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Article

Imparting Systems Engineering Experience via Interactive Fiction Serious Games

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Abstract

Serious games for education are becoming increasing popular. Interactive fiction games are some of the most popular in app stores and are also beginning to be heavily used in education to teach analysis and decision-making although they have not previously been used to impart systems engineering experience. Noting that it is difficult for systems engineers to experience all necessary situations which prepare them for the role of a chief engineer, in this paper, we explore the use of interactive fiction serious games to impart systems engineering experience and to teach systems engineering principles. The results of a cognitive viability, qualitative viability, and replayability analysis of 14 systems engineering serious games developed in the interactive fiction genre are presented. The analysis demonstrates that students with a systems engineering background are able to learn the Twine gaming engine and create a serious game aligned to the Apply level of Bloom's Taxonomy which conveys a systems engineering experience and teaches a systems engineering principle within a four-week period of time. These quickly generated games' cognitive, quality, and replayability scores indicate they provide some opportunity for high-level thinking, are of high quality, and with above average replayability, are likely to be played multiple times and/or recommended to others.

1. Introduction

Systems Engineers spend the early years of their career becoming steeped in one or more domains of engineering such as electrical, mechanical, software, human factors, or computer engineering before becoming a systems engineer. Multiple engineering domains allow them to accumulate breadth to succeed in the holistic, cross-domain discipline of systems engineering. Unfortunately, the field of systems engineering is so broad that systems engineers find themselves working for many more years without encountering many important aspects of systems engineering. For example, a systems engineer may focus on systems test for many years without developing skills in system requirements, design, or production. Providing a systems engineer with the experiences to "round them out" to become a chief systems engineer. Many experiences happen only once in a career (e.g., rapid product redesign in response to a massive system failure after fielding such as the Boeing 737 MAX Maneuvering Characteristics Augmentation System (MCAS) failure) and other valuable experiences never present themselves as experiential learning opportunities. This lack of experience becomes a problem when the individual becomes a chief systems engineer with system responsibility over the entire system lifecycle. Once in the SE role, the individual may realize they lack required knowledge and professional experience. The new systems engineer may be unable to perform the new responsibilities as well as desired and may become the cause or contributor to a failed fielding or sustainment of the system for which they are responsible.

The new, mid-level, and senior systems engineers need opportunities to gain systems engineering experience in structured processes instead of hoping for the right jobs and experiences for their development. A mechanism to convey large amounts of important systems engineering experience in efficient ways would be ideal, especially if that body of systems engineering experiences is diverse, easily and quickly digested, and effectively retained. Ideally, the mechanism to convey these systems engineering experiences should be desirable and motivating to ensure that the experiences can be "pulled" by the growing systems engineer, not "pushed" by company leadership. Serious games may provide systems engineers experiential games that may meet this need. The objectives of this research are to survey extant systems engineering serious games, analyze those which impart systems engineering experience, and survey the use of interactive fiction games in providing experiential education. Finally, this research explores the creation and effectiveness of interactive fiction games for advancing systems engineering experience as interactive fiction games have been shown to be effective in other fields, but not yet in the field of systems engineering.

2. Literature Search

2.1 Systems engineering education

The need for systems engineering education has long been noted and many papers have been written on the subject describing types, methods, and challenges [1], [2], [3], [4]. Sage identified three components of knowledge for the systems engineer—knowledge practices, knowledge principles, and knowledge perspectives [4]. Educating systems engineers on practices, principles, and perspectives is challenging because they require knowledge and skills from "all of the sciences, and from the world of professional practice," and not just from a single domain [4]. Systems engineering education is technical and also requires "social, cultural, ethical, and equity" education, an understanding of economics, and insights into organizational realities [4]. Some of the most important areas of education for the systems engineer involve problem-solving and decision-making [4]. To accomplish this education, educators and mentors used verbal explanations, analogies, logics, and mathematics [1]. Asbjornsen and Hamann noted that SEs need professional education, experience, and examples and implied that learning rate can be maximized, the forgetting factor can be minimized, and the amount of accumulated knowledge can increase if systems engineering education is experientially based [1]. As the systems engineer grows into a chief systems engineer, deep cross-disciplinary knowledge is required which can be learned through "similarities and analogies" [5]. Ideally, theory and experience must be conveyed rigorously and methodically, but also in a way that is palatable to the diversity of systems engineers practicing in the field. Systems engineering education is a life-long pursuit due to ever-changing technology, transitioning to digital processes, and constant innovations which occur in this cross-disciplinary field.

