616	766212	272793
2001	3338444	636538	1851755	2605587	753832	262657
2002	3418910	605694	1978309	2760121	781812	277123
2003	3496834	566004	2034596	2869328	834732	299206
2004	3596754	577922	2092981	2970443	877462	326358
2005	3729568	598532	2158111	3104823	946712	345165
2006	3862288	641803	2304883	3311572	1006689	363507
2007	3953926	673859	2369379	3401966	1032587	376690
2008	4030260	678105	2462109	3514442	1052333	385329
2009	4086373	672320	2490158	3575911	1085753	393757
2010	4129792	595351	2477372	3551407	1074035	382146
2011	4204786	602097	2489928	3609126	1119198	399652
2012	4274177	611490	2498388	3668974	1170586	434828
2013	4343171	612204	2544092	3732533	1188441	446459
2014	4429545	618786	2595148	3817440	1222292	456508
2015	4523296	630973	2648532	3905981	1257449	468516
2016	4627311	614439	2676076	4011970	1335894	500115
2017	4516175	604898	2723372	4106464	1383092	520030

Table 3

Arizona Labor Force and Unemployment, Ages 16 and Over – U.S. Bureau of Labor Statistics

Year	Labor Force	Employment	Unemployment	Unemployment Rate	CPI-U Index
1990	1784970	1691082	93888	0.0526	130.7
1991	1805519	1697794	107724	0.0597	136.2
1992	1873246	1732184	141062	0.0753	140.3
1993	1949162	1824338	124824	0.064	144.5
1994	2103918	1974698	129220	0.0614	148.2
1995	2229348	2109988	119360	0.0535	152.4
1996	2284875	2157865	127010	0.0556	156.9
1997	2309029	2203220	105810	0.0458	160.5
1998	2387864	2284982	102881	0.0431	163
1999	2473172	2363425	109747	0.0444	166.6
2000	2510020	2410468	99551	0.0397	172.2
2001	2584740	2461041	123699	0.0479	177.1
2002	2679574	2516348	163225	0.0609	179.9
2003	2735834	2578486	157348	0.0575	184
2004	2795555	2654812	140744	0.0503	188.9
2005	2883299	2748768	134531	0.0467	195.3
2006	2989772	2863729	126043	0.0422	201.6
2007	3034514	2918079	116434	0.0384	207.342
2008	3104408	2913363	191044	0.0615	215.303
2009	3129496	2818966	310530	0.0992	214.537
2010	3089339	2769379	319961	0.1036	218.056
2011	3037167	2748419	288749	0.0951	224.939
2012	3029298	2776596	252702	0.0834	229.594
2013	3030293	2795676	234617	0.0774	232.957
2014	3099798	2889102	210696	0.068	236.736
2015	3167199	2975304	191895	0.0606	237.017
2016	3240956	3065818	175139	0.054	240.007
2017	3327954	3165128	162826	0.0489	245.12

Table 4

Arizona K-12, Undergraduate, and Graduate Enrollments from 1990 to 2017 – NCES

Year	K-12	Undergraduate	Graduate	Undergraduates Ages 25 and Over	1st Time Freshmen	1st Time Freshman Resident & Recent HS Grad
1990	639853	238268	26299	-	62013	-
1991	656980	239826	26901	107667	59961	-
1992	673477	243854	28233	-	34685	13087
1993	709453	238132	28258	101646	42538	-
1994	737424	245167	29746	-	40121	12657
1995	743566	247263	29327	103788	42862	-
1996	799250	249507	30061	-	41553	13107
1997	814113	251781	29176	104138	38829	-
1998	622747	259063	30176	-	42247	13988
1999	872428	268599	14561	107329	38501	-
2000	877696	277003	32877	76994	43363	17137
2001	922180	289123	33922	110518	40943	11442
2002	937755	305612	34650	97112	43978	19025
2003	1012068	312578	33023	119873	45122	13780
2004	1043298	325182	33928	94649	47350	19982
2005	1094454	376412	37340	158917	76052	10999
2006	1068249	346370	39881	109108	52188	22102
2007	1087447	345212	41738	124108	49479	13301
2008	1087817	344322	46516	100060	59190	29418
2009	1077831	386403	52920	150048	68152	21835
2010	1071751	410837	55040	125375	74002	34392
2011	1080319	418861	54849	171264	73388	30965
2012	1089384	412396	55531	125799	67763	31585
2013	1102445	409739	59175	159958	65902	27733
2014	1111695	569442	101379	235835	76531	31712
2015	1109040	552150	97708	265971	71225	28083
2016	1116300	520548	97719	187288	69412	32437
2017	1121700	501391	98216	217021	65728	22326

Table 5

Arizona High School and College Educational Outcomes from 1990 to 2017 – NCES

Year	HS Dropouts	HS Diplomas	Associates	Bachelors	Masters	Doctoral
1990	-	31282	5641	13048	4687	1093
1991	18584	31264	6410	13633	4747	1056
1992	18446	31747	6727	14621	5216	1126
1993	25233	31799	7448	14757	5610	1216
1994	18410	30989	7304	14852	6049	1232
1995	19520	30008	7213	15143	6138	1210
1996	20983	34082	7809	15743	6329	1251
1997	20342	36361	8059	16440	6452	1222
1998	-	35728	8953	16936	6870	1239
1999	-	38304	8717	17957	7948	1380
2000	25632	46773	11033	17381	7885	1405
2001	26314	47175	10737	17939	8083	1511
2002	23242	49986	9955	18729	8959	1524
2003	20533	45508	11405	19576	8837	1622
2004	19980	62400	12362	20390	7825	1632
2005	22573	51066	13562	20479	8628	1713
2006	23188	52757	20634	21255	10676	1883
2007	21034	53354	19026	21797	11130	1938
2008	26173	62374	16318	23211	12148	2078
2009	24865	61145	15875	24780	13572	2077
2010	13014	64472	19036	27395	15547	2225
2011	13956	63208	20983	29829	15821	2757
2012	17920	62208	20564	32495	14961	3107
2013	17166	66700	40165	60277	27930	3646
2014	15943	67200	36077	57725	26867	3969
2015	17467	67120	31996	55684	27175	3602
2016	20806	68240	28527	55565	26094	3565
2017	24128	68750	26215	56849	27123	3891

Table 6

Arizona K-12 School Revenues from 1990 to 2017 – NCES

Year	Local	Intermediate	State	Federal	Total	Per Pupil
1990	1095575048	120225525	1165043096	209065727	2589909396	4505
1991	1200485610	131298706	1194353524	216487595	2742625435	4514
1992	1338688694	142348893	1288854642	234502667	3004394896	4695
1993	1425260812	149949843	1366933875	284615317	3226759847	4912
1994	1500357438	190760557	1411844207	299926254	3402888456	5053
1995	1574905013	168863962	1474316251	332091276	3550176502	5004
1996	1607128756	156949219	1664965599	354241539	3783285113	5130
1997	1782862125	163772321	1829487751	375298538	4151420735	5583
1998	1840642827	170220565	1981317974	408409959	4400591325	5506
1999	1979025038	173163836	2096738811	482747667	4731675352	5812
2000	2242161109	134372861	2195345363	507195513	5079074846	5988
2001	2370699597	143012807	2397669815	591915206	5919152060	6455
2002	2457746377	155770312	2961901834	630744685	6206163208	7071
2003	2662093134	187279747	3136959374	666407145	6652739400	7214
2004	2739938569	170877515	3555569587	839277605	7305663276	7791
2005	2902318218	177503039	3648870950	912542344	7641234551	7550
2006	3108264566	194272869	3898118042	952008901	8152664378	7814
2007	3316895736	204055366	4272319972	1040249250	8833520324	8071
2008	3598169493	5475696	4958859248	1076039573	9638544010	9023
2009	3866974432	5786803	5318990801	1092089969	10283842005	9457
2010	3995019230	4663469	4628420749	1164199386	9792302834	9002
2011	4036365705	244178881	3896117202	1893297529	10069959317	9343
2012	3941830923	258379586	3924368802	1639892319	9764471630	9111
2013	3855946053	269723157	3804900081	1374629292	9305198583	8613
2014	3863771373	277699510	3965426424	1278835390	9385732697	8616
2015	3899570304	273930951	4217359201	1203567314	9594427770	8703
2016	4014989632	282232976	4345426677	1277020602	9919669887	8995
2017	3950664966	287377497	4694392049	1292800480	10225234992	9293

Table 7

Arizona K-12 School Expenditures from 1990 to 2017 – NCES

Year	Instructional	Support Services	Non-Instructional	Total	Per Pupil
1990	1259424124	781305387	102418526	2143148037	4922
1991	1334963013	818363534	105333730	2258660277	4756
1992	1452792032	891328992	125422212	2469543236	4977
1993	1531544433	939132237	128909791	2599586461	5181
1994	1608982383	989791255	154730724	2753504362	5393
1995	1680405286	1040553453	190345368	2911304107	5385
1996	1811166699	1122379965	210993160	3144539824	5521
1997	1921657041	1192287662	214023931	3327968634	5909
1998	2025067647	1281783950	220621108	3527472705	5663
1999	2163072248	1350295632	227521362	3740889242	5941
2000	2380619719	1385316066	197519424	3963455209	6297
2001	2605218791	1477506786	206013771	4288739348	6914
2002	2744558344	1782542110	319004564	4846105018	7009
2003	3226029244	1912158632	257626444	5395814320	7164
2004	3530857964	2083533450	277835532	5892226946	7520
2005	3639234454	2146912503	285638495	6071785452	7044
2006	4030749506	2241296350	307910823	6579956679	7385
2007	4418229645	2379468503	332643203	7130341351	7794
2008	4751054559	2719231764	345433960	7815720283	8930
2009	4751539391	3234614046	417067177	8403220614	9691
2010	4906782729	3390138381	429834303	8726755413	9845
2011	4759456612	3387588310	440843962	8587888884	9319
2012	4506882929	3394014369	439313454	8340210752	9227
2013	4359402126	3208745693	406396877	7974544696	8497
2014	4445724216	3296728431	422076388	8164529035	8590
2015	4450090655	3336314732	434133533	8220538920	8575
2016	4487505563	3429603852	453774580	8370883995	8743
2017	4596133776	3493628283	461910853	8551672912	9086

