Active Game-based Learning of Dynamics Modeling and Simulation in Biomedical Systems Engineering

Abstract

With promotion of systems modeling and simulation in the healthcare industry, courses have been created in many undergraduate biomedical engineering curricula to address the need. However, it is challenging to teach systems modeling and simulation, which demands effective teaching tools in these courses. To answer the call, I've used serious games in my teaching in the past few years. In this paper, I first present two interesting educational games and describe the design and implementation of two game-based active learning modules. I also report several learning outcome assessments with different assessment tools, and review my self-reflection during the teaching. Better game design and development of more objective learning assessment are included in the future plan.

Keywords: game-based learning, educational game, teaching modeling, teaching simulation, system dynamics

1. Introduction

Modeling and simulation of complex dynamical systems (e.g., high dimensional, nonlinear and stochastic) is an important technical skill for engineers (Sterman 2002; Hmelo-Silver and Azevedo, 2006; Warwick 2007). However, it is challenging to teach it in conventional classrooms (Hmelo et al., 2000; Jacobson and Wilensky, 2006) due to the following reasons. First, conventional classroom teaching of systems dynamics theory in engineering schools is confined to ordinary differential equation (ODE) based modeling of low-dimensional systems and steady-state analysis of linear systems. However, most biomedical systems are high-dimensional, and highly nonlinear, stochastic, as well as more meaningful to analyze transient states. Second, most biomedical engineering students do not have strong desire or necessary prerequisite to learn the subject of systems dynamics theory rigorously. Lastly, students are often given directly the mathematical equations governed by physical or chemical laws. Hence, they do not necessarily understand how to develop dynamical system models and simulations with a more data-driven (or say semi-mechanistic) approach, which has become increasingly important in the big-data era. In response to these challenges, I introduced two game-based instruction modules to the course "Mathematical Modeling of Complex Biological, Medical, and Healthcare Systems," offered to mostly junior and senior students in the Weldon School of Biomedical Engineering at Purdue University. In this paper, I introduce two educational games that have been implemented tested in real classroom teaching. I also describe my initial implementation of the active learning modules and report preliminary assessments on the active learning outcomes.

Educational games are serious games explicitly designed with educational purposes. Well-designed educational games have long been known to resemble the real-world situations and stimulate students' learning so that the learning can be more enjoyable and learning outcomes can be improved (Van Eck, 2006). Meanwhile, the build-in learning process of games is what makes the games more enjoyable (Bainbridge, 2007). The game-based learning provides an "anchored" experience during the gameplays that multiple students or even the entire class shares with each other (Cognition and Technology Group at Vanderbilt, 1992).

In my class, I designed two educational games that closely resemble complex forms of competition between different types of agents/species/cohorts. Both games required students to actively participate as decision makers. In addition, I designed two active-learning instruction modules accordingly that utilize the two games to teach students how to model and analyze complex systems. For the implementation, I tailored the modules to be well suited to the general population of biomedical engineering junior/senior students. As a result, the active learning experience offered an excellent context for students to make immediate association from the enjoyable gameplays to modeling and simulation of complex systems dynamics. Moreover, the modules have some emphasis on operational-level decision making and its consequences. Hence, they can easily be adapted as stand-alone pieces to other systems biology and healthcare systems engineering courses, potentially through a massive online open course (MOOC) platform.

In a standard biomedical engineering curriculum, the aforementioned challenges are currently somewhat addressed in a few graduate-level courses for students who have chosen to conduct research in the area of systems science and engineering and for students who have taken sufficient mathematical prerequisites. Acknowledging the importance of systems modeling and simulation in the field of biomedicine, many biological and biomedical engineering departments have offered a technical elective course on the subject. However, these courses tend to focus on specific aspects of biomedicine and biomedical systems at a specific scale, e.g., quantitative biology or physiology. Recognizing the need of teaching the general principles and techniques of systems modeling and simulation, I undertook a series of changes since 2011 for the systems dynamics course taught in the Weldon School of Biomedical Engineering at Purdue University. With these changes, I have included more general treatment of systems modeling and simulation for disease natural history and medical intervention, both at the individual and population levels. Specifically in terms of systems modeling approaches, I include teachings on simple stochastic processes (e.g. Markov chains, birth-and-death processes, etc.), individual-based state transition modeling, and cellular automation. In addition, I introduce model-based optimization for public health policy and management with focus on recent hot topics in INFORMS such as cancer screening and infectious disease vaccination. As mentioned earlier, challenges arise when teaching these subjects. Therefore, there is a need to offer active learning to biomedical engineering majored students.

