Journal of International Technology and Information Management

AGENT-BASED MODELING AND SIMULATION APPROACHES IN STEM EDUCATION RESEARCH

Shanna R. Simpson-Singleton
Eastern Michigan University, ssimpso6@emich.edu

Xiangdong Che
Eastern Michigan University, xche@emich.edu

Follow this and additional works at: https://scholarworks.lib.csusb.edu/jitim

Part of the Computer and Systems Architecture Commons, Educational Assessment, Evaluation, and Research Commons, Educational Methods Commons, Educational Psychology Commons, Educational Technology Commons, Information Literacy Commons, Management Information Systems Commons, Management Sciences and Quantitative Methods Commons, Operational Research Commons, Other Computer Sciences Commons, Science and Technology Studies Commons, Social Media Commons, Technology and Innovation Commons, and the Theory and Algorithms Commons

Recommended Citation

Agent-Based Modeling and Simulation Approaches in STEM Education Research

Shanna R. Simpson-Singleton,
Xiangdong Che
(***Eastern Michigan University***)

ABSTRACT

The development of best practices that deliver quality STEM education to all students, while minimizing achievement gaps, have been solicited by several national agencies. ABMS is a feasible approach to provide insight into global behavior based upon the interactions amongst agents and environments. In this review, we systematically surveyed several modeling and simulation approaches and discussed their applications to the evaluation of relevant theories in STEM education. It was found that ABMS is optimal to simulate STEM education hypotheses, as ABMS will sensibly present emergent theories and causation in STEM education phenomena if the model is properly validated and calibrated.

Keywords: Agent-based Modeling (ABM), Simulation, Science Technology Engineering & Mathematics (STEM) education modeling

INTRODUCTION

This survey will examine existing simulation models of artificial societies concerning factors of education with to ascertain the applications of these approaches to the expansion and enhancement of STEM education research. Advancements in science, technology, engineering, and mathematics (STEM) constantly increase at turbulent speeds, creating a need for an upsurge in the proficiency of students at all levels of education in STEM topics. This trend has been recognized worldwide, and many global leaders have begun to take action to remain internationally competitive. The U.S. Department of Education, the National Science Foundation (NSF), and many other national agencies are driven to ensure that the U.S. increases its ranks amongst the frontrunners of global STEM progression through research initiatives that aim towards national reform in education reflected by a sizeable growth of students that are entering STEM careers (U.S. Department of Education, n.d.; NSF, n.d.a; NRC, 2011). Moreover, there have been initiatives aimed to expand the STEM proficiency of the general public

providing the holistic results of a more productive society (NRC, 2011). Thus, this literature review aspires to utilize qualitative methods to discover some of the primary attributes of education and agent-based simulation modeling that may be practical to STEM education research. The study will outline the key factors in STEM education research, define the varying paradigms of modeling & simulation, outline the methodology utilized to select the literature, summarize the model simulations, analyze the quality of the literature and its respective model simulations, assess the findings of the simulations, and present the results of the survey.

STEM EDUCATION RESEARCH INITIATIVES

The National Research Council (NRC) (2011) strongly emphasizes the need for strong STEM education for all students. User-friendly technological advancements in numerous industries utilize STEM knowledge in various tiers of employment; therefore, it is necessary that STEM education become an essential component of K-12 and college curriculums. Furthermore, those that do pursue STEM education and careers, do not represent the vast racial and ethnic diversity of the citizens within the United States, nor is there a balanced gender representation in these fields. Moreover, within the realm of STEM education, research has indicated significant achievement gaps between these groups, with a considerable achievement gap between whites and blacks as well as whites and Hispanics (NRC, 2011). Consequently, this mandates the necessity to minimize the achievement gaps in STEM education amongst underrepresented groups (NRC, 2011).

The U.S. Department of Education looks to organizations such as the National Governors Association (NGA) Center for Best Practices and the NRC to research STEM education and provide recommendations for best practices to reach national STEM education goals. In addition, the NSF provides grant funding to aid in STEM education research and to competitively fund students that may choose to pursue STEM education and careers (NSF, n.d.b).

The NRC (2011) cites the following objectives to advance national STEM education:

- Increase the number of students that obtain advanced degrees and enter STEM careers with growth in women and minorities that partake in these STEM paths;

- Increase the capability of students that can enter a labor force that requires STEM skills while again, supporting growth in women and minorities personnel in these fields;
- Improving STEM knowledge for every student irrespective of their future pursuits in STEM education and careers.

Explorative efforts by the NRC, NGA, CCSSI, NGSS, NSF, and the U.S. Department of Education have directed their research towards these national goals, resulting in principals that focus on the factors outlined in Table 1.

RESEARCH FACTORS INFLUENCING EMERGENT THEORIES IN STEM EDUCATION

Table 1. Factors influencing emergent theories in STEM education.

STEM Curricula	Schools	Teachers	Students
- Rigorous courses - Integrated STEM education within non-STEM subjects - Faculty training - Real-life applications - Learning beyond the classroom - Procedural and conceptual skills - Hands-on applications	- Classroom resources - Student/teacher ratio - Technical support - Accountability - Qualified STEM teacher recruitment & retention	- Content knowledge - STEM pedagogy - Self-efficacy - Self-fulfilling prophecies - Motivation - Creativity - STEM support services	- Equal access to quality STEM education - STEM interest - Self-efficacy - Motivation - Creativity - Content knowledge - STEM support

These factors listed in Table 1 results in emergent theories that suggest that the U.S. STEM goals are to be best achieved with well-trained teachers implementing a

nationally common, yet rigorous, STEM education including supplemental STEM education interventions (NRC, 2011) that motivates and sufficiently prepares students to enter STEM majors in college. Subsequently, this follows with persisting theories that charge institutions of higher learning with the task of readying its students for proficiency in STEM careers by continuing to address the above-listed factors (NGA Center for Best Practices, 2011). These emergent theories resulted in the formation of K-12 Common Core Standards for mathematics developed under the guidance of the NGA Center for Best Practices (CCSSI, 2017). Additionally, the Next Generation Science Standards (2013) were developed with foundational theories from the NRC (2012) publication, A Framework for K-12 Science Education: Practices, Crosscutting Concepts, and Core Ideas. The educational STEM concepts, systems, and models outlined in these standards fuel future research that is often supported by national agencies such as the U.S. Department of Education and the NSF.

SIMULATION MODELING OVERVIEW

Simulation modeling, in general, provides a means to test the hypothesis for an intricate longitudinal study in a very short period of time, making it applicable to the research exploration in STEM education. There are numerous methods of simulation modeling that can be grouped into the subsequent classifications: Discrete Event (DE), System Dynamics (SD), and Dynamic Systems (DS) (Borshchev & Filippov, 2004; Csala, 2012). Discrete event modeling is a process-oriented sequential flow with occurrences at certain times that indicate a change in state (Csala, 2012). System dynamics provides a holistic view of entities in a system, and how they interact is "through 'feedback' loops, where a change in one variable affects other variables over time, which in turn affects the original variable" (MIT SDEP, 1997, p. 1). Dynamic systems are a predecessor to system dynamics, but it utilizes numerous state variables with several associated differential equations (Borshchev & Filippov, 2004) creating a higher accuracy, but a greater complexity than system dynamics (Csala, 2012).

Each of these methods of simulation modeling may be advantageous in certain situations and industries but may prove to be somewhat deficient as it relates to modeling educational research trends. DE simulation represents a sequential progression of events with processes and decision flow blocks. Here, the sole focus is the process instead of the agents within the process (Csala, 2012), which is not optimal for an educational system where there may be several processes contributing simultaneously, not sequentially. Moreover, the critical focus is not the process; rather, the focuses will be on the outcomes based upon the interactions

amongst students, teachers, and other education-based institutions. SD and DS models can be applied to social studies such as education, but it is more applicable to policy studies as these simulations conceptualize from solitary cases and hypothesize the outcomes for the agents involved (Borshchev & Filippov, 2004).

A more recent approach to simulation modeling is the Agent-based (AB) method. Unlike DE, SD, and DS, agent-based modeling and simulation (ABMS), also known as multi-agent modeling, is a bottom-up and decentralized method that is free of dynamics that define the global behavior of the system (Borshchev & Filippov, 2004; Csala, 2012). In this method, agents and environments are defined and interactions are freely composed to result in an emergent global behavior (Csala 2012). This method is appropriate for education research as it is more capable of signifying theories of causation based upon defined agent behaviors.