Table 8

Arizona SET and NonSET Employment and Earnings – U.S. Bureau of Labor Statistics

	SET Industries				NonSET Industries			
Year	Median annual pay	Employees	Establish-ments	Weighted avg pay	Median annual pay	Employees	Establish-ments	Weighted avg pay
1990	29378	157746	5623	35251	20049	2703086	159161	20639
1991	31008.5	159326	6225	37040	21015	2702019	172700	21324
1992	32588	159119	6788	38719	21991	2750275	181325	22433
1993	33864	161577	7071	40014	22852	2881907	183452	22766
1994	36086	167250	7736	42255	23653.5	3060887	192026	23530
1995	37527	180055	8405	43792	24262	3256317	196774	24307
1996	39876	189770	9057	45741	25454	3437855	200039	25300
1997	42354	199748	9723	49103	27109	3589264	205168	26451
1998	43035	210690	10393	53119	28379.5	3774884	209435	27964
1999	45895	214040	10990	54985	29155	3920459	210498	29200
2000	50032	229220	11918	59000	30558	4045869	215422	31141
2001	41466	229730	12504	58882	26403	4178737	224148	32014
2002	44391.5	216127	12829	59564	27336.5	4190807	228274	32710
2003	42630	210673	13218	61605	27127	4206464	237590	33628
2004	44623	213444	13285	65834	28965	4370161	243516	35121
2005	51399	217642	13721	68213	31408	4733637	261338	36743
2006	52409	229071	15108	71552	32246.5	4972076	284760	38541
2007	55492	240632	16865	74541	33580	5029264	301454	39943
2008	58141	240613	17369	75489	34732	4898996	305489	40862
2009	56975	228705	15528	76384	35084	4537797	281896	41099
2010	58239.5	224263	15724	78456	32905	4462926	273887	41497
2011	54660	224675	16002	82197	35404	4505788	272187	42672
2012	59583	227314	16001	84867	35428	4589791	277117	43686
2013	59393.5	233731	15878	86146	36364	4711725	271157	43915
2014	63589	234764	16421	89476	37611	4813599	277530	44835
2015	59538	237824	15986	90733	37892	4947278	281236	45798
2016	58408	243455	15850	91414	37853	5085714	288611	46413
2017	66800.5	234561	15892	94529	39594.5	5219022	299123	48104

Table 9

Arizona State Tax Revenues, Expenditures, and GDP in Millions – Bureau of Economic Analysis

Year	GDP (2012 $USD)	Property Tax	General Expenditures	K12 Expenditures	Higher Education Expenditures
1990	116697.009	-	-	-	-
1991	117182.494	-	-	-	-
1992	129103.26	2582	-	-	-
1993	135730.452	-	-	-	-
1994	148869.292	-	-	-	-
1995	160187.885	-	-	-	-
1996	172841.955	-	-	-	-
1997	168550.5	2984	-	-	-
1998	183138.4	-	-	-	-
1999	198095.9	-	-	-	-
2000	207793.3	-	-	-	-
2001	212656.2	-	-	-	-
2002	219311.3	4254	-	-	-
2003	233342	-	-	-	-
2004	243246	4868	30080	6530	3128
2005	263061	4938	32980	6942	3448
2006	277288.3	5894	35703	7738	3575
2007	284907	6233	39256	8509	3925
2008	277477.1	6710	35821	9184	4250
2009	255080.7	7141	43798	9091	4243
2010	257484.7	7184	43014	8332	4408
2011	263211.1	6995	42733	8066	4582
2012	268288.8	6847	41517	7899	4765
2013	270148.9	6747	42255	7464	5073
2014	273406.9	6635	42845	7961	5065
2015	279455.1	7077	44999	7733	5468
2016	288266.6	-	-	-	-
2017	297161.9	-	-	-	-

Table 10

Arizona Spending by Function from 2010 to 2015 – National Association of State Budget Officers

Year	K-12 Education	Higher Education	Public Assistance	Medical	Corrections	Transpiration	Other
2015	14.3%	12.7%	0.6%	30.3%	2.9%	4.2%	35.1%
2014	18.3%	16.9%	0.1%	31.0%	3.8%	5.5%	24.4%
2013	18.6%	14.3%	1.2%	29.8%	3.5%	5.6%	27%
2012	19.0%	13.5%	1.0%	32.0%	3.6%	6.4%	24.6%
2011	20.0%	13.9%	0.2%	33.9%	3.5%	6.2%	22.3%
2010	22.0%	12.6%	0.3%	27.7%	3.8%	5.6%	28.0%

Table 11

State Tax Collections by Source in 2016 – U.S. Census Bureau, "2016 Annual Survey of State Government Tax Collections by Category"

State	Property Taxes	Sales & Gross Receipts	Licenses	Income Taxes	Other Taxes
Arizona	6.4%	59.1%	3.3%	30.9%	0.2%
Nevada	3.5%	79.1%	8.1%	N/A	9.3%
New Mexico	2.0%	53.6%	6.3%	27.9%	10.2%
Utah	N/A	42.8%	4.1%	52.3%	0.7%

Table 12

U.S. Federal Aid to State Budgets in 2014 – U.S. Census Bureau, "2014 State and Local Government Finances Survey"

State	Total Federal Aid ($ in thousands)	Federal Aid (as % of General Revenues)	Ranking (by % of General Revenues)	Est. 2014 Population	Aid (per Capita)
Arizona	$10,549,101	35.5%	11	6,719,993	$1,570
Nevada	$2,842,077	24.8%	46	2,833,013	$1,003
New Mexico	$5,371,390	34.5%	17	2,083,024	$2,579
Utah	$4,206,286	28.1%	35	2,941,836	$1,430

APPENDIX B

VENSIM SIMULATION RUN OUTPUT PLOTS

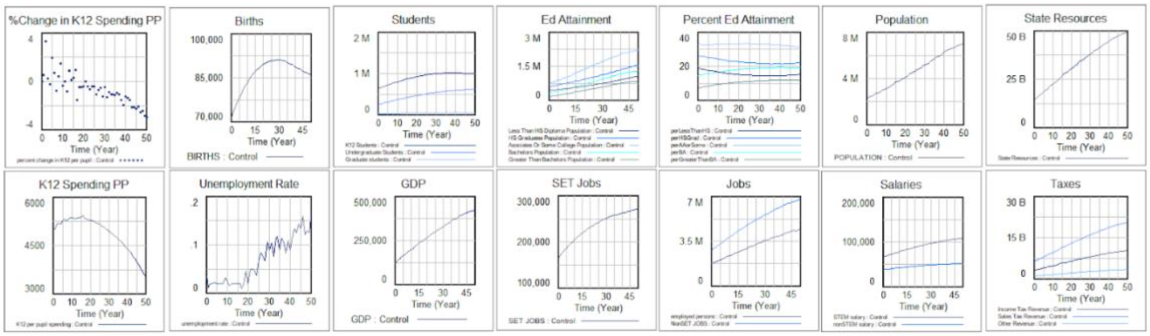

Figure 1. Vensim Output Plots for Scenario 1 Controlled K-12 Spending from 1990 to 2040. In this scenario, the model is run from 2020 to 2040 with the assumption that the apportionment of the state budget to K-12 expenditures continues to decrease at a rate of 0.3% per year.

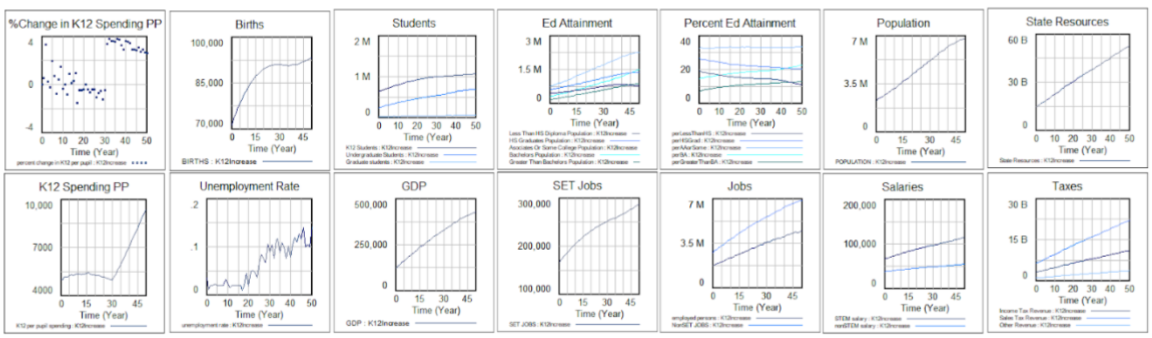

Figure 2. Vensim Output Plots for Scenario 2 K-12 Spending Increase from 1990 to 2040. Scenario 2 K-12Increase, in this scenario, K-12 funding will increase after 2020. Starting in 2020, each year, the state will allocate additional 0.3% of the state budget to K-12 expenditures.