The two "playful" educational games introduced are "Humans vs. Zombies in the Avatar World" and "POX: Saving the People". The first game, which is a web-based Flash game, was inspired by the live-action game predominantly played at U.S. college campus and is believed to be analogous to cancer invasion with the evolutionary game theoretic perspective (Gatenby and Gawlinski, 2003). The second game is a board game with the aim of stopping disease spread through established herd immunity (Keeling and Rohani, 2008). The gameplay dynamics well resembles the intricate dynamics in a real-world public health system after a disease outbreak. In both games, students are required to actively participate as decision makers and the impact of their decisions on system behaviors can be immediately assessed by some algorithm intrinsic to each game. I associated the gameplay with thought-provoking questions prior to and after the gameplay to enhance the active learning experience. I ran these game-based learning modules in my class from fall 2011 to fall 2013. When I taught this course again in fall 2015, I did not run the learning modules intentionally, which resulted in having the students enrolled in the control group for outcome comparison.

The remainder of the paper is organized as follows. In Section 2, I introduce the backgrounds on game-based learning, my nonlinear system dynamics course, and the biomedical engineering undergraduate curriculum with focus on systems science and engineering. I also introduce the origins of the two games. In Section 3, I discuss the adaptation of the games and the associated game-based learning modules. In Section 4, I report a few preliminary learning outcome assessments and provide my reflection on the module design and implementation. In Section 5, I draw conclusions and outline a plan of further improvement.

2. Background

Game-based Learning

Serious games have long been employed as a means of education (Kahne, 2014). These games are designed to balance subject matter with game play so as to enhance players' ability to apply the subject matter to real-world practice. They are used to inspire motivation through active learning, which includes constant interaction during the gameplay and prompt feedback to the game players. Moreover, serious games encourage teamwork, and provide a flexible and safe virtual environment for skill enhancement (Pivec 2009). Most of these games substantiate problem solving scenarios that spark creatively (Shearer, 2013; Liu et al., 2011).

Game-based learning is a type of game play with defined learning outcomes. It is an increasingly universal character throughout college and continuing education (The New Media Consortium, 2009). It is an expansive category, ranging from simple paper-and-pencil games like word searches all the way up to complex, massively multiplayer online, and role-playing games (The New Media Consortium, 2010). The success of game-based learning lies in active participation and interaction is at the center of the learning experience. To some extent, this success reflects that current learning methods are not engaging students enough (Green and Bavelier, 2012).

There are three main approaches to creating games that simulates learning are: integrate existing games; building games from scratch by the instructor; and creating games from scratch by the students. The most time- and cost-effective approach in the design is to incorporate existing games into the classroom with understanding of the learning outcomes that the instructor has for the course (Van Eck, 2006). In my class, I used one existing game and adapted another existing game. Both games involve role plays, which allow students to apply acquired knowledge to construct their decisions, experiment their decisions in the virtual game environment, and receive prompt feedback in the form of quantifiable consequences or rewards.

The Standard “Systems Science and Engineering” Curriculum in BME

To BME students under a standard undergraduate curriculum, they obtain basic understanding of systems from a Signals and Systems course in their junior year typically offered by the electrical (and computer) engineering department. This course focuses on continuous-time linear systems and introduces selected system design examples in telecommunication. Nevertheless, it does not give students much exposure to nonlinear systems of multiple dimensions and dynamics in these nonlinear systems. Furthermore, the course does not include any teaching on how systems science can be applied to studying biomedical systems. As for the mathematical foundation, BME undergraduate students take a course on ordinary differential equations in their freshman or sophomore year. Further, they in that course focus solely on analytically derive the solution $x(t)$ to 1 or 2-degree ODEs with routine procedures. When the students advance to junior or senior year, it is difficult for them to see the connection between that course and any course dealing with dynamical systems.