For decades, technology has been a foundational aspect of systems engineering education. As early as 1992, Verma, et al., noted that systems engineering education and training efforts should be supported with computer-based courseware [6]. Although initially computer-based courseware implied the use of engineering software (such as requirements, manufacturing, cost estimation and other software packages) in the systems engineering classroom, in the 2020s, researchers are inventing computer games to teach systems engineering [7], [8], [9], [10], [11]. One of the most important requirements for software used for systems engineering education is the ability to put the student into situations where they can explore “what-if” scenarios [6] as they enable the student to explore the complexities of real-life systems engineering in a non-threatening fashion.

Capable systems engineers must develop “scar tissue,” which reflects the wisdom gained from their systems engineering experiences, both good and bad, to perform their responsibilities effectively [12]. Many of their responsibilities involve decision making which must be done in context. Unfortunately, gaining the experiences required to enable this type of decision making takes time. One Massachusetts Institute of Technology (MIT) researcher reported in 2006 that it takes at least 10-15 years to grow a capable systems engineer [13]; ostensibly much more time is required to grow a chief systems engineer. With 15-20 years required to develop senior systems engineers, many systems engineers have only a few short years to contribute as a fully proficient systems engineer. having taken almost their entire career to gain the requisite knowledge and experience. As mentioned previously, some experiences come once-in-a-career, such as the Boeing 737 MAX Maneuvering Characteristics Augmentation System (MCAS) failure, the Ariane 5 control software error, or the Apollo 13 oxygen tank explosion. The systems engineers responsible for dealing with these situations had to rely upon their accumulated experience to-date to innovate responses to these new problems. The question can then be asked: Is it possible to “accelerate the maturation of SEs in the workforce” by providing simulated experiences [7] which could more effectively and rapidly prepare a systems engineer for the challenges that will confront them?

Hearkening to Sage’s thought that “research is exceptionally important for [systems] engineering education” and that faculty must “remain at the cutting edge of technology” to “deliver education for professional practice” [4] it becomes clear that systems engineering training and education must continually change to remain current. One way to continually update SE education materials is to involve students in creating systems engineering educational material. “Students are an inseparable and integral part of…research” and there is “a major role for students” in the development of systems engineering educational materials [4]. Effectively, the combined experiences of students, faculty, and industry and government can be used to create systems engineering educational materials which are current and future looking. This all-hands approach to identifying and developing educational materials appropriate for the systems engineer results in an understanding and appreciation of diversity, different cultures and business practices, a multidisciplinary perspective, and a focus on technical skills [4].

2.2 Systems engineering serious games

Many definitions of the term “serious game,” exist. A common definition recognizes a serious game as one “whose primary focus is on informing and persuading the reader/player about an issue or perspective through the actions taken in the game” [14]. Aside from the *Systems Engineering Experience Accelerator (SEEA)* [7], there have been relatively few systems engineering-focused serious games created to-date. Each of them is unique in their approach, focusing on a specific aspect of systems engineering, have been developed to varying levels of maturity, and have inherent strengths and weaknesses. A brief survey and analysis of all known systems engineering-related serious games is presented below in chronological order from each game’s publication date.

2003 – The Faculty of Information Technology at the University of Technology, Sydney taught a requirements engineering course to second year undergraduate students in which they employed constant role playing [15] with the aim of teaching requirements engineering techniques. This unnamed "game" was referred to as *UTS-RE* by [16].

2008 – *RE-O-Poly* is a requirements engineering board game (a la Monopoly™) developed for those new to requirements engineering and was designed to teach and enforce requirements engineering best practices, including methods for requirement conflict resolution and prioritization [17]. It was refined and evaluated by undergraduate and graduate students, faculty, and industry professionals via three case studies.