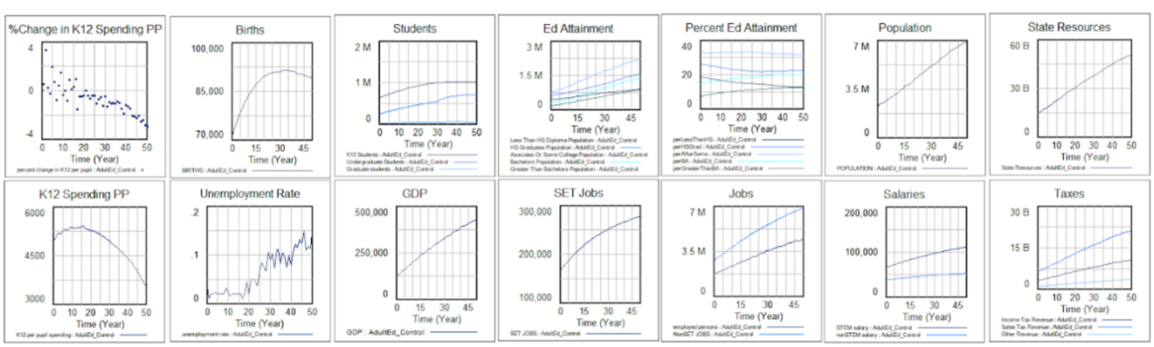

Figure 3. Vensim Output Plots for Scenario 3 Adult Education with Controlled K-12 Spending. Scenario 3 AdultEd_Control, in this case, new adult education programs are implemented (or the existing programs are given extra support). Adult education becomes twice as effective as it was

prior to 2020. Therefore, starting in 2020, GED conversion rates go from 3% of the less than high school diploma population to 6% of the less than high school diploma population per year. Other adult education programs which double in effectiveness are delayed undergraduate enrollment, associate degree earners, and some college re-enrollments.

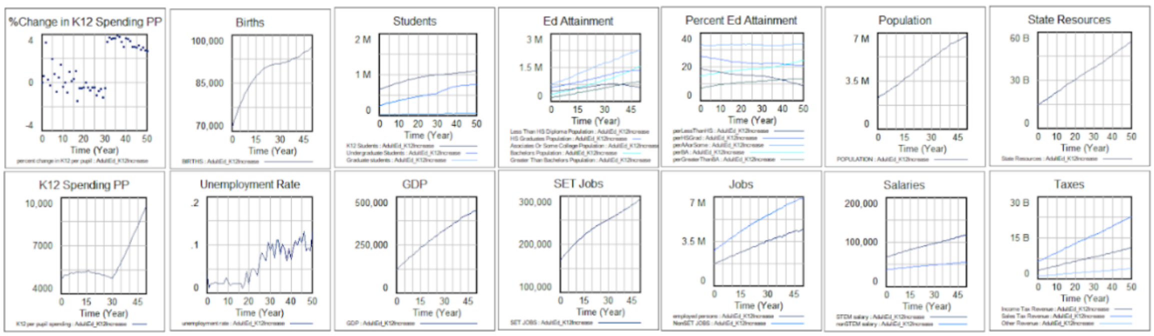

Figure 4. Vensim Output Plots for Scenario 4 Adult Education with K-12 Spending Increase. Scenario 4 AdultEd_K-12Increase, in this scenario, the effects of the K-12 funding increase intervention and the adult education intervention are combined.

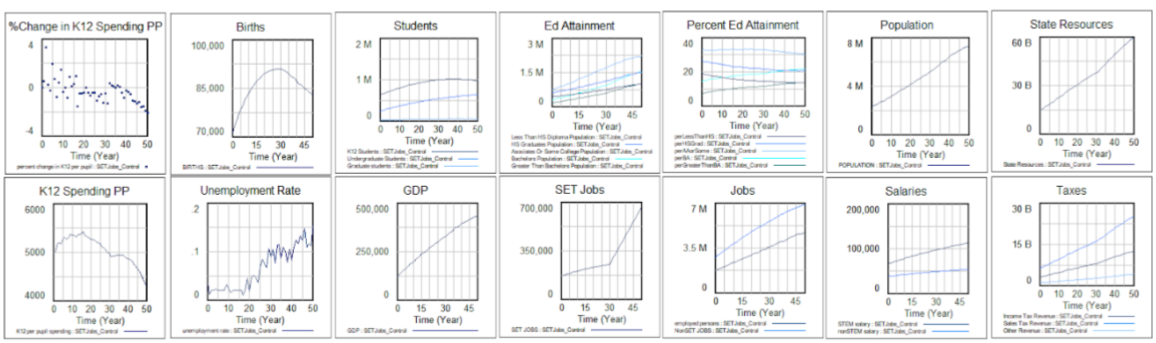

Figure 5. Vensim Output Plots for Scenario 5 SET Jobs Increase with Controlled K-12 Spending. Scenario 5 SETJobs_Control, in this case, SET industries are persuaded to move to Arizona, which introduce 20,000 new SET jobs per year that are filled with 20,000 new migrants, 60% of which are assumed to have a bachelor's degree and the remaining 40% are assumed to have a graduate degree.

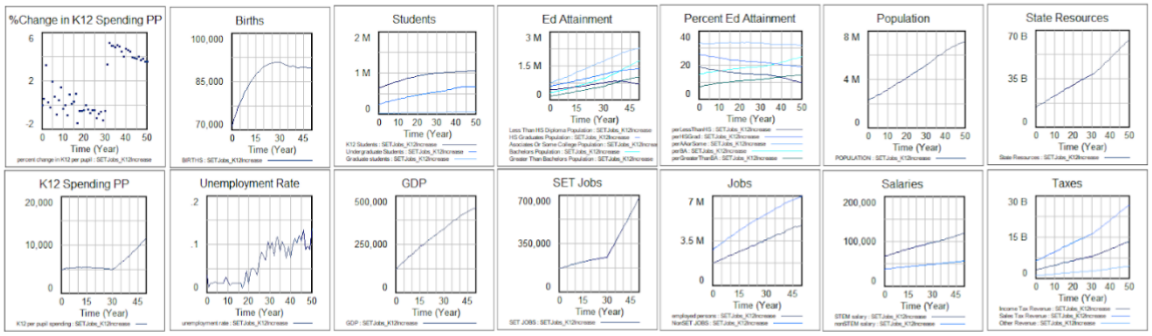

Figure 6. Vensim Output Plots for Scenario 6 SET Jobs Increase with K-12 Spending Increase. Scenario 6 SETJobs_K-12Increase, in this scenario, the effects of the K-12 funding increase intervention and the SET jobs intervention are combined.

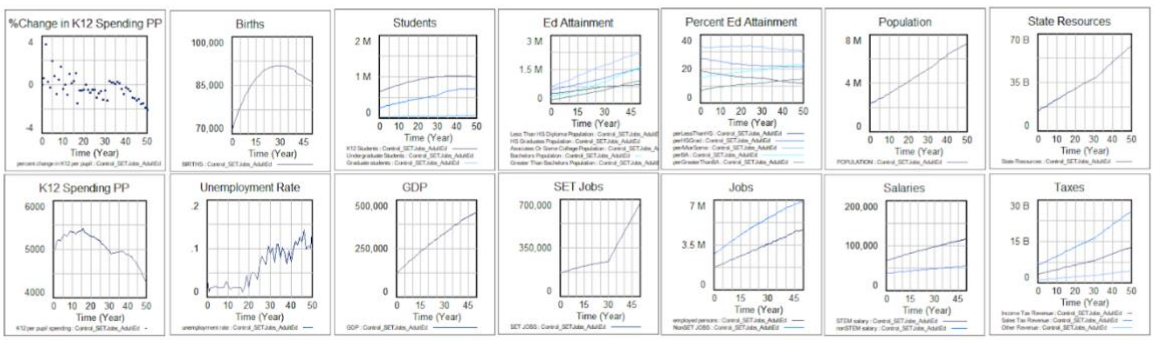

Figure 7. Vensim Output Plots for Scenario 7 Controlled K-12 Spending with Adult Education with SET Jobs Increase from 1990 to 2040. Scenario 7 Control_AdultEd_SETJobs, in this scenario, the effects of adult education intervention and the SET jobs intervention are combined.

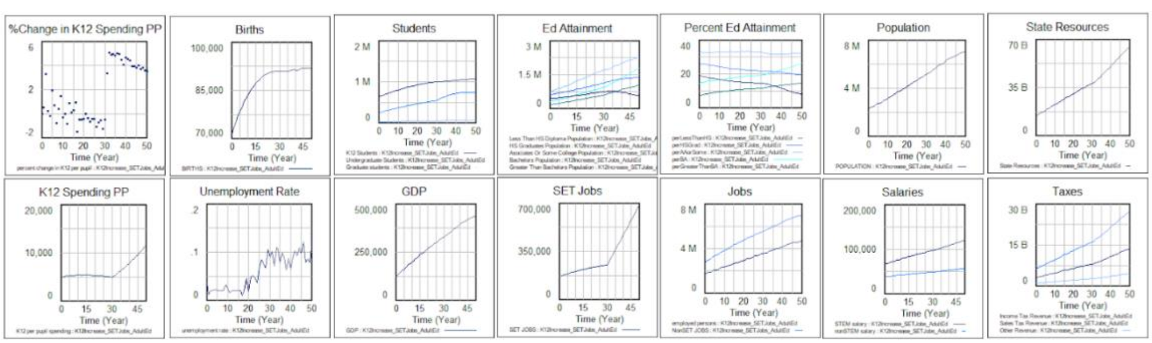

Figure 8. Vensim Output Plots for Scenario 8 K-12 Spending Increase with Adult Education with SET Jobs Increase from 1990 to 2040. Scenario 8 K-12Increase_AdultEd_SETJobs, the effects of the all three intervention are combined.