A System Dynamics Course

The course “Mathematical Modeling of Complex Systems in Biology, Medicine, and Health Care” is an undergraduate technical elective course offered to BME juniors and seniors. In the first half of the course, we introduce key concepts on systems dynamics, such as phase plane, bifurcation, stability diagram, and discuss classic examples such as harmonic oscillation. We derive all the results based on the ordinary differential equation representation of the system dynamics. In the second half, we introduce alternative modeling approaches of systems dynamics and their mathematical foundations, including stochastic processes, discrete-event simulation, and state-transition model. We also focus on mathematical modeling in cancer and infectious diseases, and use these real-world applications to examine the materials leant in the first half of the semester with the applications. For an outline of class schedule, please see Appendix A.

The Game “Humans vs. Zombies in the Avatar World”

The game “Human vs. Zombie in the Avatar World” was inspired by the live-action reality game basically of the same name (*http://humanvszombies.org*). Since the live-action game began to be played in 2005 at Goucher College in Maryland**,** it has gained popularity throughout U.S. college campuses. The game has now developed an international fan base and received prominent press coverage from the New York Times, the Washington Post, NPR, and the Associated Press. Many students in my class have experience about the game.

“Humans vs. Zombies” is a game of tag. The objective of the zombies is to win when all human players have been tagged and turned into zombies, whereas the objective of the humans is to survive long enough for all of the zombies to starve. All players begin as humans, and one is randomly chosen to be the “original zombie.” The original zombie tags humans and turns them into zombies. A zombie must tag at least one human every 48 hours by reporting the victim's ID. Otherwise, it starves to death and is out of the game. When tagged by a zombie, humans are required to surrender their ID cards. One hour after being tagged, the humans tie a bandanna around their heads and turn themselves into members of the zombie team. Now they can tag humans. On the other hand, humans may stun a zombie. A stunned zombie may not interact with the game in any way for 15 minutes. This includes shielding other zombies from bullets or continuing to run toward a human. If shot again while stunned, the zombie's stun time is reset back to 15 minutes. For this game, some areas on campus are designated to be "no play zones", where the game is permanently suspended and no players may be stunned or tagged. These areas include bathrooms, health centers, libraries, indoor athletic facilities, academic buildings, and so on. Some other areas on campus are merely "safe zones", where gameplay continues but humans cannot be tagged. These areas include dorm rooms and dining halls.

In systems science and engineering language, this live-action game is a game played by two types of competing entities in a largely decentralized fashion even though some collaboration among the entities of the same type may emerge as the game goes on. The objective of each type of entities is to survive by attacking and annihilating the other type. This spirit of the game can be seen in many ecological and biological systems with competing entities. In my class, I teach the Lotka-Volterra model, an important mathematical model that captures the dynamics of the prey and predator populations. For teaching the model, I adapted the game "Humans vs. Zombies" to a computer-based serious game. I present more details on my adaptation in Section 3.

The Game "POX: Saving the People"

The "POX: Saving the People" game implemented in my class is a direct use of the game "POX: Saving the People" (*www.tiltfactor.org/pox*), invented by Dr. Flanagan and the tiltfactor lab at Dartmouth College. The game is a board game that challenges a team of players to vaccinate and cure people until herd immunity is established, i.e., the disease is fully contained. In addition to the physical board game set, its iPad version is also available to download with a minimal fee.

At the beginning of the game, a deadly disease is assumed to have broken. The game is won when the disease can no longer spread to infect others, no matter which direction its spreads. The game is lost if five people die or if all infection chips have been played. A game set is composed of a squared game board comprising equal number of vertical and horizontal lines, 28 POX *scenario* cards, 50 blue (immunization) chips, 40 red (infection) chips, and 5 black (death) chips.

We next describe the game rules in detail. To start the game, shuffle a deck of cards and place it face down beside the board. Place a red chip on each of the two red spaces on the board to indicate the originally infected people. Before play begins, players should agree to a difficulty level – the number of people allowed to die before the game is lost. The suggested difficulties correspond to the power of the intervention, e.g., chicken soup is equivalent to 4 deaths, cough medicine 3 deaths, IV fluids 2 deaths, intensive care 1 death, and miracle 0 deaths. Once the difficulty level is selected, the play begins. Players take turns. Each turn follows the same steps: 1) draw a card; 2) add red infection chips as directed by the card drawn (either Spread or Outbreak); 3) check to see if anyone has died; and 4) vaccinate or cure as many people as the drawn card states.