THE ARCHITECTURE OF AGENT-BASED MODELING AND SIMULATION (ABMS)

The majority of the educational models surveyed within this work utilize ABMS. Generally, the configuration of an ABM includes objects/agents, interactions, rules, and environment (Csala, 2012). The objects, or agents, are assigned certain traits and characteristics with rules that define their behavior, which determines how they interact with other agents and the environment (Macal & North, 2010). Csala (2012) also defines several states within the ABM that include the simple state, transition, composite state, pseudo history state, and the branch pseudo state.

- The simple state contains the control for the ABM,
- The environment and the agents are defined by varying characteristics, behavior rules, and interaction rules,
- The composite state includes an assembly of states with mutual behaviors,
- The pseudo history state tracks the prior state called within the composite state,
- The branch pseudo state determines the conditional branching between the transitions, which are triggered by events or rules (Csala, 2012).

Collectively, this structure of simulation modeling, seen in Figure 1, enables the agents to act as individuals and produce a global behavior to be explored by researchers.

Figure 1. Simplified ABM Structure
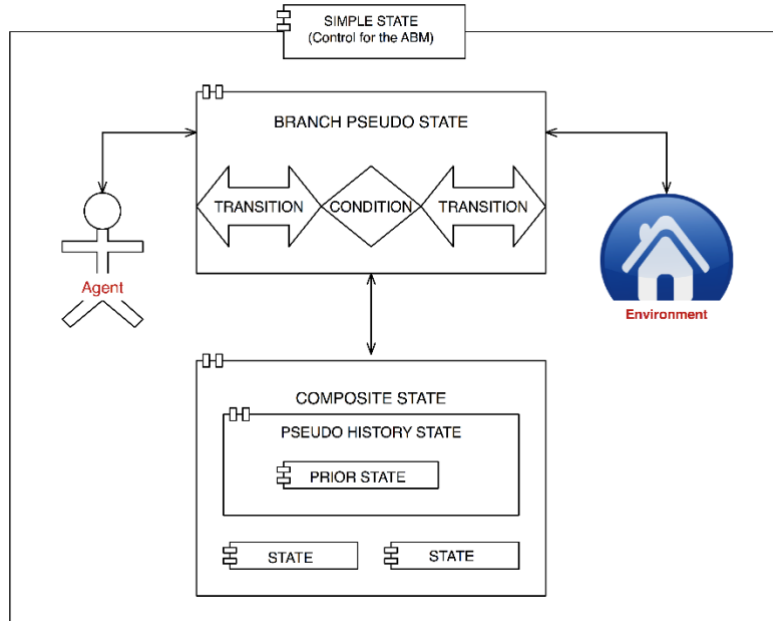
SURVEY OF STEM EDUCATION RESEARCH WITH ABMS APPROACHES

Research regarding STEM education is extensive. Table 1 indicates the numerous variables that are intricately involved in the development of successful STEM education policies and practices. It is not viable to include all of the known factors that affect STEM education into one model; thus, this survey explores an assortment of factors from various models. Additionally, simulation modeling is a relatively new method of exploration for STEM education. As a result, there are very few published papers regarding this topic. For these reasons, this paper aims to take a qualitative approach to investigate the STEM education research factors that were explored and systematically connect this limited collection of works to the following questions.

1. How are existing STEM education simulation models structured?
2. How are existing education simulation models applicable to STEM education research?

3. How can existing education simulation models be applied to teachers implementing STEM education?
4. How is the ABMS architecture applied to education simulations?

METHODOLOGY

To encapsulate the topic of agent-based modeling and simulation education approaches that are relative to STEM education research, a thorough systematic search within relevant databases, journals, and search engines was conducted to directly address the questions for this survey. The following databases were investigated from their respective commencement dates to September 28, 2019: Elsevier, ERIC, Esearch, Google Scholar, ProQuest, Sage, and Web of Science; in addition, the Google search engine was utilized in this search. The Journal of Artificial Societies and Social Simulation (JASSS), the Journal of Science Education Technology (JSET), and the Journal of Simulation (JOS) were hand-searched from January 1, 2011 to September 28, 2019. The literature search included the successive terms with their respective synonyms and/or alternative words or expressions that are appropriately correlated (see
Table **4**): "STEM", "Education", "Simulation", and "Modeling," as well as the following keywords for the hand-searches (see
Table **4** Item D): "school" and "teaching." These searches were not constrained by the research design if a framework and/or methodology was provided for the simulation. Supplementary literature was ascertained by inspecting and hand-searching the references lists of relevant articles (see Table 3). Moreover, there were additional inspections of the search results that did not necessarily directly answer the questions but were published in a journal that may contain research prospects (see
Table **4**). All hand-searches were explored within the first twenty results. The detailed filters, searches, and strategies are provided in Appendix E.

The results are subsequently surveyed within this review, followed by an assessment and comparative analysis addressing the following characteristics within each simulation:

- Explanatory details of the framework/structure of the model
- Calibration and verification of the model
- Replicability of the model
- Relevance of the model to STEM education research
- Relevance and/or application of the model to STEM teachers

MODEL SUMMARIES

The research objectives of each simulation were assessed to determine the applicability of the simulations to STEM education research yielding the subsequent relational mapping and classifications seen in **Error! Reference source not found.**. The primary structures of the frameworks were surveyed for each model simulation presented within the literature resulting in the following summaries.

**Figure 2. Applications of Simulations to STEM Topics.**
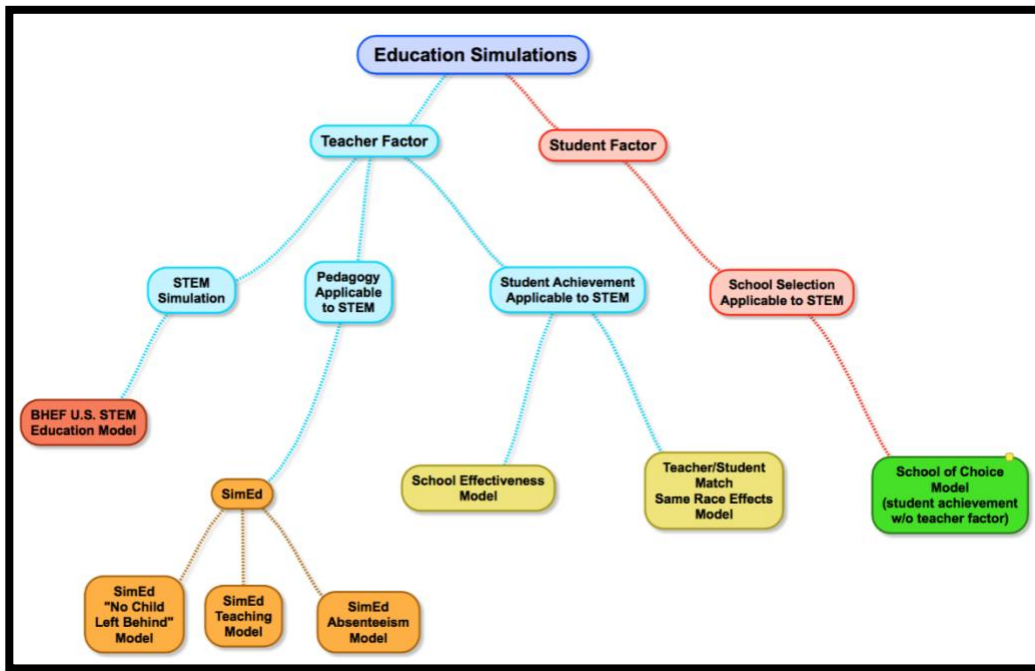
SIMULATION FRAMEWORKS

The surveyed research objectives and simulation frameworks within the literature for each model simulation yielded the following tables and figures demonstrating a simplified graphic for each simulation, as seen in Figures 3-12.

The BHEF U.S. STEM Education Model is directly focused on STEM education with the primary purpose of increasing the number of students that obtain STEM degrees and enter STEM fields as a profession. This is a macro-level system dynamics simulation collaborated with national data, which found that STEM proficient teachers would increase the number of students that enter STEM college majors, and bridge & cohort intervention programs will retain students past their freshman year of college. Figure 3 shows the simulation framework for this model, and the prominent research methods include:

- Programs to retain mathematics proficient & STEM interested students in college STEM majors are explored.
- The effects of teachers on mathematics proficiency & STEM interests are explored.
- The target student age level for mathematics proficiency & STEM interests is explored.