APPENDIX C

REGRESSION MODEL R-SCRIPT OUTPUT FILES

```
lm(formula = Births..Per.Year. ~ +adult.population..25..years.old...annual. +
    GDP.in.2012..Millions.of.dollars, data = mydata)

Residuals:
     Min       1Q   Median       3Q      Max
-11418.6  -1210.5    185.4   1237.4   7538.7

Coefficients:
                                            Estimate Std. Error t value Pr(>|t|)
(Intercept)                                7.459e+04  3.778e+03  19.746  < 2e-16 ***
adult.population..25..years.old...annual. -2.567e-02  3.287e-03  -7.809 3.64e-08 ***
GDP.in.2012..Millions.of.dollars           4.530e-01  4.066e-02  11.142 3.46e-11 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 3130 on 25 degrees of freedom
Multiple R-squared:  0.9125,    Adjusted R-squared:  0.9055
F-statistic: 130.3 on 2 and 25 DF,  p-value: 5.983e-14
```

Figure 1. R-script Output for Stepwise Regression of Birth Dataset from 1990 to 2017.

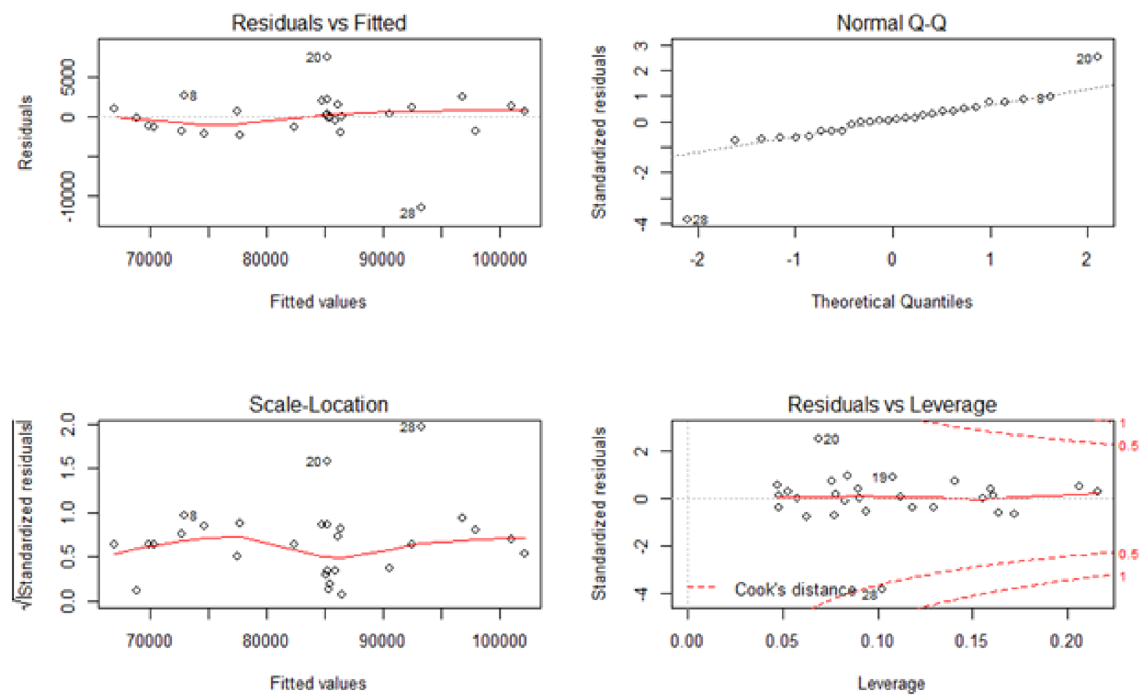

Figure 2. Residuals vs Fitted, Normal Q-Q, Scale-Location, and Residuals vs Leverage Diagnostic Plots for Birth Regression from 1990 to 2017.

```
Call:
lm(formula = SETtotalemployees ~ SETweightedavg + Pop25Plus_Bachelors.OR.Higher,
    data = mydata)

Residuals:
   Min     1Q Median     3Q    Max
-13388  -5449  -1678   3399  21791

Coefficients:
                               Estimate Std. Error t value Pr(>|t|)
(Intercept)                  -1.242e+05  3.144e+04  -3.951 0.000561 ***
SETweightedavg                4.824e+00  5.676e-01   8.498 7.68e-09 ***
Pop25Plus_Bachelors.OR.Higher -5.971e-02  1.745e-02  -3.423 0.002142 **
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 7785 on 25 degrees of freedom
  (42 observations deleted due to missingness)
Multiple R-squared:  0.9288,    Adjusted R-squared:  0.9231
F-statistic: 163.1 on 2 and 25 DF,  p-value: 4.511e-15
```

Figure 3. R-script Output for Stepwise Regression of SET Jobs Dataset from 1990 to 2017.

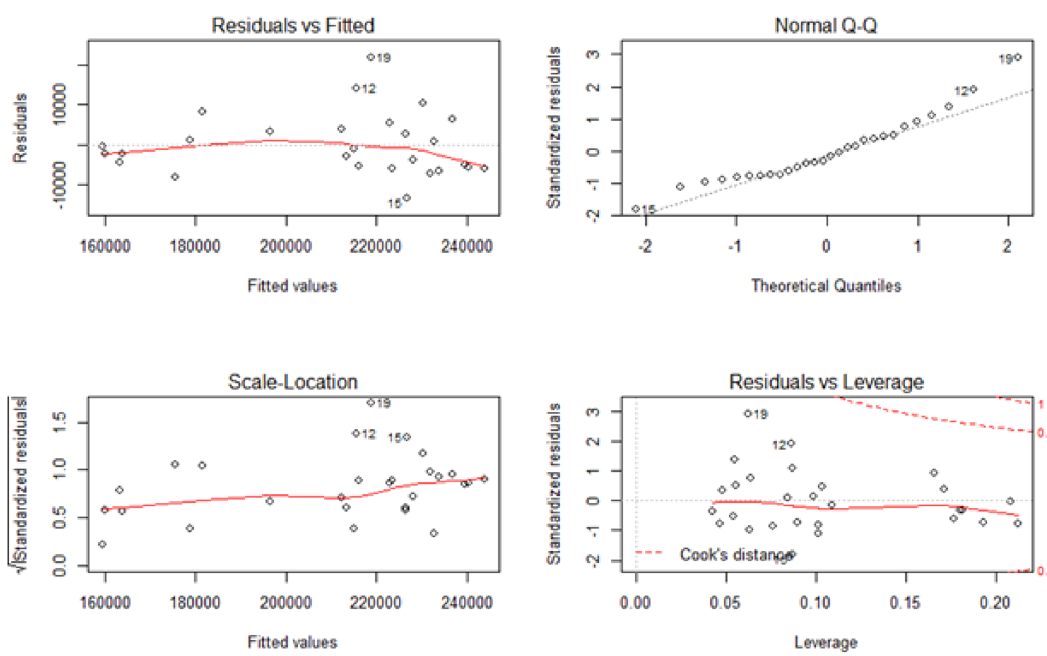

Figure 4. Residuals vs Fitted, Normal Q-Q, Scale-Location, and Residuals vs Leverage Diagnostic Plots for SET Jobs Regression from 1990 to 2017.

```
Call:
lm(formula = nonSETtotalemployees ~ adult.population..25..years.old...annual. +
    nonSETweightedavg + Pop25PlusBachelorsORHigher, data = mydata)

Residuals:
    Min      1Q  Median      3Q     Max
-326394  -63525     347   99586  257786

Coefficients:
                                           Estimate Std. Error t value Pr(>|t|)
(Intercept)                              -5.181e+06  8.899e+05  -5.822 5.29e-06 ***
adult.population..25..years.old...annual. 7.055e-01  2.301e-01   3.067  0.00529 **
nonSETweightedavg                         1.810e+02  2.865e+01   6.317 1.57e-06 ***
Pop25PlusBachelorsORHigher               -1.126e+00  5.261e-01  -2.141  0.04266 *
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 159900 on 24 degrees of freedom
Multiple R-squared:  0.9642,    Adjusted R-squared:  0.9597
F-statistic: 215.4 on 3 and 24 DF,  p-value: < 2.2e-16
```

Figure 5. R-script Output for Stepwise Regression of NonSET Jobs Dataset from 1990 to 2017.