Two types of cards can be drawn that indicate the scenario faced. They are *spread* cards and *outbreak* cards. The scenario may state the direction to spread the disease, whom will be infected by, or who can be vaccinated, or aftermath of the outbreak. When a *spread* card is drawn, every infected person spreads the disease, infecting healthy people in the direction(s) stated by the card. If, because of immunized people, no new infections occur, then one may vaccinate or cure twice the amount shown on the card. When an *outbreak* card is dawn, a red infection chip must be placed on a healthy people matching the type shown on the card. If there is no such person, the outbreak cannot be next to someone who is immunized or infected. If there is no such person, the outbreak does not occur, and one may vaccinate two people instead of one.

Now we talk about the characters in the game. At the start of the game, there are three groups of people: *infected*, *healthy*, and *vulnerable* people. The red spaces on the board indicate people who are infected at the start of the game. The infection may spread from them to adjacent healthy people. They may be cured and become immunized during the course of the game. The gray spaces on the board are healthy people. If healthy people become infected, they may be cured. The last group in the game is vulnerable people, represented by the yellow spaces. These are people who cannot be vaccinated, such as pregnant women, newborns, and people with weakened immune systems. Immunization chips cannot be placed on them, and they will die immediately if infected.

In the last step of a turn, the player can vaccinate or cure people according to the drawn card. Any healthy person may be selected to vaccinate. Once vaccinated, that person becomes immunized and can never become infected. Thus, a blue immunization chip is replaced on the board accordingly. Any infected person can be selected to cure. Once cured, the corresponding red infection chip is replaced with a blue immunization chip. Immunized people can never be infected.

Finally, we talk about the death occurrence in the game. There are two ways that a death may occur: 1) any infected person surrounded on all possible sides by infected people will die; and 2) whenever a person who cannot be vaccinated (a yellow space) becomes infected, that person immediately dies. Dead people cannot be cured or vaccinated. The game is lost when too many people die, based on the chosen game difficulty.

In systems science and engineering language, this board game represents a control system with stochastic spatiotemporal dynamics and a finite control space. In principle, the gameplay dynamics can be modeled with cellular automaton. I introduced cellular automation as a modeling approach in lately developed cancer invasion models first and then scheduled this game to offer a more active learning opportunity. After the game module, I started to teach mathematical modeling in infectious disease epidemiology; thus this game also helped expose the students to basic concepts in infectious disease control. In Section 3, I will introduce the instruction module design in detail.

3. Design and Implementation

In this section, I discuss the design and implementation of the two game-based learning modules. For the learning module "*Humans vs. Zombies in the Avatar World"*, we also describe the adaptation of the live-action game. The criteria for the learning module design and implementation are listed as follows. The modules must (1) facilitate active learning, which is the most important criterion; (2) be closely related to the subject of systems modeling; and (3) give emphasis on the application domain. In addition, the modules should not interfere with the course schedule nor give me and the students much burden.

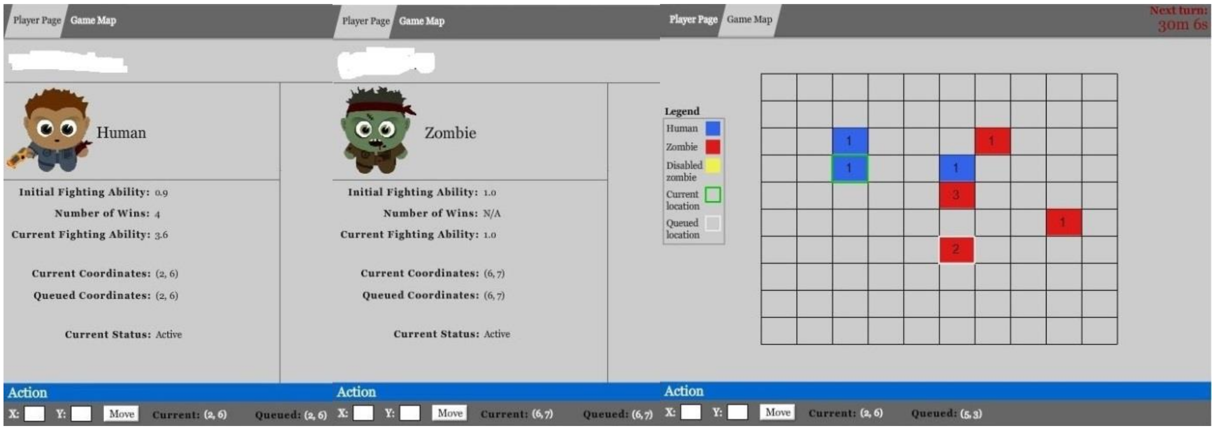
The Learning Module with "Humans vs. Zombies in the Avatar World"