Figure 3. Simplified Diagram of the BHEF U.S. STEM Education Model. Adapted from "Increasing the number of STEM graduates: Insights from the U.S. STEM Education & Modeling Project" by the Business-Higher Education Forum, 2010, p. 6. Copyright 2010 by the BHEF.
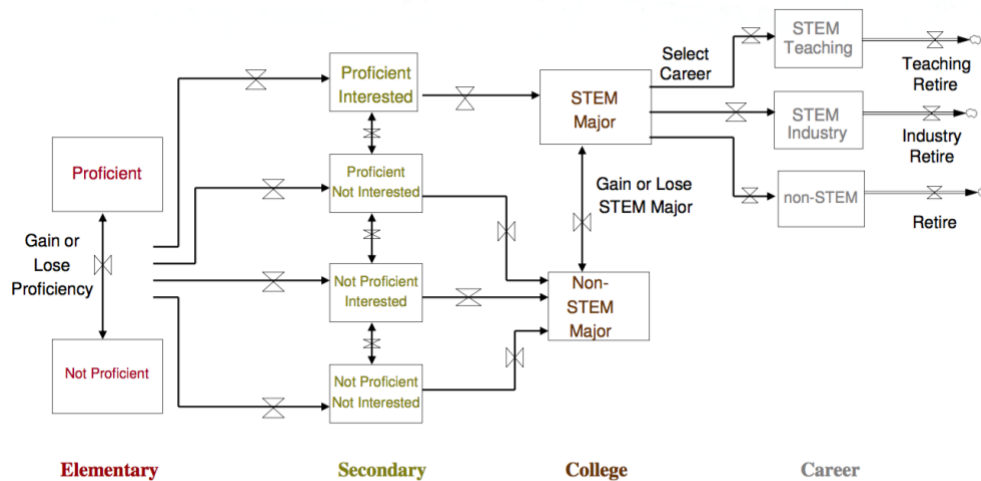
SimEd is an education model aimed towards the interactions between varying agents such as students, teachers, principals, and superintendents within a school district, schoolhouse, and/or classroom environment, demonstrated in Figure 4, that

determines the effects of interactions with these agents and environments on student achievement. It is an agent-based model that can approach education on the macro- or micro-level of investigation, and it is collaborated by an interview method with education professionals. The overall structure of the simulation can be seen in Figure 7. This structure utilizes the following research methods:

- The quantity of teachers and students is user-defined.
- The dialogic framework utilizes a model based upon the Game Theoretic Model, Iterative Prisoner's Dilemma, and the Meta-Game of Learning (MGL).
- Lessons are delivered to the students in a traditional lecture-feedback model or in an intelligent learning system model that is inclusive of an intelligent tutoring system.
- The progression rates of the lessons are compared for each lesson model.
- Motivation and emotion levels are compared for each lesson model.

Three models were created from this framework. *The SimEd Model* examines teacher & student interactions, as seen in Figure 5, Figure 6, and Table 2, on the micro-level within the classroom setting and the outcomes of two different teaching methods: the lecture feedback model (historically traditional teaching method) and the tutorial model (individualized teaching method). It was found that students progressed faster, and their motivation and emotional levels were higher with the tutorial method in comparison to the lecture feedback model.

Figure 4. SimEd sub-institutions. Adapted from "SimEd: Simulating Education as a Multi-Agent System" by E. Sklar, M. Davies, and M.S.T. Co, 2004, Proceedings of the Third International Joint Conference on Autonomous Agents and Multiagent Systems, p. 2. Copyright 2005 by IEEE Explore.
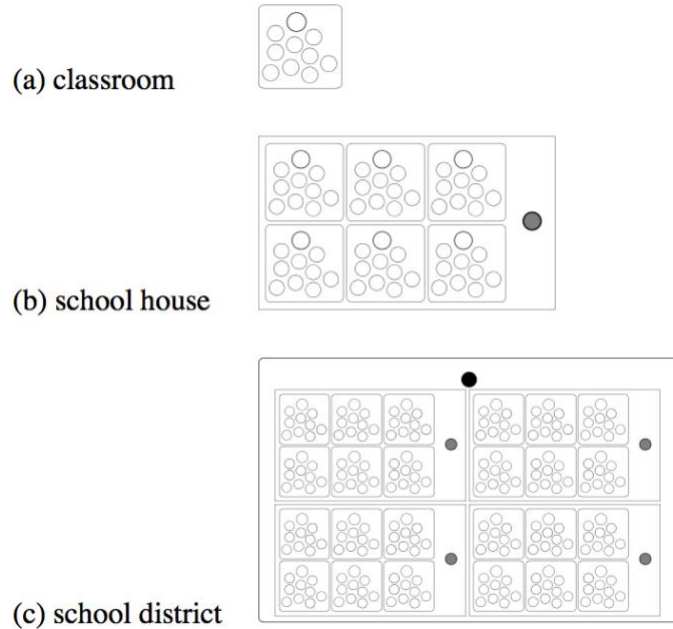

Table 2.

STUDENT	right	wrong
TEACHER: hard	learning	frustration
easy	verification	boredom

Note. Meta-Game of Learning for questions in SimEd model. Adapted from "Multiagent Simulation of Learning Environments" by E. Sklar and M. Davies, July 2005, Proceedings of the Fourth International Joint Conference on Autonomous Agents and Multiagent Systems, p. 3. Copyright 2005 by ACM.

Figure 5. Teacher behavior model in SimEd model. Adapted from "Multiagent Simulation of Learning Environments" by E. Sklar and M. Davies, July 2005, Proceedings of the Fourth International Joint Conference on Autonomous Agents and Multiagent Systems, p. 4. Copyright 2005 by ACM.

Figure 6.Student behavior model in SimEd model. Adapted from "Multiagent Simulation of Learning Environments" by E. Sklar and M. Davies, July 2005, Proceedings of the Fourth International Joint Conference on Autonomous Agents and Multiagent Systems, p. 5. Copyright 2005 by ACM.
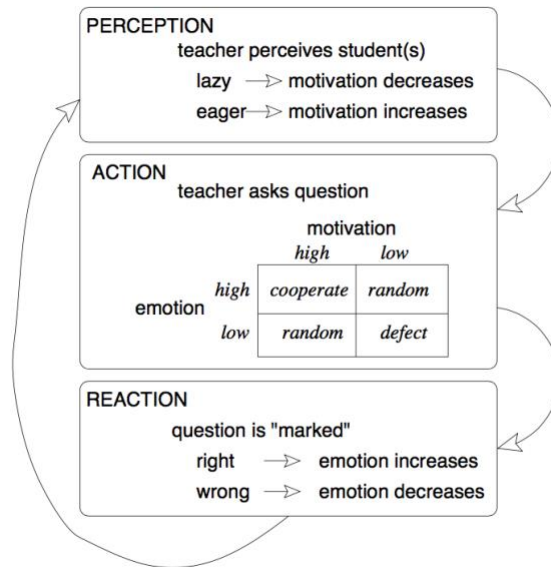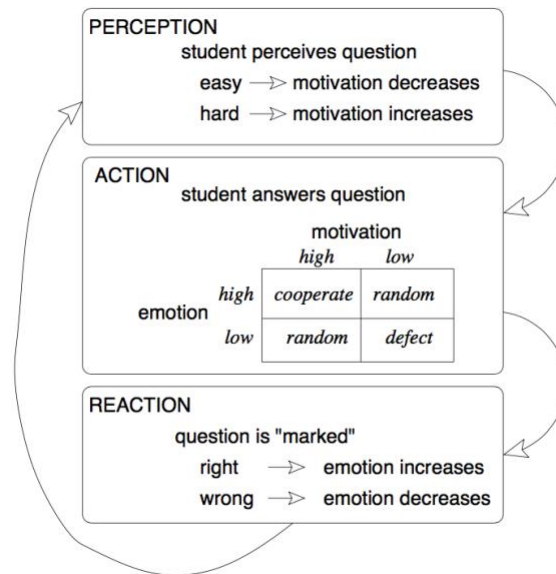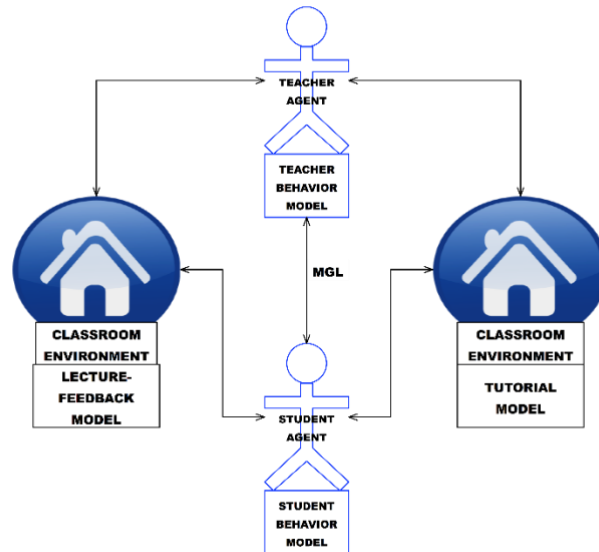
Figure 7. SimEd Simulation Summary. Adapted from "Multiagent Simulation of Learning Environments" by E. Sklar and M. Davies, July 2005, Proceedings of the Fourth International Joint Conference on Autonomous Agents and Multiagent Systems.