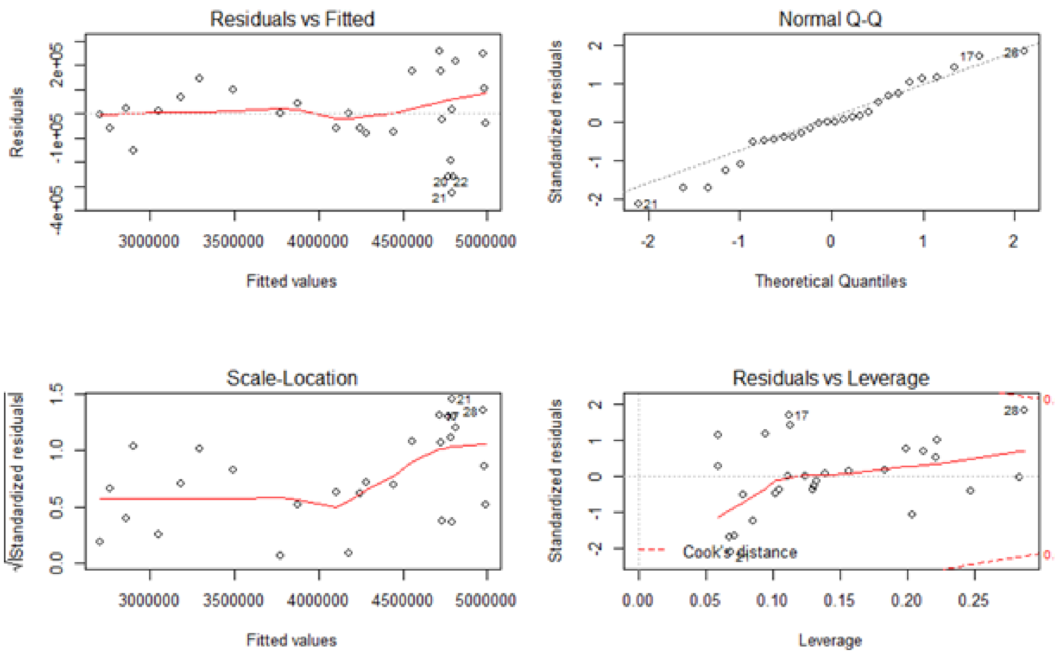

Figure 6. Residuals vs Fitted, Normal Q-Q, Scale-Location, and Residuals vs Leverage

Diagnostic Plots for NonSET Jobs Regression from 1990 to 2017.

```
Call:
lm(formula = GDP.in.2012..Millions.of.dollars ~ SETtotalemployees +
    nonSETtotalemployees, data = mydata)

Residuals:
     Min       1Q   Median       3Q      Max
-11423.1  -5029.2    507.2   2911.7  14499.0

Coefficients:
                       Estimate Std. Error t value Pr(>|t|)
(Intercept)          -5.182e+04  1.408e+04  -3.681  0.00112 **
SETtotalemployees    -3.662e-01  1.682e-01  -2.177  0.03916 *
nonSETtotalemployees  8.496e-02  5.930e-03  14.328 1.47e-13 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 7078 on 25 degrees of freedom
Multiple R-squared:  0.9864,    Adjusted R-squared:  0.9853
F-statistic: 903.9 on 2 and 25 DF,  p-value: < 2.2e-16
```

Figure 7. R-script Output for Stepwise Regression of GDP Dataset from 1990 to 2017.

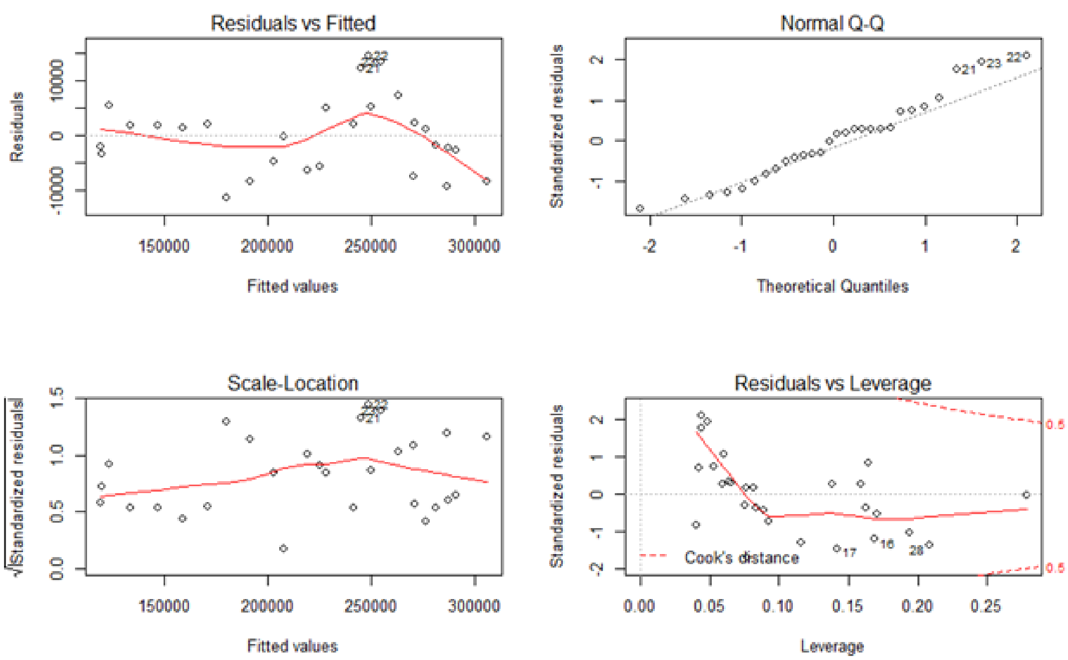

Figure 8. Residuals vs Fitted, Normal Q-Q, Scale-Location, and Residuals vs Leverage Diagnostic Plots for GDP Regression from 1990 to 2017.

```
Call:
lm(formula = PovRate ~ UnemployRate + Laborforce, data = mydata)

Residuals:
      Min        1Q    Median        3Q       Max 
-0.016008 -0.006517  0.002146  0.005545  0.015276 

Coefficients:
             Estimate Std. Error t value Pr(>|t|)    
(Intercept)   0.22476    0.06246   3.598 0.003656 ** 
UnemployRate  0.65810    0.12214   5.388 0.000163 ***
Laborforce   -0.17550    0.09709  -1.808 0.095777 .  
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 0.009484 on 12 degrees of freedom
Multiple R-squared:  0.7636,	Adjusted R-squared:  0.7242 
F-statistic: 19.38 on 2 and 12 DF,  p-value: 0.0001745
```

Figure 9. R-script Output for Stepwise Regression of Poverty Dataset from 1990 to 2017.

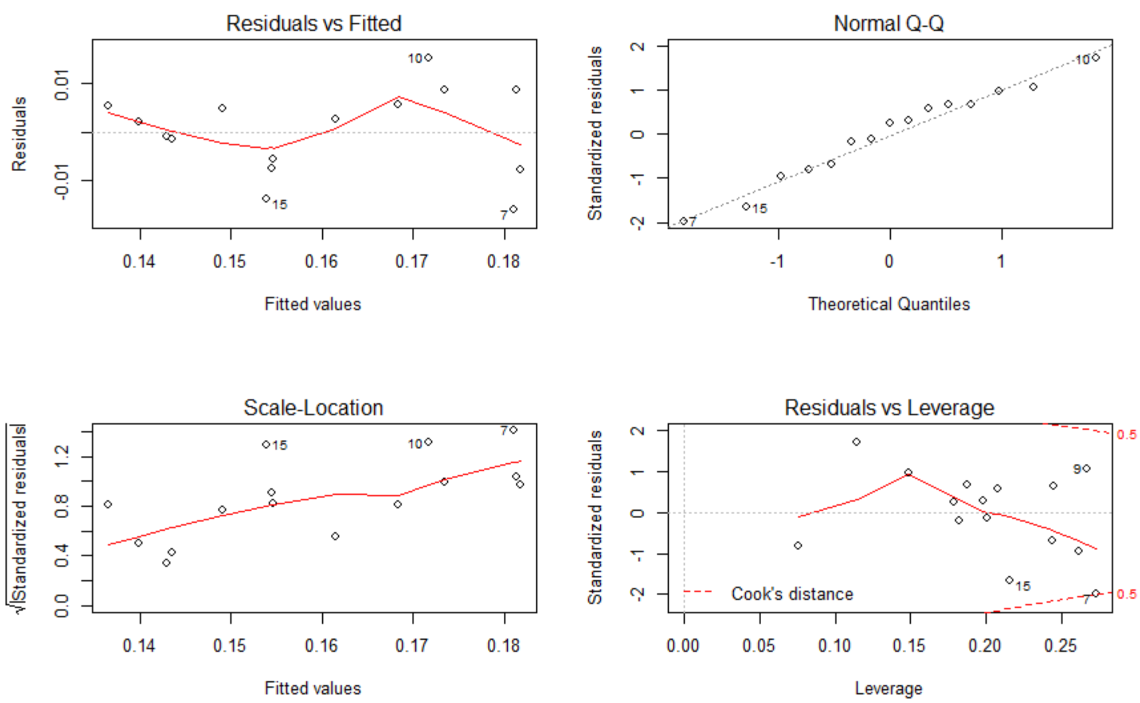

Figure 10. Residuals vs Fitted, Normal Q-Q, Scale-Location, and Residuals vs Leverage

Diagnostic Plots for Poverty Regression from 1990 to 2017.