I made several important changes when adapting the live-action game "Humans vs. Zombies" to a web-based computer game. They are 1) the human and zombie populations are of the same size; 2) each player is only allowed to move at discrete time points among a board with squares arranged on a grid; 3) the winning is determined by a pre-specified set of decision rules developed by me who acts as an arbitrator; and (4) there are no "no play zones" or "safety zones".

The computer-based game is built in Adobe Flash, which is a software platform used for creating vector graphics, animation, games and rich internet applications that can be viewed, played and executed in Adobe Flash Player. Adobe Flash is frequently used to add interactive multimedia content to web pages. In addition, PHP, a server-side scripting language, is used around the game to facilitate user login and play recording. Once a user has logged in, PHP creates a session variable to indicate the user is in an active session. This allows the game to be loaded on the user's page. Then the Adobe Flash instructs a code to be sent to PHP for the current active user session. The returned information is used to determine which player is playing the game. In the game, there are five main components: Map, Player, Play Period, Action, and Battle Manager.

We briefly describe these components in the following. The *Map* displays current players on a grid. Before the game starts, the *admin* user (the instructor) needs to specify a number of following settings for the Map, e.g., the dimensions of the grid. A *Player* corresponds to a logged-in user. The *admin* user specifies whether each player is a human or a zombie initially. There are a number of attributes that apply to each player such as its position, its number of wins already cumulated, and so on. The *admin* user specifies the length of the *Play Period* as well. For a list of the parameters set by the *admin* user, please refer to Appendix B.

Within each play period, the *total length* parameter indicates the number of days the game is being played. Each period contains multiple sessions and each session contains multiple turns. At one turn, each player is allowed to submit one action to indicate where it intends to move to. Hence, after each turn, the collective state of the players may be changed. The *Battle Manager* component is responsible for determining the outcome of the battle between humans and zombies at each square in each turn. To determine the outcome, an algorithm is used to generate a random number with a predefined formula based on the *fighting ability* of each human and zombie residing at the focused square. To configure the game play, the *admin* user also needs to specify the initial fighting ability, the battle winning reward, and the battle format. See Figure 1 for snapshots of the human and zombie pages as well as the game board. Please see Appendix C for more information about the game design.



[redacted]

Initial Fighting Ability: 0.9
Number of Wins: 4
Current Fighting Ability: 3.6
Current Coordinates: (2, 6)
Queued Coordinates: (2, 6)
Current Status: Active
Current: (2, 6) Queued: (2, 6)

[redacted]

Initial Fighting Ability: 1.0
Number of Wins: N/A
Current Fighting Ability: 1.0
Current Coordinates: (6, 7)
Queued Coordinates: (6, 7)
Current Status: Active
Current: (6, 7) Queued: (6, 7)

Current: (2, 6) Queued: (5, 3)

(a) Human Avatar Interface (b) Zombie Avatar Interface (c) Game Map Interface

Figure 1. Snapshots of the interfaces appear in the game "Humans vs. Zombies in the Avatar World". On subfigures (a) and (b), the interfaces also show the game clock to the next turn as shown on the right upper corner of subfigure (c). For the interest of space, it is omitted. The parameters in the middle of subfigures (a) and (b) indicate the attributes and variables of a human and a zombie, respectively. A player enters the action information at the bottom of the window for the next move. The map displays the current game status.

With the PHP, log files can be generated at the end of each turn and be released to the players through a secured file storage site. More importantly, it offers convenience to me to gauge each student's interest and develop analysis questions based on the information collected. To benefit me and the students for reviewing the gameplay, we use a downloadable Microsoft Excel macro for data visualization.