The SimEd Absenteeism Model further examines teacher & student interactions on the micro-level within the classroom setting and the outcomes of two different teaching methods with student absenteeism in the manner outlined in Figure 8 with the following research methods:

- The quantity of teachers and students is user-defined.
- The dialogic framework utilizes a model based upon the Game Theoretic Model, Iterative Prisoner's Dilemma, and the Meta-Game of Learning (MGL) seen in Table 2.
- Lessons are delivered to the students in a group lecture method or the individualized tutor teaching method.
- The progression rates of the lessons are compared for each lesson model.
- Ability, motivation, emotion, and belief sets are compared for each lesson model.

It was found that students in the group lecture setting progressions were not as proficient as those within the individualized tutoring sessions.

Figure 8. SimEd Absenteeism Simulation Summary. Adapted from "SimEd: Simulating Education as a Multi-Agent System" by E. Sklar, M. Davies, and M.S.T. Co, 2004, Proceedings of the Third International Joint Conference on Autonomous Agents and Multiagent Systems.
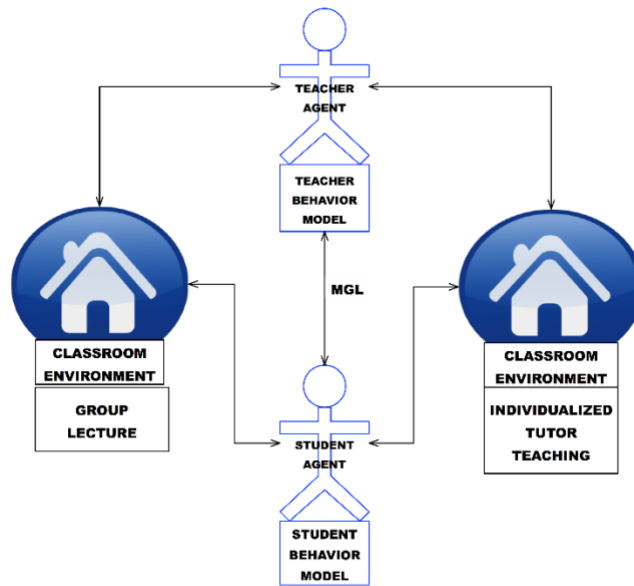

The SimEd "No Child Left Behind" Model inspects interactions amongst superintendents, principles, teachers, and students at an intermediate-level in the district, schoolhouse, and classroom, as are noted in Figure 4 and Figure 9 with the fundamental framework of SimEd seen in Figure 7. It examines transfer rates for the district and schoolhouse established by their decisions to designate students to classrooms based upon randomly assigned students and teachers with a uniform distribution or based upon the Student-Teacher Achievement Ratio (STAR) policy that designates lower student/teacher ratio, where it was found that the STAR policy resulted in fewer student transfers.

Figure 9. SimEd "No Child Left Behind" Act Simulation Summary. Adapted from "SimEd: Simulating Education as a Multi-Agent System" by E. Sklar, M. Davies, and M.S.T. Co, 2004, Proceedings of the Third International Joint Conference on Autonomous Agents and Multiagent Systems.
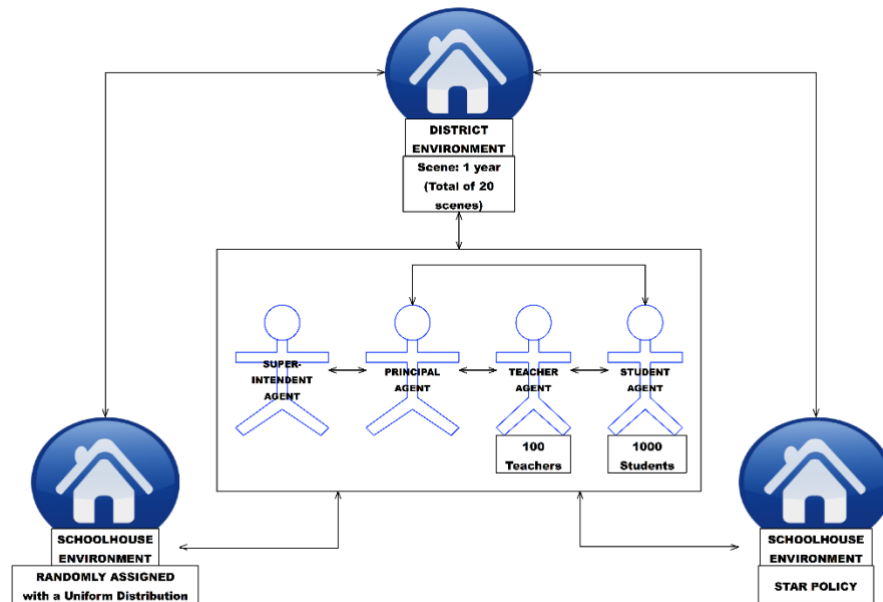

The School of Choice Model is aimed at determining if a student's ability to choose the school they attend will result in district-level achievement improvement while addressing issues of overpopulation at the schools of choice. This micro-level agent-based simulation is calibrated with data from Chicago Public schools and focuses on students as agents and schools as the environments, which revealed that student achievement rates are affected by the number of students that choose to participate in a lottery-based school of choice program. The students that participate in the school of choice program are compared to those that do not. The interactions between the students and the environment are outlined in Figure 10, and the model also includes variables that measure the better available capacity to aid in the study of the measure of an acceptable access capacity for the choosing students within the model.

Figure 10. School of Choice Model Summary. Adapted from "Interpreting School Choice Treatment Effects: Results and Implications from Computational Experiments" by S. Maroulis, 2016, Journal of Artificial Societies and Social Simulation, 19(1), p. 7-15
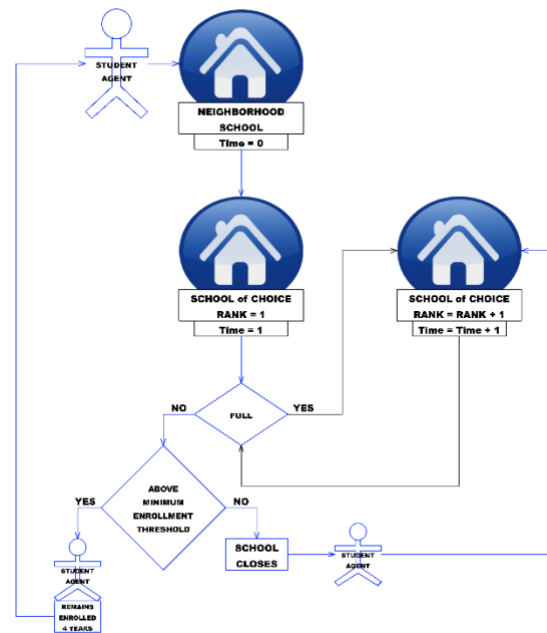
The School Effectiveness Model has the primary objective of comparing and contrasting multilevel modeling (MLM) to agent-based modeling (ABM) by simulating pupil performance based upon pupil peer groups and the self-fulfilling prophecy produced by teacher bias towards students and their peer groups as seen in Figure 11. Here, the mean value of the overall pupil performance is compared to that of other schools. In addition, "the model assumes that a combination of friendship dynamics based on homophily and self-fulfilling prophecy based on teacher expectations bias can produce differential achievement among students and schools" (Maroulis, 2016, p. 5). This model has an intermediate level examination that is collaborated with London education data where the simulation compares the mean of school performance within a district, and it ascertained that neither MLM nor ABM is a more superior modeling method because the MLM determines significant differences without an indication of causation, while ABM does provide notions of causation. The simulations indicate that peer groups do affect pupil performance as the teacher expectations are biased to these peer groups and thus influence positive or negative pupil outcomes based upon this bias.