2010 – *Requirements Island* is billed by its developers as a "playful" environment which has a two-fold goal of teaching requirements engineering while entertaining the players [18]. It is an "escape" type game classified by the developers at the "Remember" and "Understand" levels of Bloom's Taxonomy. Because of this, it is not be appropriate for teaching the creative application of systems engineering. The game was evaluated by two experiments with information technology students as the game players.

2011 – An unnamed 3D simulation game (we nicknamed *UWS*) developed by researchers at the University of the West of Scotland was designed to teach requirements collection and analysis using "games-based learning" [19]. The game assigns each player a role and uses a set of scenarios to provide an environment in which the player practices delivering a software system. It was tested in five studies using a pre-test / post-test, experimental/control group format study to compare classical teaching methods (i.e., the control group) to the game-based learning approach (i.e., the experimental group).

2011 – When playing *Earth Defense*, middle-school, high-school and undergraduate students learn techniques for interviewing, eliciting requirements, and making requirements-related decisions [20]. The game immerses the player in a life-like situation while eliminating the stress of having to interview real people. The player goes through a design phase into a simulation phase and visualize the results of their requirements elicitation in the form of system performance. *Earth Defense* was validated through three user studies (middle-school, high-school, and undergraduate students).

2012 – *System Analysis and Design Game Based Learning System (SADGBLS)* is a role-playing game set in a simulated 3D office environment in which the player can choose a role and solve systems analysis problems [21]. The game is qualified in an experiment of 63 third-year college students in which 33 students play the game to learn systems analysis and 30 act as a control group learning systems analysis in a classical fashion. The authors of the game report that student game players more effectively learn the systems analysis material and demonstrated a higher motivation for learning.

2012 – *UbiRE* is a requirements engineering game which provides a simulated smart home as the context of the game and allows the player to explore requirements engineering for ubiquitous systems (i.e., Internet-of-Things) [22]. Usability data was collected from players which quantified the playability in ten different categories.

2013 – The most fully-developed systems engineering serious game is the *Systems Engineering Experience Accelerator (SEEA)* [7], [23] [8], [9], [10], [11] which used technology to "create a simulation that will put the learner in an experiential, emotional state and effectively compress time and greatly accelerate the learning of a systems engineer faster than would occur naturally on the job" [24]. The *SEEA* underwent nearly a decade of development and was eventually deployed at the United States Defense Acquisition University (DAU). Although the *SEEA* team possibly achieved their goal of providing "a new paradigm capable of halving the time to mature a senior SE," it was not without challenges. Schedule delays, difficulty in obtaining data from instructor / student trials, economic challenges, and especially the significant amount of time required to develop new scenarios for the *SEEA* [11] motivates the need to determine if systems engineering experience acceleration can be achieved in a more efficient fashion.

2014 - *Space Tug Skirmish (STS)* is a "multi-player card game designed to teach players with no experience in systems engineering about basic concepts of the design and operation of complex systems in an uncertain environment" [25]. It was developed as part of MIT's Systems Engineering Advancement Research Initiative (SEAri) with the intention of shrinking the learning curve of first year graduate students as pertaining to systems engineering research methods [25]. An effort to implement STS as an online multi-player game began in 2013, but it is unknown if this effort was ever completed. At the time of its creation, the developers of STS declared it a success based on 1) student players claiming to have learned the concepts it was to teach and 2) the fact that STS covered all facets of the Serious Game Design Assessment Framework [26] but admitted a more formal assessment of the game is required [25].

2015 – *SimGreen* is a serious card game designed to help players learn environmental topics which enable them to integrate green philosophies and actions into a company [27]. The game assesses the player's success by counting the number of environmental topics the player can integrate. *SimGreen* cuts across systems engineering, environmental engineering, and management boundaries. It was assessed in an 8-session experiment.

2015, 2017 – Students taking the *Systems Engineering and Design* course at the University of Groningen, The Netherlands, are "encouraged to view the course as a 'serious game'" in which they hold a design competition and effectively create their own serious game [28], [29]. Additionally, the students also play the *GasBoard* digital multiplayer serious game which is used to visualize the bio-gas system they are designing. This digital game was based upon an earlier board game.