With this adaptation, this web-based game mimics the real-world game Humans vs. Zombies. The game, though, differs from the live-action game in several aspects. First and foremost, players cannot make any observation to determine their movements since each player's movement may be completely random and is only restricted by the board boundary but independent of the previous moves. Second, the game is played within a fixed length of period and each player can only make the move within prespecified time windows. Third, the outcome of the fight is determined partially based on random number generation. Lastly, a battle can be made between a group of humans and a group of zombies and its outcome may be determined collectively by the two sides.

This web-based game and its live-action counterpart were introduced in the first lecture of the course as a motivating example. Students were given a rule sheet at the end of the first lecture. Two 1-month play periods were used in the semester. The first one was in the first month. The second one was in the third month, about two weeks before the finals week. During each play period, each play session lasted a few hours in a day. The start time of a session was recommended to be 5 – 6 pm and the end time was recommended to be 12 – 1 am. This duration is typically when undergraduate students are awake but not committed to class attendance. In addition to providing bonus points to students who played well, I would also provide bonus points to students who played actively. I, together with the TA, periodically checked the log files to identify students that are not active. Based on our experience, the active level of playing this game was positively correlated with the academic performance and final grade. So in class, I'd more encourage those relatively inactive students to participate in class discussion.

After the first play period, all the play data were released to students who were then motivated to analyze the data to discover knowledge that may be useful in the second play period. A set of questions were given to the students between the two play periods to guide them in the data analysis. These questions ranged from basic descriptive statistics to pattern recognition. They were posed progressively based on the difficulties. At the end of the second month, students were challenged to propose methods to simulate the gameplay dynamics and further synthesize their playing strategies to achieve better outcomes in the second play period. After the second play period, the same set of questions was posed to students but more emphasis was given on systems modeling and predictive analytics.

The Learning Module "POX: Saving the People"

Infectious disease prevention and control is clearly of national necessity. Using applications from this area has been rewarding to the learning of students as they gain the social awareness and learn how to create socioeconomically and ethically sensible solutions, which are important learning outcomes in engineering curricula these days. Implementation of an active learning module on infectious disease prevention and control helps students achieve these learning outcomes in addition to learning the scientific subject.

The learning module implementing the game "POX: Saving the People" was scheduled in a 50-minute lecture in the third month of the semester when mathematical modeling of infectious disease would be the subject. At the beginning of the lecture, I took about 5 minutes to present a real-world scenario that the Centers for Disease Control and Prevention was faced with the challenge of establishing herd immunity in several major metropolitan areas, including New York, Los Angeles, Atlanta, and Houston, following a viral disease outbreak. I asked the students to discuss the concept of herd immunity within the specific context. Then the students were divided into 4 groups of 5 to 6 people. One person in a group was designated to be the gameplay recorder who did not participate in the gameplay. During the gameplay, the group members decided if they wanted to discuss the next move together or left the decision solely to the person who was in charge of the turn.

There were two play sessions of 15 minutes each. At the beginning of the first play session, I handed the recorder a prompt sheet for recording the gameplay dynamics. (See Appendix D for the prompt sheet) There was a competition among the groups. When a group established the herd immunity, they would announce it and I recorded the number of moves and time it took. I then asked them to see if they could replicate the gameplay based on the recording and commented on which is preferable between individual decision making and collective decision making on the moves. After the first play session, I asked the winning group to reflect on their decision making strategy and asked the groups that did not establish the herd immunity to reflect on their mistakes. I also asked a number of questions to the class. Sample questions are listed as follows:

1. How to make the game more difficult other than allowing fewer people to die?
2. If you play EVIL, in addition to spreading the disease at a particular direction, what else could you do?
3. Were you able to record all system phenomena with the prompt sheet? Are there additional features about the gameplay dynamics you want to include?
4. With the gameplay log, can you replicate the gameplay?
5. How much time did you spend on making a vaccine/cure decision on a turn?
6. Was there any argument among your group members? Were you guys interactive or passive during others' turns?

The above example questions had different emphases in the teaching. The first two questions were used to provoke student's thoughts on the gameplay dynamics and how the dynamics is correlated with the game parameters. The next two questions were used to challenge the students to think about how to describe the dynamics of a complex system. The last two questions were used to evaluate the group decision making. After spending five minutes on these questions, we moved on to the second play session, in which the difficulty level was increased. Again when a group established the herd immunity, they would announce it. After the second play session, I again asked several winning groups to reflect on their decision making strategy I also asked a number of questions related to system modeling and playing strategies. Sample questions are listed as follows.