APPENDIX D

COMPARISON OF SIMULATION SCENARIOS FOR OUTCOME PARAMETERS

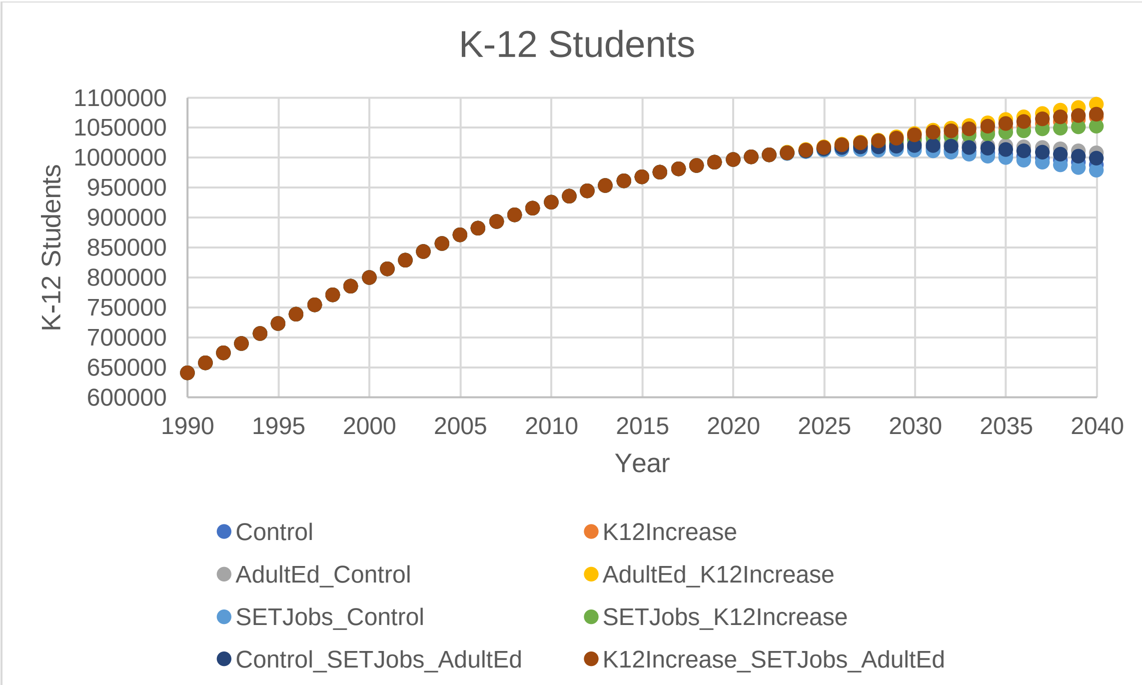

Figure 1. Arizona K-12 students from 1990 to 2040.

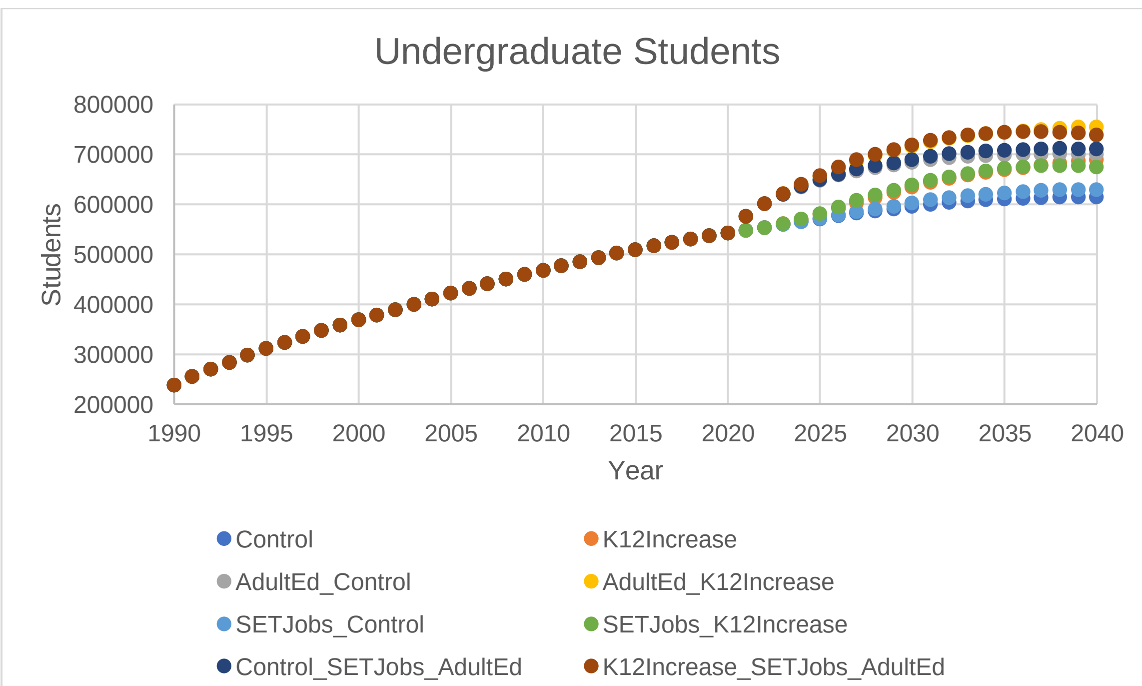

Figure 2. Arizona undergraduate students from 1990 to 2040.

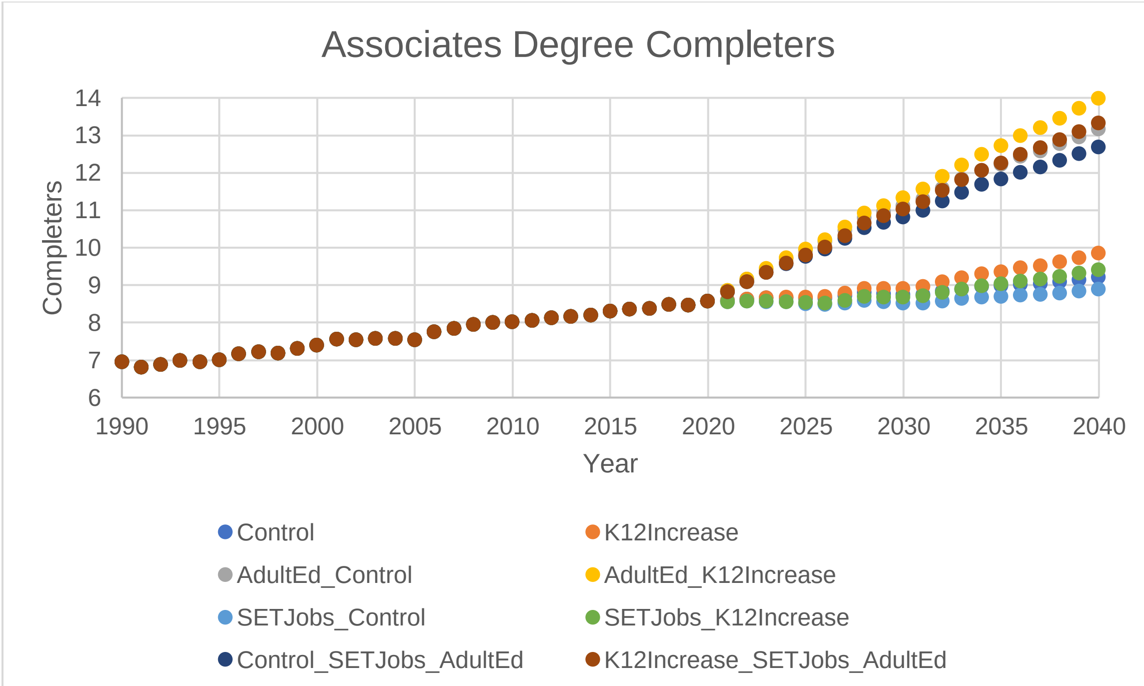

Figure 3. Arizona associate degree completers from 1990 to 2040.

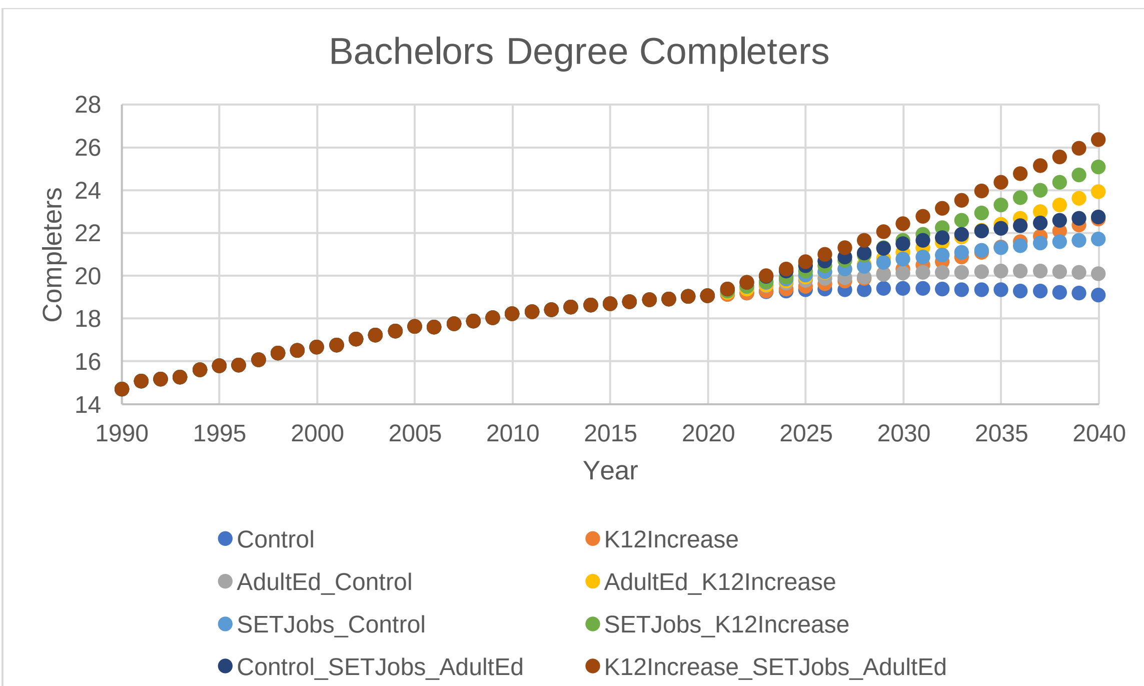

Figure 4. Arizona Bachelor's Degree Completers from 1990 to 2040.