Figure 11. School Effectiveness Model Summary. Adapted from "Analyzing Differential School Effectiveness Through Multilevel and Agent-Based Modeling," by M. Salgado, E. Marchione, and N. Gilbert (2014), Journal of Artificial Societies and Social Simulation, 17(4) 3, pp. 1-11.
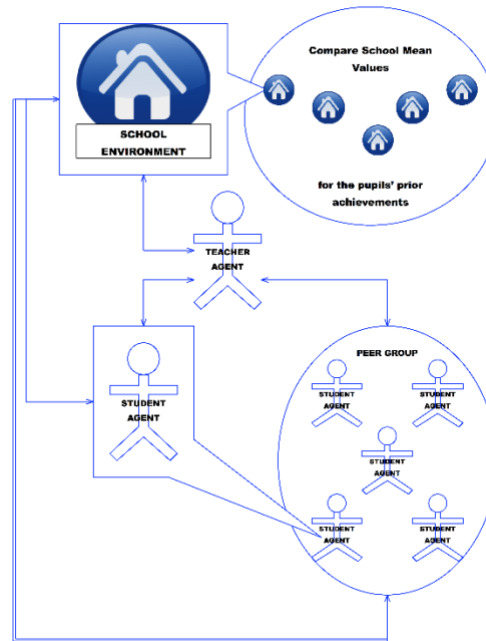
The Teacher/Student Match Same Race Effects Model explores the education gap created between white and black students with the premise that teachers that are of a different race than their students will create an achievement gap between students of a different race and students of their own race. The interactions between the teachers and students are outlined in Figure 12 with the following research methods:

- The student agents all have the same academic abilities, family resources, and quality of teachers.
- The model investigates the educational and psychological features of the same race teacher effect.
- One hundred simulations are executed.

This agent-based model is collaborated with NCES data and verified with NEAP data, which revealed that the education gap did exist amongst the black students with white teachers where it is reported that the black students are below average with a greater gap existing in the lower grade levels.

Figure 12. Teacher & Student Match Same Race Effects Model Summary. Adapted from "Using Artificial Societies to Understand the Impact of Teacher Student Match on Academic Performance: The Case of Same Race Effects" by G. Montes, 2016, Journal of Artificial Societies and Social Simulation 15(4) 8: pp. 1-9.
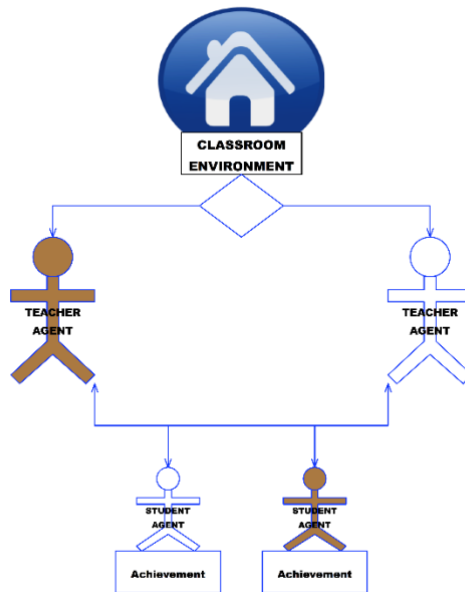
QUALITY ANALYSIS

The quality of the literature is assessed based upon the criteria detailed in the subsequent table. This ensures that the questions are objectively addressed in a systematic manner. The purpose of this study is to determine the optimal approach to utilize simulation and modeling to further STEM education research; therefore, it is necessary to critique the quality of the data surveyed regarding each model. It is of the utmost importance to present models that have been calibrated and verified by reliable sources as a means to substantiate the findings produced by the simulations. It is also of the highest priority that the models are presented in detail within the literature so that future researchers can replicate and expand these studies. Hence, this survey will critique the quality of the emergence of these

criterions based upon the factors seen in Appendix A as they are reported within the literature.

Table 3.

Evaluation Simulation Model	(1) Explanatory details of the framework/ structure of the model	(2) Calibration & Verification of the model	(3) Replicability	(4) Relevance to STEM Education Research	(5) Relevance and/or Application to STEM Teachers
BHEF U.S. STEM Education	Generalized	Conceptualized	Conceptualized	Detailed	Detailed
SimEd	Detailed	Conceptualized	Conceptualized	Conceptualized	Generalized
SimEd: Absenteeism	Detailed	Conceptualized	Conceptualized	Generalized	Conceptualized
SimEd: "No Child Left Behind" Act	Detailed	Conceptualized	Conceptualized	Conceptualized	Conceptualized
School of Choice	Detailed	Conceptualized	Conceptualized	Conceptualized	Conceptualized
School Effectiveness	Detailed	Detailed	Detailed	Conceptualized	Conceptualized
Teacher / Student Match Same Race Effects	Detailed	Detailed	Detailed	Detailed	Detailed

ASSESSMENT & EVALUATION

A comprehensive exploration in the findings of each model can be seen in Appendix D. The manner in which each model is collaborated and verified along with the sample populations can be seen in Appendix C. The data in these appendices and the subsequent model and simulation assessments yield the Evaluation of the survey compiled in **Error! Reference source not found.**.

RESULTS

In general, simulation modeling may be suitable and valuable to teachers, schools, school districts, and other relevant personnel as a tool to increase the number of students that pursue STEM majors and obtain STEM degrees, especially those belonging to demographic populations that are traditionally underrepresented in STEM fields. Simulation models are useful for educational policy changes as they model the effects of current and new educational policies without the cost, time, and human subjects disadvantages that are associated with more traditional educational longitudinal studies. The following are the results of this literature review of education simulations that are applicable to STEM education.

Questions 1: How are Existing STEM Education Simulation Models Structured?

There is only one model, the BHEF U.S. STEM Education Model, that is directly related to STEM education research. This model is structured as a systems dynamics model. It monitors students as they progress from elementary school to their career fields. In this model, students that are proficient in mathematics are deemed STEM proficient. In addition, secondary students can follow one of four branches: STEM proficient and STEM interest, STEM proficient and without STEM interest, not STEM proficient, and not STEM proficient and without STEM interest. In this model, only the students on the proficient with STEM interest move on to choose a STEM major at a post-secondary institution, followed by pathways that model attrition rates. If the student remains on the STEM path, their career paths are STEM teaching, STEM industry, or non-STEM related before reaching retirement.

The structure of existing STEM education simulation models is relevant to teachers, administrators, and other interested parties, as it provides a research-based

infrastructural system of education that can be explored and expanded to meet the individual needs of various environments, such as classrooms, schools, and districts. The current research indicates that mathematics proficiency and STEM interest have a strong bearing upon the pursuit of a STEM career. Educators and researchers interested in moderators such as gender, race/ethnicity, socioeconomic status, etc. can expand this open-source model to determine how these factors affect STEM interest and mathematics proficiency to potentially develop interventional strategies for improvement.

Questions 2: How are Existing Education Simulation Models Applicable to STEM Education Research?

All of the other models incorporate topics that can be precisely mapped to an area of concern noted by the previously mentioned national organizations charged with improving U.S. STEM education, which can be seen in **Error! Reference source not found.**: Column (4). This mapping to STEM topics can be seen in Figure 2. Again, the BHEF U.S. STEM Education model directly pertains to STEM education research , as stated above.