1. Can you model the system phenomena you have observed? What would be a good modeling approach for this system?
2. Can you summarize your gameplay strategies that seem to be beneficial as for now?

In addition, I also attempted to provoke students' thoughts on enhancing the social awareness with the game. I asked them how they thought the game can be improved to help the general public understand herd immunity.

Here are a few additional remarks on implementing this module. First, the class size was first around 45 students in 2009 -- 2011, and dropped to around 25 students after 2012 when BME undergraduate students were no longer mandatory to take this course. With the former size, we needed two lectures. With the latter size, we needed only one lecture. Second, I held the lecture(s) in the Educational Design Laboratory of the Purdue University Discovery Learning Research Center to facilitate the teamwork I encourage during the gameplay. Third, I announced the bonus points given to the winning team(s) to encourage the students' active participation. In the final exam, the students were asked to write a reflective essay on how to improve the module.

4. Preliminary Assessment and Self-Reflection

The preliminary assessment was made through three channels. First, I made real-time observations on the two games and the implementation of the two game-based learning modules. For the game "Humans vs. Zombies in the Avatar World", the students seemed to become increasingly inactive playing the game even with increased encouragement from me (e.g., promising bonus towards the final grade). In addition, few students actually read the log files released online. Next, the data analysis questions were enticing but most of the student treated them simply as additional homework assignments. Several students asked me to clarify how to report gameplay statistics due to lack of prior knowledge on the subject of probability and statistics. In addition, compared to other materials intended to covey with the game, knowledge on data-driven modeling and game situation based control did not seem to be well disseminated during the gameplay. Finally, the students felt the play sessions were too frequent and the complete randomness on the system state made the game less meaningful. However, almost all the students thought the game was interesting and potentially viable to serve as an active learning experience. This conclusion is verified by the survey results described later. However, the learning component should be more emphasized with improved study question design.

For the game "POX: Saving the People", some students did not familiarize them with the game rule prior to the learning module even though they were requested. As a result, the class did not progress as quickly as I expected. In addition, the group decision making made some students quite passive in the game play especially in the second play session. Those thought-provoking questions were good but more pre-class reading was needed and the questions should be released prior to class to give the students time to prepare. The students' preliminary survey confirmed these observations. Some of the students thought the first play session should be longer and the second play session should be shorter.

The second assessment involves an actual course activity, namely one key item required by the term project. The item asks the students to include in their project report a discussion on "the potential impact of mathematical/computational modeling in BME". This item is worth 5 out of 100 points in the project report. In 2013, the average score among the 19 students taking the class were 4.32 and the standard deviation was 0.34. In 2015, the average score among the 17 students taking the class were 3.76 and the standard deviation was 0.25. Our results suggest that, without consideration of the potential differences among the two classes of the BME junior/senior students, the learning outcomes of the 2013 class are better than those from 2015 with statistical significance (*p*-value of a t-test is close to 0).

The third assessment involves an end-of-the-semester student self-reporting survey. The four survey questions are well aligned with the learning outcomes selected from the ABET's list of BME student outcomes and currently approved by my department. This survey was administered in 2013 and 2015. Note that I implemented the two game-based learning modules in 2013 while did not in 2015. In 2013, I asked an additional question to assess the benefit of the game-based learning modules on improving their learning if the student's answer to the corresponding learning outcome question is either "Strong Agree" or "Agree". All the survey questions applied a 5-point Likert scale. The survey questions are reported in Appendix E. With the results from the two years, I conduct a comparative study. Our results in Table 1 again suggest that, without considering the differences, the learning outcomes are better in 2013 for all four questions. However, the improvements are considered to be not statistically significant with an unpaired *t* test. Keeping the assumption on the student populations, we argue that use of the game-based active learning modules may have helped improve the learning outcomes (see Table 2).

Table 1: Comparison of student self-report survey results between 2013 and 2015

	2013						2015						
Question	SA (5)	Agree (4)	Neutral (3)	Disagree (2)	SD (1)	Avg. Score (n = 19)	SA (5)	Agree (4)	Neutral (3)	Disagree (2)	SD (1)	Avg. Score (n = 17)	*p*-value
Q1	11	8	0	0	0	4.58	8	7	2	0	0	4.35	0.147
Q2	7	10	2	0	0	4.26	4	8	5	0	0	3.94	0.113
Q3	12	7	0	0	0	4.63	11	5	1	0	0	4.59	0.418
Q4	12	7	0	0	0	4.63	10	5	1	1	0	4.41	0.188

Q1: The course has helped you improve your ability of identifying and/or describing how biomedical engineering solutions affect society?