2017 – According to its developers, the graphical, web-based *Life Cycle Assessment (LCA) Game* was created to teach the quantitative life cycle assessment method which assesses the environmental impact of a system across its life cycle [30]. The *LCA Game* places the player into a simulated industrial plant where they assess a coffee machine. The game was qualitatively evaluated by 265 university students and is billed as an LCA educational tool for college students as well as industry workers.

2017 - *Multiple Interoperable Systems for joint Control of Hybrid threats through Intelligent Extended Fusion (MISCHIEF)* is a serious game focused on teaching system of systems engineering principles [31]. It is a web-enabled, multi-player game in which the players interact dynamically, experiencing situations and making decisions which educate the players on architecture definition, capability-based design, and system interoperability. Uniquely, *MISCHIEF* is capable of stochastically autogenerating its own scenarios based upon reference data. *MISCHIEF* is in the early stages of development, although it has been play tested in both academic and industrial settings.

2019 – A serious game called *Biyubi* was developed to teach undergraduate students how to identify stakeholders, develop requirements elicitation questions, and conduct requirements elicitation interviews [32]. The game was qualified by 94 senior undergraduate students, half of whom learned from *Biyubi* and half of whom learned from the "chalk and talk" method. *Biyubi* players showed greater confidence in eliciting requirements and greater satisfaction with their learning than classically-taught students.

2019 – *Humans vs. Zombies in the Avatar World* is a web game based upon the popular live-action *Humans vs. Zombies* [33]. It teaches systems dynamics from a systems science and systems engineering perspective with a biomedical engineering emphasis and enables the developer's Lotka-Volterra model curriculum presented to college juniors and seniors.

2019 – *POX: Save the People* is an adaptation of a popular board game which introduces "control systems with stochastic spatiotemporal dynamics" [33]. Like *Humans vs. Zombies in the Avatar World*, it also conveys systems dynamics game-based learning in the context of biomedical engineering.

2020 – *Requengin* is a serious game designed to help undergraduate students learn ISO/IEC/IEEE 29148:2011 Systems and Software Engineering – Lifecycle Processes – Requirements Engineering in an interactive way [16]. Rather than teaching the entirety of systems and software engineering, *Requengin* focuses on requirements engineering for the software engineer (although it can also be applied towards systems engineering). *Requengin* is designed to teach stakeholder requirements definition and analysis.

2.3 Interactive fiction serious games

The goal of serious games is to deliver education to the game player (i.e., student) by providing opportunities for remembering, understanding, applying, analyzing, evaluating, and creating (i.e., Bloom's Taxonomy which is a model used to classify learning objectives into levels of specificity). Education provided "through problem-based and experiential learning via the game's procedures" is known as procedural rhetoric [34]. And if the serious game's procedures are defined through a work of interactive fiction, then that interactive fiction serious game can "provide a context for embodied action and choices" [35] and allow the player to "approach a subject in an active way and construct their own representations" [36] to enable and expedite their learning. Although many definitions of interactive fiction exist, a good one is a "text-based branching narrative that takes input from a user, either through a parsing prompt where users type actions for their character to perform or through hypertext links users click to select an action or choice" [14]. Most interactive fiction games are designed for entertainment purposes, but there is a growing body of interactive fiction games which fall more in the realm of "edutainment" or in other words, interactive fiction serious games. This genre of serious game is being developed to teach students formally enrolled in a school (at all levels) as well as workers seeking additional on-the-job training.