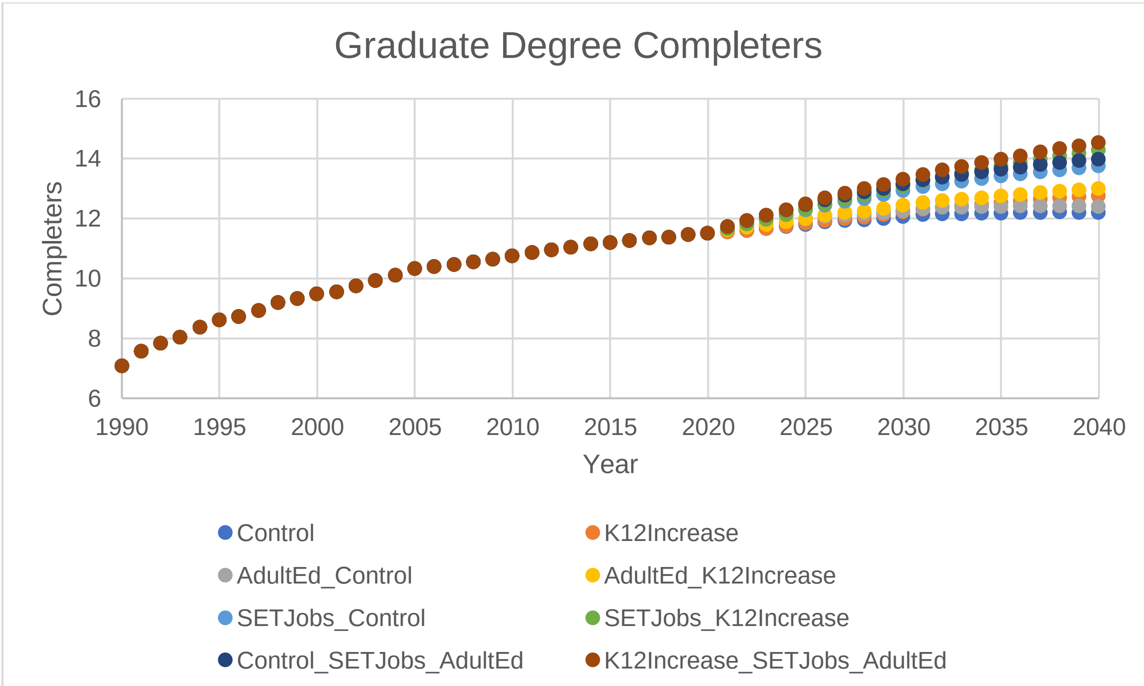

Figure 5. Arizona Graduate Degree Completers from 1990 to 2040.

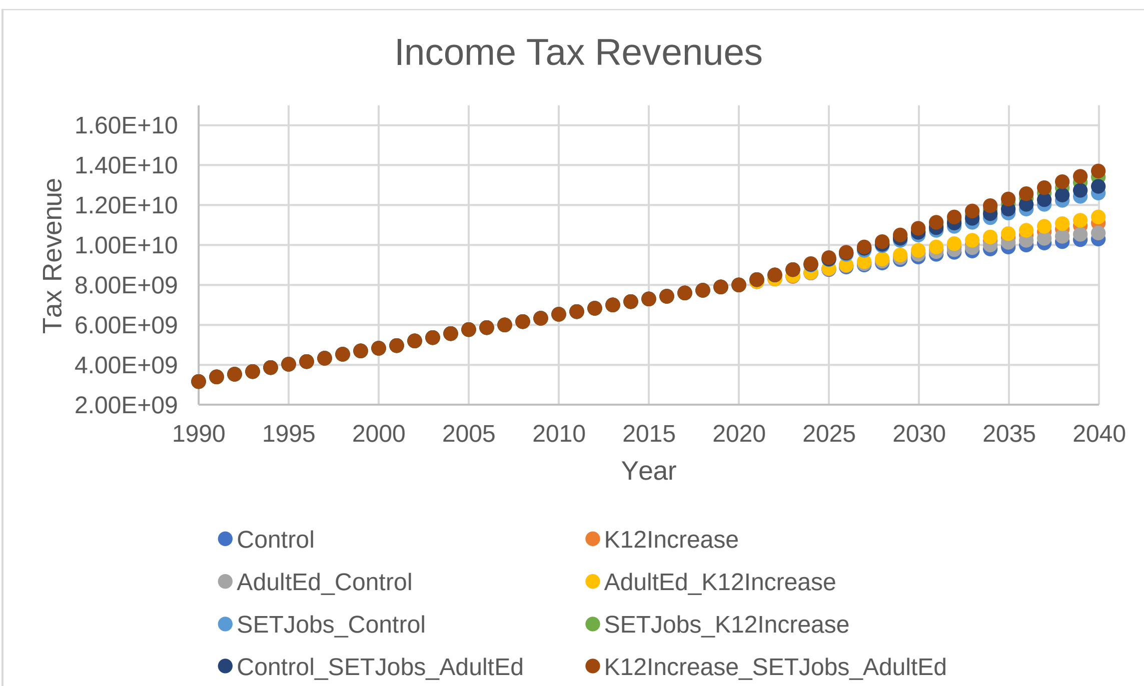

Figure 6. Arizona Income Tax Revenues from 1990 to 2040.

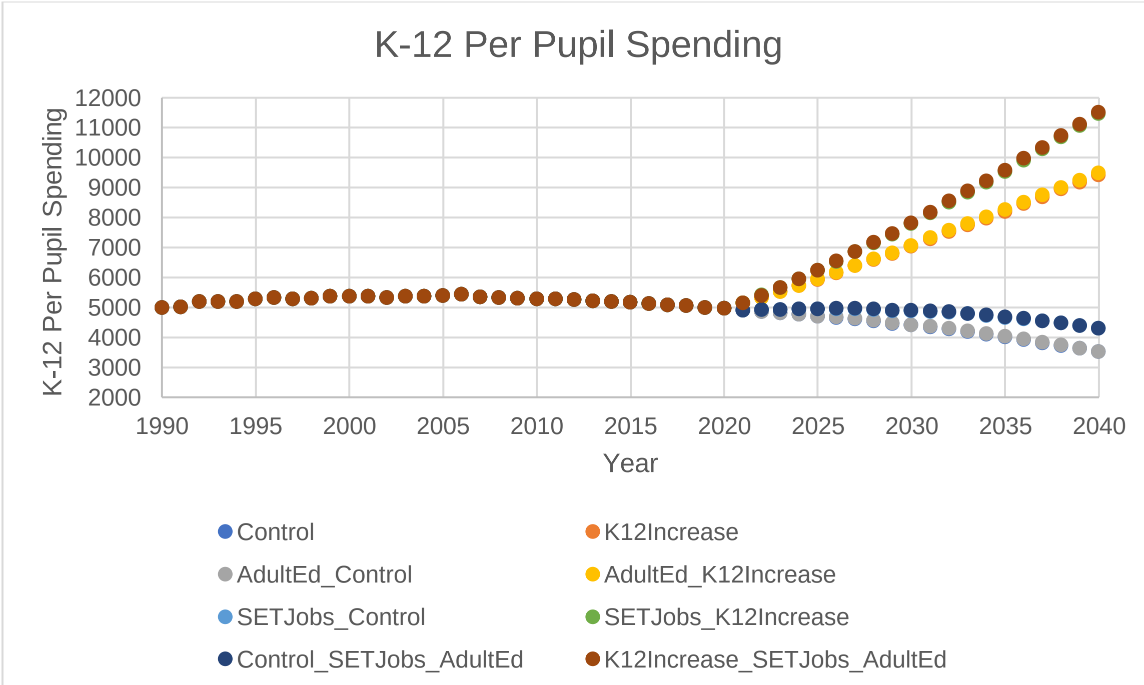

Figure 7. Arizona K-12 per Pupil Spending from 1990 to 2040.