Q2: Do you think the course has helped you improve your ability of collecting relevant technical information, data, and ideas from multiple sources?

Q3: Do you think the course has helped you improve your understanding of how to apply engineering and science techniques, skills, and tools at the system level?

Q4: Do you think the course has helped you improve your ability of recognizing, identifying, and describe the need for an engineering solution to address current challenges in life science and medicine?

SA: Strongly Agree; SD: Strongly Disagree

Table 2: Student assessment on the use of the game-based learning modules (n = 19)

Question	Strongly Agree	Agree	Neutral	Disagree	Strongly Disagree
Q1	13	4	2	0	0
Q2	12	3	3	1	0
Q3	6	8	3	2	0
Q4	5	10	4	0	0

In summary, our assessments suggest that the students enjoyed the games and felt they learned relevant subjects more actively. This has likely led to improvement on the subjective learning outcomes. The self-reflections and comments from the students' surveys confirm this implication.

After carrying out the two learning modules, I also made self-reflection at the end of the semester for continuous improvement. Personally, I felt that the one thing to improve upon the most is developing more explicit connections between the gameplay and the mathematical modeling. This has been quite challenging from an instructional viewpoint. With the gameplay, the students clearly enjoyed the class more but did not necessarily improve the learning outcomes. I felt this would need better design in both the game and the learning module. The games should be made more interactive and the learning modules should have a clearer application context. Good thought-provoking questions must be designed to facilitate students' learning. These questions should also be placed and paced better in the modules. Finally, to make the games more realistic, additional environmental factors should be incorporated. For example, the game grids for "Human vs. Zombie in the Avatar World" could be modified to include more realistic geographic boundary, e.g., a particular campus for the first module and a particular city for the second module. Finally, to teach systems optimization together with system dynamics modeling, outcomes should be associated to each action or move and these outcomes should be tallied automatically and better presented to the students.

Now I make specific remarks on implementing each learning module. For the first module, the data analysis part somewhat fell short. To improve the learning experience, some introduction must be done on probability and statistics. Alternative modeling approaches other than ODEs should be taught earlier in the semester to be coordinated with the game play. For the second module, to make the learning more socially relevant, some background knowledge on CDC and its infectious disease control policies should be provided to the students. In class, more sophisticated and challenging scenarios for disease control should be designed. The associated questions should be asked more sequentially. Finally, I have also planned to develop the Flash version of the game. With the computer game, I can implement this module similar to the first one throughout the semester.

5. Conclusions and Future Work

In this paper, I present and discuss the design and implementation of two game-based learning modules for my class "Mathematical Modeling for Complex Systems in Biology, Medicine, and Healthcare". The two modules were implemented in the class for several years. Preliminary assessment was conducted and both qualitative and quantitative data were collected. Self-reflection was made with the main purpose of improving the modules and enhancing the active learning experience.

The design and implementation criteria are related to several key challenges in teaching complex systems dynamics and operations research applications. These challenges lie in the teaching of (1) alternative modeling approaches; (2) modeling and analyzing higher-dimensional systems; (3) analyzing transient states of the system; and (4) data-driven modeling. Through self-reflection and objective survey data, I have identified improvement directions.

In terms of future work, I plan to design more objective learning outcome assessment metrics and tools to investigate the effect of the game-based learning modules. In terms of module design, I plan to focus more on achieving better interaction not only in the game design but also in the teaching of dynamical system simulation. Better thought-provoking questions must be designed. I also plan to design a semi-quantitative questionnaire with more focus on the game related learning outcomes and administer it at several time points during the modules so that I can get cross-sectional objective data. Meanwhile, I plan to hold multiple informal interviews with the students to better gauge their interests in a real-time fashion. Additionally, I plan to transfer the two modules to massive online open course (MOOC) units and explore the possibilities of embedding the modules in other residential courses. Finally, I plan to recruit student groups of larger sample size with the establishment of the MOOC course for conducting the hypothesis testing.

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