Interactive fiction offers many advantages as a genre of serious game, including:

- The textual nature of interactive fiction games "accommodate game designers and players with special needs" allowing the games to be created and played by those with physical, neurological, and mental health challenges [37]
- Creating serious interactive fiction games enables research, allows the creation of a persuasive space, and focuses the game creator's implementation of procedural rhetoric [14]
- Interactive fiction serious games blend education and entertainment [38]
- Producing interactive fiction serious games fosters "curiosity, engagement, and creativity" in both the game developer and the game player [35]

Interactive fiction serious games designed for education have become more numerous and diverse in purpose. A selection (in alphabetical order) includes the following:

- *9:05 and Lost Pig*: Interactive fiction games for learners of English as a foreign language [39]
- *Amnesia in the Atlantic*: A conversational game presenting marine biodiversity challenges [40]
- *Depression Quest*: A Twine game in which you play as someone living with depression. The first Twine game to be hosted on Steam and some proceeds from the game benefit the National Suicide Prevention Lifeline [41]
- *eCases*: A set of Twine interactive fiction serious games created to teach clinical decision making for Doctor of Pharmacy degree candidates [42]
- *EnigmAI*: A Unity 5.0 game which uses the Twine interactive fiction engine combined with the Cradle plugin to create a serious game for 4th year telecommunications students to teach concepts and prepare them for tests [43]
- *Flair*: A game designed as a treatment for social anxiety disorder [44]

- *Pit in the Warehouse*: A dialogical escape room crossed with interactive fiction procedures to demonstrate game-based learning [45]

Numerous tools / engines exist to enable the creation of interactive fiction games. Some are free and/or open source (e.g., Twine, Quest, Squiffy, TADS, Ren'Py, Adrift, Inky, Inklewriter, Inform 7, ChoiceScript, StoryNexus) while others are not (e.g., TyranoBuilder, Visual Novel Maker). Popular game engines such as Unreal and Unity can also be used to creative interactive fiction games, although they were not specifically designed for that purpose. Many of the gaming engines require no coding skills to use but offer the ability to augment the game under development with code. For example, one of the most popular gaming engines, Twine, uses a visual interface in which the author creates "passages" and the connections between them. In its essence, the game becomes a state machine in which the player's choices determine the movement from passage to passage. Twine also allows the author to use variables, logic, images, sound, cascading style sheets (CSS), JavaScript, and other technologies to embellish the games. Other interactive fiction gaming engines require coding in special languages (e.g., ChoiceScript, Inform, Ink, TADS, Ren'Py) or modern programming languages such as Python.

Many authors of interactive fiction games choose to host their games on websites offering free access to the game, such as the Interactive Fiction Data Base (www.ifdb.org), while others choose to host on commercial digital distribution platforms such as Steam (Windows macOS, Linux, iOS, Android), Google Play (Android), or the App Store (iOS). The distribution of educational interactive fiction serious games is often handled within the educational institution rather than offering the games free to the public or charging for their use through commercial digital distribution. Although this enables the original purpose for which the educational games were designed, this limited distribution prevents other prospective students from also benefiting from the games.

2.4 Assessing serious games

Although a search of the literature clearly identifies a growing trend in the creation of interactive fiction serious games, it is important to be able to rigorously assess each game's usefulness and quality. A variety of methods have been proposed such as gameplay observation, analysis of questionnaires, and game play interviews [46] as well as case studies [17], experiments [18], [21], user studies [19], [20], surveys [22], the Serious Game Design Assessment Framework [26], qualitative assessments [30], the Rubric for Evaluating Digital Educational Games [47], the Educational Video Game Evaluation Rubric [48], iRubric: Serious Game Design Evaluation Rubric [49], and informal play testing [31] among others. Researchers have identified factors which are important in influencing the learning effectiveness of a serious game [50], [51]. Some serious game assessment methods are more easily implemented, some lend themselves to statistical analysis, and others are designed to assess a game for a specific purpose. One such method is the Video Game Higher Order Thinking Evaluation Rubric which is used to analyze "the inherent tendency a video game may have to encourage higher order thinking in its users" and is paired with the Video Game Cognitive Viability Scale [50]. We chose this rubric for our research because of its focus on higher-level critical thinking assessment, its long track record of usefulness, its compatibility with interactive fiction serious games, and the simplicity of its implementation. We paired it with our own Qualitative Rubric to assess the usefulness, entertainment value, and quality of each game, created a simple two-question Replayability Rubric to assess the "replayability" of each game, and also asked four Free Form questions to capture the game's name, author, genre, and educational level according to Bloom's Taxonomy. Existing rubrics for quality and replayability could not be found, so had to create them, but followed the style of the Video Game Cognitive Viability Scale.