The SimEd model addresses pedagogies that are applicable to STEM education research. National education agencies have repeatedly reported that the manner in which students are educated has a strong bearing upon proficiencies and student interest in potential fields of STEM studies (NRC, 2011). The SimEd model provides the framework for simulating the effectiveness of pedagogical policies that are in place to minimize achievement gaps between students of varying demographics, which is cited by the NSF (n.d.a.) and the NRC (2011) as being a key factor to increase STEM majors within the United States. Simulation provides a swifter exploration of the effectiveness of new policies, which may prove to be of interest to educators and researchers implementing policy changes to increase STEM proficiencies and interests amongst students that are underrepresented in STEM fields.

The School Effectiveness model and the Teacher/Student Match-Same Race Effects model both address student achievement. These models continue the discussion of the achievement gaps that exist amongst underrepresented populations. These models may be of interest to educators and researchers as the output of STEM majors in effective STEM-focused schools has been explored by the NRC (2011). The School Effectiveness model demonstrates how these factors can be simulated and explored; therefore, the foundational structure of this model can be tailored to examine the potential results of institutional changes directly targeted towards school effectiveness in mathematics and other STEM areas of

study. In addition, the Teacher/Student Match-Same Race Effects model serves as an interest to educators and researchers as a means of professional development. This model demonstrates how social and psychological constructs have an effect on the achievement gaps in educational systems.

Finally, as stated by the NRC (2011), effective STEM Schools of Choice are often waitlisted for student enrollment. The School of Choice model will serve as an interest to educators and researchers in exploring potential polices as solutions to issues of educational access in STEM. This simulation allows for an expeditious exploration of different factors that affect access to high performing STEM schools and the retention of students within these STEM schools of choice. Again, because it is a simulation, it can be adapted to meet the unique needs of differing school districts and include factors and variables that are necessary for customization towards STEM education.

Question 3: How can Existing Education Simulation Models be Applied to Teachers Implementing STEM Education?

As seen in **Error! Reference source not found.**: Column (5) and Figure 2, all of the models tend to exhibit some relationship to applications that are relative to the teaching aspect of STEM education research. With the exception of the BHEF U.S. STEM Education Model and the School of Choice Model, the structure of the models included student and teacher agents that interact with each other. This indicates that regardless of the environment and education policies being researched, the teacher-student interaction is pivotal to improvements in student achievement and outcomes in STEM Education. It naturally follows that STEM capable teachers will increase the output of STEM capable students, which supports the research findings within the BHEF U.S. STEM Education Model. This should prove to be useful to teachers interested in increasing STEM majors and can be expanded to target students within demographical categories that are underrepresented in STEM majors.

Question 4: How is the ABMS Architecture Applied to Education Simulations?

As seen in Appendix B, the majority of the simulations are structured to utilize ABMS architecture at the micro or intermediate research level, while those that are not, are structured in a manner that can be easily incorporated into this paradigm. The commonalities amongst the majority of the structures include a classroom environment, student & teacher agents, and behavior models that are calibrated and verified with national datasets to ensure the validity of the causal results that may be produced by the simulation. As seen in some models within this study, this

structure can be expanded to include schools and districts with the necessary agents for these respective environments to address macro-level policy interests.

Collectively, these results confirm that ABMS is a useful tool to address STEM education research and the teaching factors associated with this research. Most of the models can be improved by expanding the reported details regarding the calibration & verification of the model. This will increase the ability of future researchers to replicate the findings and expand upon the model simulations.

DISCUSSION

The previously discussed models and simulations have expressed that it is feasible and beneficial to utilize these methods to explore education research topics. Furthermore, the BHEF U.S. STEM Education Model demonstrates that it is a reasonable expectation to apply these methodologies to simulate STEM education inquiries. Hence, it is judicious to adapt existing education models to meet the need of STEM education research efforts for future endeavors.

FUTURE DIRECTIONS FOR ABMS AND STEM EDUCATION RESEARCH

This research takes a qualitative approach to the exploration of several educational models that are applicable to factors that affect STEM education. Future studies should include a quantitative analysis of these models as various modeling and simulation paradigms are defined and illustrated with numerous mathematical models framed from a diverse assortment of quantitative datasets. In the majority of the models surveyed, agent-based modeling and simulation is a recurring theme. This emergent premise deems to be appropriate as ABMS has the capabilities to not only simulate and produce experimental results, but also offers insights into causation (Montes 2012). Moreover, Izquierdo, Olaru, Izquierdo, Purchase, & Soutar (2015) presents methods and examples of a means to utilize fuzzy logic to represent emotions and social dilemmas via NetLogo entailing the use of a fuzzy logic extension for the software package, while Kahl & Hansen (2015) communicates the ability to model and simulate the psychological construct of creativity in NetLogo. The foundation presented in these models and simulation, in conjunction with the groundwork and theories provided in the education models and simulation that is detailed in this paper, attests to the potentials of the ABMS paradigm in STEM education research.

It is illustrated that the factors that are of interest to broaden and improve upon STEM education through literacy and proficiency can be modeled in an agent-based system. Bell (2016) explores the theory that the shortage of persons entering STEM careers can be addressed through "well-motivated, highly qualified STEM teachers" (p. 63). Many highly qualified STEM teachers choose to leave the profession (NGA Center for Best Practices 2001); therefore, we must research incentives and motivation to retain these teachers. We perceive that motivation is related to emotional and psychological influences. Kilday, Lenser, & Miller (2016) detect the effects of the emotional and psychological states of teachers on student success in STEM programs. Proper teacher training, self-efficacy, and self-fulfilling prophecy are two factors of exploration in this case (Salgado, Marchione, & Gilbert 2014; Stohlmann, More, & Roehrig 2012), as these aspects are significant to successful STEM education.

Similar motivational factors have a detrimental role in student retention and success in STEM education. Capable students must remain motivated for retention, and those that are below average academically must be given support to be competitive. Again, this relates to emotional and psychological influences that pertain to the student (Kilday, Lenser, & Miller, 2016; Stohlmann, More, & Roehrig, 2012; NGA Center for Best Practices, 2011; NRC, 2011). These emotional and psychological states can be incorporated into agent-based models with the more traditional existing data, such as classroom size, student resources, demographical data, economic data, and assessment data to build a model that simulates various interventions to offer insight into studies of causation.

LIMITATIONS OF MODELING AND SIMULATION IN STEM EDUCATION

The limitations of modeling and simulation lie in the ability to validate the results. Existing datasets may be employed for verification, which may produce an accurate model. There may be circumstances that result in unique models that cannot be validated, as the dataset simply may not exist. In this case, the results of the simulation are merely a hypothesis of what may transpire in real-life. A conceivable solution to this limitation is the validation of the model by an expert panel of STEM educators. Further resolution may be achieved by collaborating the model with subsets of available education data sources. Modeling and simulation do provide an efficient alternative to longitudinal studies, but the most comprehensive conclusions would arrive from a simulation utilized in conjunction with data from experimental, quantitative, and qualitative research.

CONCLUSION

Organizations such as the U.S. Department of Education, National Science Foundation, National Governors Association Center for Best Practices, and the National Research Council have funded research and developed standards for STEM education. These research efforts have resulted in common core focuses such as the Next Generation Science Standards (NGSS) that are directly related to grade-level standards in STEM education (NGSS, 2013). In addition to the NGSS recommendations, the National Governors Association Center for Best Practices, and the National Research Council provide a multitude of STEM education data and variables for future study within their publications (NGA Center for Best Practices, 2011; NRC, 2011; NGSS, 2013). Modeling and simulation are suitable to examine the quantitative variables. A paradigm, such as ABMS, renders feasibility to also incorporate these qualitative variables into simulations. These models and simulations are further enhanced with the ABMS strengths to examine causation revolutionizing the possibilities of STEM education research.