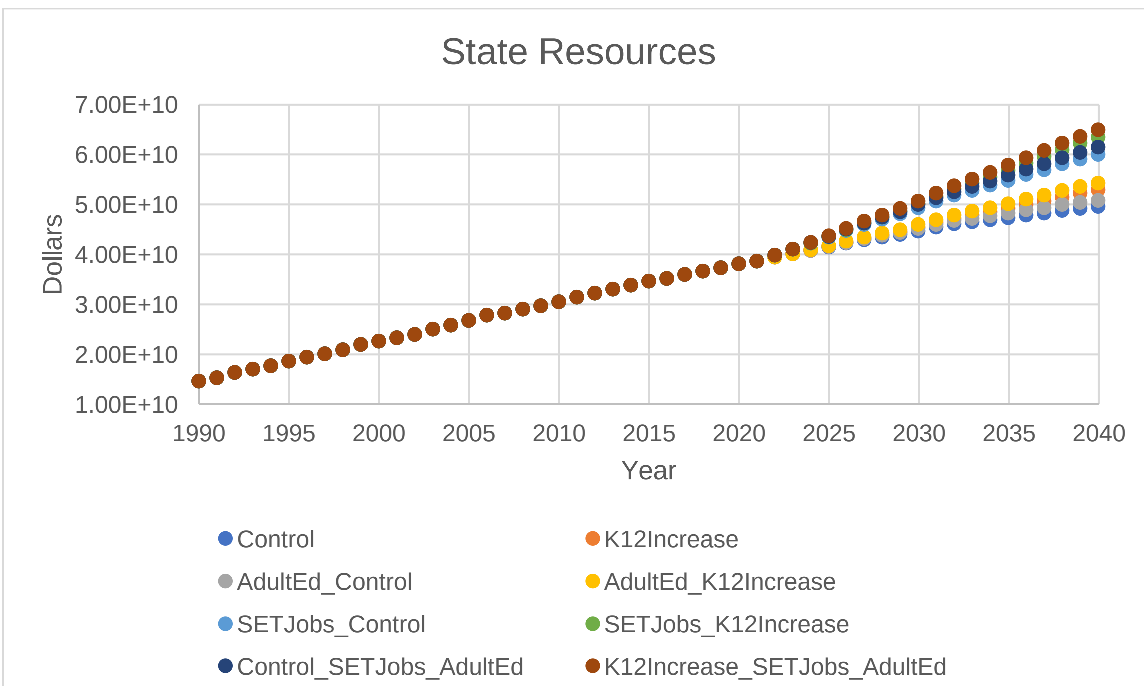

Figure 8. Arizona State General Fund from 1990 to 2040.

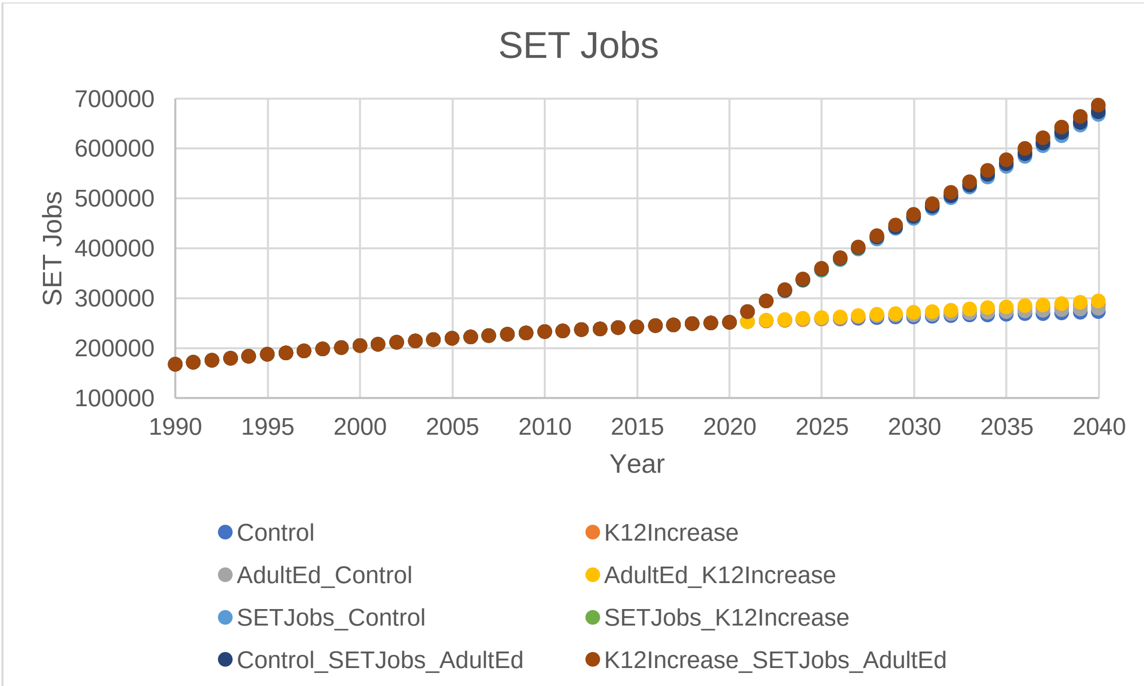

Figure 9. Arizona SET Jobs from 1990 to 2040.

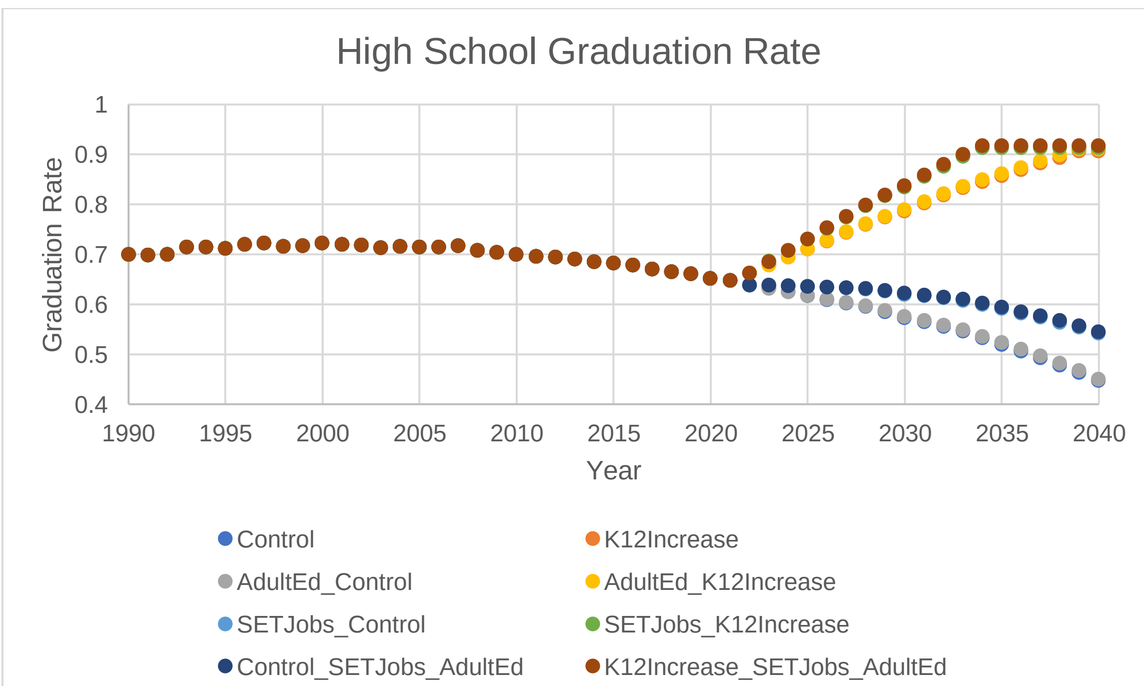

Figure 10. Arizona High School Graduation Rate from 1990 to 2040.

APPENDIX E

STATEMENT OF CO-AUTHORS GRANTED PERMISSIONS

Chapter 3 of this dissertation was formerly published in the journal of Simulations & Gaming. Co-authors on this work include Dr. Hinrichs, Dr. Seager, & Dr. Clark. All co-authors have granted their permission to include this previously published journal article in this dissertation.

BIOGRAPHICAL SKETCH

At 4 years old, Lauren was diagnosed as dyslexic and struggled daily with reading and writing. Determined not to be limited by her age or learning-disability, Lauren graduated with her B.S.E. in Civil Engineering at 18 years old (Chi Epsilon) and her M.S. at age 20 (Tau Beta Pi). Lauren’s early academic achievements and service leadership were highlighted by U.S. News and World Report, The State Press, and other news articles. Lauren’s passion for science, technology, engineering, and mathematics (STEM) began in 2009, when she learned the importance of civil infrastructure while building a house for a homeless family in Juarez, Mexico. Lauren has since built ten houses in Mexico and led the 2012 ASU Engineers Without Borders rainwater collection project construction in Bondo, Kenya. Lauren has always felt that with STEM education, we can enable students with the tools to become leaders and problem-solvers who possess the capacity to improve others' quality of life. Aspiring to empower others through STEM education, Lauren received a Science Foundation Arizona Graduate Fellowship and began competing in the Miss America Organization and the Miss USA pageant. With over 1,200 hours of volunteering in K-12 STEM outreach, Lauren was recognized with the Quality of Life Award and placed as 1st runner-up to Miss Arizona 2016 and 3rd runner-up to Miss Arizona USA in 2019. During her doctoral studies, Lauren was given the opportunity to deliver nearly 30 conference presentations, in ten states and three different countries. She wrote three conference proceedings papers and created two peer-reviewed curriculum lesson plans. Lauren also published two 1st author, peer-reviewed journal articles, with two more in-progress. Having achieved her doctorate in systems engineering, Lauren plans to continue her efforts to innovate solutions to wicked problems by leveraging research-based approaches for analyzing complex, socio-technical infrastructure systems. Dr. Lauren R. McBurnett Naufel, is now a post-doctoral researcher for the Decision Center for Educational Excellence at Arizona State University, where she utilizes simulations and games to teach complex systems thinking skills for increasing students' and stakeholders’ adaptive capacities and decision-making abilities to address the U.S. infrastructure crisis. In addition to her contributions designing, developing, and facilitating the LA Water Game and the Arizona Educational-Workforce Simulation, she has designed simulations and games for training, education, and research teams while working as a research analyst for the Center for Naval Analysis FFRDC in Arlington, VA.