3. Method

3.1 Interactive fiction serious games for systems engineering

We have made the point in this article that accumulating a broad swath of engineering experience is a necessary step in becoming a systems engineer. It is challenging to accumulate the required knowledge and experience, however, without taking a substantial amount of time to do so. Furthermore, classical systems engineering education focuses on teaching the responsibilities, methods, tools, and languages of the systems engineer, but struggles to impart the experiential wisdom so necessary for the systems engineer's success. Furthermore, we have demonstrated that systems engineering serious games are growing in quantity and popularity. Among the various genre of serious games, interactive fiction is recognized as a useful way of conveying experiential learning, or in other words, of providing the game player the opportunity to step into a virtual experience and learn from it as if it was real. But it has not yet been tested in the domain of systems engineering. Virtual role-playing enables learning and retention of information [52], effective application in real life of what was learned virtually [53], and increased ability to solve problems [54]. More than just being useful in conveying experiential learning, interactive fiction stories "are marvelous means of summarizing experiences, of capturing an event and the surrounding context that seems essential. Stories are important cognitive events, for they encapsulate…information, knowledge, context, and emotion" [55]. Indeed, "digital storytelling is…intimate and participatory…with deep and lasting power" [56]. The question then becomes, can systems engineering experience be effectively imparted via an interactive fiction serious game? Aside from the research presented in this article, no other attempts at exploring this possibility are known.

Multiple times per year, cohorts of mid- to senior-level engineers attend the United States Air Force Institute of Technology (AFIT) to obtain graduate degrees (MS or PhD) or graduate certificates in systems engineering. These students have incredible backgrounds as scientists, technologists, engineers, and mathematicians. Some are practicing systems engineers, and many already hold masters or doctorate degrees in their domain of expertise. They come to AFIT to not only learn the responsibilities, methods, tools, and languages of the systems engineer, but to also impart their experiences to each other as they progress as a cohort through the graduate program. A common scene in class involves two or more students swapping stories on engineering challenges they faced, the successes and failures they experienced, and the solutions they innovated. As part of their systems engineering education, numerous guest speakers with impeccable credentials in important areas of systems engineering such as cyber security, agile software, or model-based systems engineering, are brought into the classroom to also share their experiences with the students. The end goal is to educate the students, not just with the "facts and figures" of systems engineering, but with the experiential knowledge they require as they progress forward in their careers, many destined to become chief engineers, directors of engineering, or other senior engineering leaders. Recognizing the need to find new and better ways of sharing systems engineering experiences and remembering that there is "a major role for students" in the development of systems engineering educational materials [4], we require our graduate students to create a systems engineering serious game during their final graduate course, Advanced Topics in Systems Engineering. Once created, each student plays all the games, having an opportunity to immerse themselves in new systems engineering experiences. The creation and playing of the games contribute toward the students' systems engineering learning.

The systems engineering serious game assignment requires students to work together in groups of two or three students to create their game which simultaneously imparts a systems engineering experience and teaches a systems engineering concept. Students use the Twine [57] game engine with its default Harlowe story format to create their game in the interactive fiction genre. Twine is straightforward and quickly learned, which is crucial because the students only have three weeks to learn the gaming engine, create, and test their serious game. The Twine game development environment is drag-and-drop and allows the game designer to create a state machine which describes player "states" associated with different scenes or passages of the overall digital story. Students are encouraged to base their serious game on a real systems engineering event from their past but are allowed to fabricate a realistic new one if needed. They think about what they learned from their experience (both good and bad) and identify what they deem important to pass on to others to propel their systems engineering learning. Students most commonly present numerous opportunities to make systems engineering decisions, some in challenging and ambiguous circumstances. The serious games are required to be re-playable, allowing the student to make different decisions and choose different paths each time they play, obtaining different results. Students are provided the checklist in Table 1 to guide them in their serious game development.