REFERENCES

Bell D (2016). The reality of STEM education, design and technology teachers' perceptions: a phenomenographic study. International Journal of Technology and Design Education 26: 61-79. doi: 10.1007/s10798-015-9300-9

Borshchev A & Filippov A (2004). From system dynamics and discrete event to practical agent based modeling: reasons, techniques, and tools. In J. Coyle (Chair) The 22nd International Conference of the System Dynamics Society, Oxford, England. Retrieved from http://web.ics.purdue.edu/~hwan/IE680/Final%20Presentation/Po-CHing/From%20SD%20and%20DE%20to%20Practical%20Agent%20Based%20Modeling%20Reasons%20Techniques%20Tools%2004.pdf

Business-Higher Education Forum (BHEF) (2010). Increasing the number or STEM graduates: Insights from the U.S. STEM Education & Modeling Project (BHEF Publication). Retrieved from http://www.bhef.com/sites/default/files/BHEF_2010_increasing_the_number_of_stem_grads.pdf

Common Core State Standards Initiative (CCSSI) (2017). Development Process. Retrieved from http://www.corestandards.org/about-the-standards/development-process/

Csala D (2012). SD vs. ABM: ESM504 – System Dynamics for Business Policy [Slides PDF document]. Retrieved from http://www.academia.edu/3105560/Agent-Based_Modeling_vs._System_Dynamics

Izquierdo L R, Olaru D, Izquierdo S S, Purchase S & Soutar G N (2015). Fuzzy logic for social simulation using NetLogo. Journal of Artificial Societies and Social Simulation 18(4), 1-24. doi: 10.18564/jasss.2885

Kahl C H & Hansen H (2015). Simulating creativity from a systems perspective: CRESY. Journal of Artificial Societies and Social Simulation, 18(1) 4, 1-22. Retrieved from http://jasss.soc.surrey.ac.uk/18/1/4.html

Kilday J E, Lenser M L & Miller A D (2016). Considering students in teachers' self-efficacy: examination of a scale for student-oriented teaching. Teaching and Teacher Education 56, 61-71. doi: 10.1016/tate.2016.01.025

Macal C M & North M J (2010). Tutorial on agent-based modeling and simulation. Journal of Simulation 4, 151-162. doi: 10.1057/jos.2010.3

Maroulis S (2016). Interpreting school choice treatment effects: results and implications from computational experiments. Journal of Artificial Societies and Social Simulation, 19(1), 7-15. doi: 10.18564/jasss.3002

MIT SDEP (1997). System Dynamics. Retrieved from http://web.mit.edu/sysdyn/sd-intro/

Montes, G. (2012). Using artificial societies to understand the impact of teacher student match in academic performance: the case of same race effects. Journal of Artificial Societies and Social Simulation 15(4) 8: 1-9. Retrieved from http://jasss.soc.surrey.ac.uk/15/4/8.html

National Governors Association (NGA) Center for Best Practices (2011). Building a science, technology, engineering, and math education agenda: an update of state actions. Washington, DC: NGA. Retrieved from http://www.nga.org/files/live/sites/NGA/files/pdf/1112STEMGUIDE.PDF

National Research Council (NRC) (2012). A framework for K-12 science education: practices, crosscutting concepts, and core ideas. Committee on a Conceptual Framework for New K-12 Science Education Standards Board on Science Education, Division of Behavioral and Social Sciences Education. Washington, D.C. The National Academics Press. Retrieved from https://www.nap.edu/download/13165

National Research Council (NRC) (2011). Successful K-12 STEM education: identifying effective approaches in science, technology, engineering, and mathematics. Committee on Highly Successful Science Programs for K-12 Science Education Board on Science Education and Board on Testing and Assessment, Division of Behavioral and Social Sciences Education. Washington, D.C. The National Academics Press. Retrieved from http://www.stemreports.com/wp-content/uploads/2011/06/NRC_STEM_2.pdf

National Science Foundation (NSF) (n.d. a). About the National Science Foundation. Retrieved from https://www.nsf.gov/about/

National Science Foundation (NSF) (n.d. b). Improving Undergraduate STEM Education. Retrieved from https://www.nsf.gov/funding/pgm_summ.jsp?pims_id=504976

Next Generation Science Standards (NGSS) (2013). The next generation science standards executive summary (NGSS Release). Retrieved from http://www.nextgenscience.org/sites/default/files/Final%20Release%20NGSS%20Front%20Matter%20-%206.17.13%20Update_0.pdf

Salgado M, Marchione E & Gilbert N (2014). Analyzing differential school effectiveness through multilevel and agent-based modeling. Journal of Artificial Societies and Social Simulation. 17(4) 3: 1-11. Retrieved from http://jasss.soc.surrey.ac.uk/17/4/3.html

Sklar E & Davies M (2005). Multiagent simulation of learning environments. In M. Pechoucek, D. Steiner, & S. Thompson (Chairs), Proceedings of the fourth international joint conference on Autonomous agents and multiagent systems, Utrecht, Netherlands. Retrieved from http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.86.3351&rep=rep1&type=pdf

Sklar E, Davies M & Co M S T (2004). SimEd: Simulating education as a multi agent system. In N. Jennings & M. Tambe (Chairs), Proceedings of the third international joint conference on Autonomous agents and multiagent systems, New York City, New York, USA. Retrieved from http://ieeexplore.ieee.org/document/1373619/

Stohlmann M, Moore T J & Roehrig G H (2012). Considerations for teaching integrated STEM education. Journal of Pre-College Engineering Education Research, 2(1), 28-34. doi: 10.5703/1288284314653

U.S. Department of Education (n.d.). Science, technology, engineering and math: education for global leadership. Retrieved from http://www.ed.gov/stem

APPENDIX A

Assessment Criteria	Evaluation		
	Detailed	Conceptualized	Generalized
(1) Explanatory details of the framework/structure of the model	The details of the model and each component has been presented and explained in detail.	The details of the model and each component have been presented and abstractedly explained.	A general overview of the model has been presented.
(2) Calibration & Verification of the model	The datasets utilized to calibrate and verify the model have been provided inclusive of the respective population & sample associated with the datasets.	The datasets utilized to calibrate and verify the model have been provided without the population & sample or The model has been calibrated and verified by an unspecified expert.	The author had not delineated the datasets nor the population & sample.
(3) Replicability	Model specifications are fully presented in a manner in which the study can be replicated.	Model specifications are abstractedly presented, but the study can be replicated with technical research.	The model has been generally specified and cannot be replicated without contacting the authors for further details.
(4) Relevance to STEM Education Research	The objectives of the model are directly related to a STEM topic.	The objectives of the model are directly related to an education topic that is an area of concern in STEM education research.	The objectives of the model are related to an education topic, but are not applicable to STEM education research.

(5) Relevance and/or Application to STEM Teachers	The objectives and findings of the model can be correlated to STEM teachers or pedagogy.	The objectives and findings of the model are indirectly related to STEM teachers or pedagogy.	The objectives of the model are not related to STEM teachers or pedagogy.

APPENDIX B

Simulation Overview					
Simulation Model	Paradigm	Simulation Level	Agents	Environment	Software
BHEF U.S. STEM Education	System Dynamics Modeling	Macro	Students	• Elementary • Secondary • College • Career	Vensim
SimEd	Multi Agent System	Micro	• Students • Teachers	Classroom	• Repast • Netlogo
SimEd: Absenteeism	Multi Agent System	Micro	• Students • Teachers	Classroom	• Repast • Netlogo
SimEd: "No Child Left Behind" Act	Multi Agent System	Intermediate	• Students • Teachers • Principals • Superintendents	• Schoolhouse • District	• Repast • Netlogo
School of Choice	Agent-based Modeling & Simulation	Micro	Students	• Neighborhood School • School of Choice	Netlogo
School Effectiveness	• Agent-based modeling &	Intermediate	• Students • Teachers • Peer Group	Schoolhouse	Netlogo (A modification to the

	simulation (ABMS) • Multilevel modeling (MLM)				Party Model included in the software package)
Teacher / Student Match Same Race Effects	Agent-based simulation model (ABMS)	Micro	• African American/Black Students • White Students • African American/Black Teachers • White Teachers	Classroom	Netlogo

APPENDIX C

Simulation Data Summary		
Simulation Model	Population & Sample	Calibration & Verification
BHEF U.S. STEM Education	• U.S. Citizens • Permanent U.S. Residents	• Education experts • National education data • National Labor data • U.S. Census data • Conducted reviews of educational research • The model verification was not delineated.
SimEd	Not delineated.	Conversations and observations with affiliates in professional teaching within multiple grades
SimEd: Absenteeism	Not delineated.	Conversations and observations with affiliates in professional teaching within multiple grades
SimEd: "No Child Left Behind" Act	Not delineated.	Conversations and observations with affiliates in professional teaching within multiple grades
School of Choice	Not delineated.	Chicago Public Schools
School Effectiveness	• 48 schools are sampled from the dataset • 878/2000 students are sampled from the data set	A subset of "The London Education Authority's Junior School Project Data for pupils' mathematics progress over 3 years from entry to junior school to the end of the third year in junior school (Nuttall et al. 1989)" (Salgado, Marchione, & Gilbert 2014, p. 3) [SEP]

Teacher / Student Match Same Race Effects	• 800 students (122 black) • 50 teachers (4 black)	• The model is simplified and calibrated with the Condition of Education 2009 dataset (National Center of Education statistics of U.S. Department of Education) • The model is verified with the National Assessment of Education Progress (NAEP) long-term study dataset.

APPENDIX D

Detailed Simulation Findings Simulation Model	
BHEF U.S. STEM Education	• Bridge & cohort programs result in the retention of STEM college majors beyond the Freshman year • STEM capable teachers result in an increased math proficiency and STEM interests in students • Target middle school students with high math proficiency to increase STEM interests and STEM college majors • Apply the above recommendations in a joint effort to better approach the BHEF goal of doubling the number STEM graduates that enter into the STEM industry
SimEd	• Classes with a low standard deviation progressed more than a class with a higher standard deviation. • The lecture feedback model had a lower progression than the tutorial model. • Motivation and emotion levels are lower in the lecture feedback model than in the tutorial model.

SimEd: Absenteeism	• The group lecture method
	   o An average progression rate of 44.57%
	   o With 17% absenteeism, an average progression rate of 37.96%
	• The individualized tutor teaching method
	   o An average progression rate of 84.01%
	• With 17% absenteeism, an average progression rate of 79.45%

SimEd: "No Child Left Behind" Act	• The first simulation employing the model with randomly assigned students and teachers utilizing a uniform distribution o Transfer rate transpired on a regular bases

	o 90% of students never transferred • The second tutor simulation employing the STAR policy with a mixture of low and high student-teacher ratios in schools within the district o Transfer rate transpired less than the random uniform distribution o 97% of students never transferred
School of Choice	• "Experimentation with the model reveals that as the student participation rate rises, the magnitude of the treatment effect falls, even when there are no differences in distribution of school quality and student preferences across districts" (Maroulis 2016, p.2) • Achievement increases as "students favored achievement relative to geographic proximity [and]… the greater fraction of students who participated in the program" (Maroulis 2016, p.4). • The "mean achievement of choosers in comparison must necessarily decrease as more students take advantage of the opportunity to choose (Maroulis 2016, p. 5). This is further affected by better availability of capacity, where it increases the gap between the choosers and non-choosers.
School Effectiveness	• The MLM model is fairly accurate in determining significant differences, but it did not indicate any causes such as peer groups, socio-economic status, and teacher effects. The ABM model is able to address some of these issues. • The experimentation demonstrated that peer groups do create a difference in achievement in students. • The MLM performs better, but the results are not as complete as the ABM. It is suggested that a more detailed ABM could be built to counteract this affect, although the ABM is found to be sufficient as is. • The MLM and the ABM compliment each other. It is perceived that the best results are from the use of the MLM and ABMS models together, as the MLM is data driven and the ABMS is both data and theory driven (Salgado, Marchione, & Gilbert 2014). • Neither model is superior to the other, but when utilized together, one will get a more broad idea of the research topic at hand, while the other better demonstrates causation.
Teacher / Student Match Same Race Effects	• The achievement gap exists • Black students were below the average • White students were above the average • Larger gaps exist in the earlier grade levels

APPENDIX E. SYSTEMATIC REVIEW METHODS & STRATEGIES

Literature Research Sources

Databases
- Elsevier
- ERIC
- Esearch
- Google Scholar
- ProQuest
- Sage
- Web of Science

Journals
- Journal for Artificial Societies and Social Simulation (JASSS)
- Journal of Simulation (JOS)
- Journal of Science Education Technology (JSET)

Search Engines
- Google

Inclusion Criteria

- Contains a simulation model
- The model simulated education or a STEM factor (see Table 1 & **Error! Reference source not found.**) as system
- The education aspect of the simulations shows an interaction between, teacher, student, school, and/or district environments and agents
- Addresses one or more questions (directly or indirectly)

Exclusion Criteria

- The simulation did not relate to at least one of the factors addressing STEM education listed in Table 1 (See Figure 13 for STEM education mappings)
- The literature did not outline the framework and methodology for the simulation

Search Keywords, Filters, and Strategies

Table 4 outlines the strategies utilized to develop the collection of journals that were hand-searched for prospective articles. Table 5 identifies the filters and the results for the databases, journals, and search engines outlined above.

Table 3. Search Filter for Journals Addressing STEM & Education

A.   Filter for a STEM Education Simulation
Keyword Search in Web of Science: (agent-based modeling AND science technology engineering and mathematics education) Selection Criteria: lists articles related to simulating and educational systems returned in the search
Relevant Results: • Journal of Science Education Technology
Keyword Search in Google: (social simulation and education journal -"gaming") Selection Criteria: lists journals specialized in simulation within the first 10 results of the search and includes educational systems within the published articles

Relevant Results:
    • Journal for Artificial Societies and Social Simulation (JASSS)
    • Journal of Simulation (JOS)

Table 4. Search Filter for Systematic Review Articles

A. Filter for a STEM Education Simulation Model	
Filter: ("STEM" OR "S.T.E.M" OR "Science Technology Engineering Mathematics" OR "Science Technology Engineering and Mathematics") AND ("Simulation" OR "Computer Simulation" OR "Agent-based Simulation") AND ("Modeling" OR "Model") AND "Education"	
Database Results:	
Elsevier	No relevant results
Esearch	No relevant results
ERIC	No relevant results
Google Scholar	No relevant results
Google Search Engine	The BHEF U.S. STEM Education Model
ProQuest	No relevant results
Sage	No relevant results
Web of Science	No relevant results
Journal Results:	
JASSS	No relevant results
JOS	No relevant results

JSET	No relevant results

B. Filter for an Education Simulation Model	
Filter: ("Simulation" OR "Computer Simulation" OR "Agent-based Simulation") AND ("Modeling" OR "Model") AND "Education"	
Database Results:	
Elsevier	No relevant results
Esearch	No relevant results
ERIC	No relevant results
Google Scholar	No relevant results
Google Search Engine	The BHEF U.S. STEM Education Model
ProQuest	No relevant results
Sage	No relevant results
Web of Science	No relevant results
Journal Results:	
JASSS	No relevant results
JOS	No relevant results
JSET	No relevant results

C. Filter for a Simulating Education Model	
Filter: "Simulating Education"	
Database Results:	
Elsevier	No relevant results
Esearch	No relevant results
ERIC	No relevant results
Google Scholar	• SimEd: Simulating Education as a Multi Agent System • Multiagent Simulation of Learning Environments
Google Search Engine	• SimEd: Simulating Education as a Multi Agent System • Multiagent Simulation of Learning Environments
ProQuest	No relevant results
Sage	No relevant results
Web of Science	No relevant results
Journal Results:	
JASSS	No relevant results
JOS	No relevant results
JSET	No relevant results

D. Filter for a Simulating Education Model within the Journals outlined in Table 3 ONLY	
Filter: "school" Selection Criteria: Related to a school factor that effects STEM education (NGA, 2011; NRC, 2011; NRC, 2012). See Figure 14.	
JASSS	• Interpreting School of Choice Treatment Effects • Analysing Differential School Effectiveness Through Multilevel Agent-based Modelling
JOS	No relevant results
JSET	No relevant results
Filter: "teaching" Selection Criteria: Related to a school factor that effects STEM education (NGA, 2011; NRC, 2011; NRC, 2012). See Figure 15.	
JASSS	• Using Artificial Societies to Understand the Impact of Teacher Student Match on Academic Performance: The Case of Same Race Effects
JOS	No relevant results
JSET	No relevant results (with neither the Filter: "teaching", nor the Filter: "teaching" AND "simulation")

The preponderance of the results from the above-mentioned searches were not relevant as they discussed the utilization of simulation for educational topics within a multitude of STEM and non-STEM disciplines but did not simulate STEM education, education, or related processes as a system itself. Therefore, it can be determined that based upon the methodologies, filters, and strategies outlined in Appendix E and the Methodology section of this study, that the literature reviewed is exhaustive as it relates to the questions and topics within this work.