Table 1. Systems engineering serious games checklist

Teach a systems engineering concept (e.g., technical or technical management process)
Impart a systems engineering experience (real- or made-up that you wish to pass on to others)
Effectively employ the MDA Framework (i.e., mechanics, dynamics, and aesthetics)
Use the Twine interactive fiction game engine with the Harlowe 3.2.2 story format
Include ~3 main characters—a protagonist, an antagonist, and a complicating character
Provide a catchy title for your game
Provide an icon for your game (1024 x 1024px)
Do NOT use real names, organizations, or events that negatively tie your game to specific people
Choose one of the plot types provided by your Professor (recommended)
Organize your story in 3 dramatic phases (recommended)
Include ~100 passages with 1 or more clickable decisions or plot furtherance links per passage
Make the game "re-playable" with different endings or results each time
Categorize the audience for your game as either Junior-, Mid-, Senior- or Executive-level. You may also categorize it for All audiences if appropriate
Identify which level of Bloom's Taxonomy your game is targeting
Graphics and sound are optional
Inappropriate language and situations are NOT acceptable
Make it fun!

Two sets of systems engineering interactive fiction serious games were developed over the course of two academic quarters which occurred with one year separation. The first set of six games was developed by ten students assigned to five groups and one professor who created an example game. The students were junior- to mid-level engineers (military and civilian), most of whom did not have a graduate degree. The second set of eight games was developed a year later by twenty-four students assigned to eight groups. These students were almost all senior-level civilian engineers, many with decades of experience as practicing systems engineers and almost all holding masters or doctorate degrees in engineering. All students within each group played all of the games created by that group completely through at least once. Students were not required to report how many times they replayed each game. The students played the games over the course of one week at which time they submitted their cognitive viability, quality, and replayability scoring rubrics for each game. In general, students from both the younger and older cohorts reported that they enjoyed creating and playing the games, although one senior student reported that the serious game assignment was "silly" because systems engineers will "never use Twine on-the-job." A detailed description and analysis of the games and the scoring provided by the students is presented next.

3.2 Assessing cognitive viability, quality, and replayability

The Video Game Higher Order Thinking Evaluation Rubric consists of twenty true or false questions, each equally weighted, and the sum of all true answers is the Video Game Cognitive Viability Score (Table 2). A score of 0 – 8 indicates little cognitive viability (i.e., an arcade game); a score of 9 – 13 indicates the lower range of cognitive viability (i.e., few opportunities for higher order thinking); 14 – 18 is the mid-range (i.e., probably acceptable for some higher order thinking opportunities), a score of 15 – 19 is the upper range indicating the game "holds several positive characteristics lending itself to higher order thinking;" and a score of 20 indicates a game with near perfect cognitive viability.

The Qualitative Rubric (Table 3) is our eight-question evaluation in which the students respond to each question with a discrete value from 1 to 5 where 1 represents a poor quality, 3 is average quality, and 5 is high quality. Each question carries an equal weight. The sum of all scores was called the Qualitative Viability Score and games scoring from 8 - 16 were deemed to be of low quality, 17 – 24 indicated average quality, 25 – 32 represented high quality, and games scoring 33 – 40 were superlative with respect to mechanics, dynamics, aesthetics, education, and entertainment.

The Replayability Rubric (Table 4) captures the evaluator's true / false answers to two questions. The Replayability Score is either a 0, 1 or 2 and is calculated by tallying the number of true responses from the evaluator. A score of 0 represents the evaluator would not play the game again and would not recommend it to others; 1 indicates a 50% likelihood of playing the game again or recommending it; and the perfect score of 2 is reserved for highly recommended games. The questions comprising the Cognitive, Qualitative, Replayability, and Free-Form rubrics are included in tables 2 - 5.

Table 2. Cognitive rubric questions

Valid responses = True / False; rubric scores range from 0 to 20
Requires the player to assume a role in the game, rather than simply play
Offers meaningful interaction, such as dialogue with NPCs
Has a storyline
Has a complex storyline with characters users care about
Offers simple puzzles
Has complex puzzles requiring effort to solve
Uses graphics & sound
Allows multiple views of the game (e.g., camera pans and the ability to zoom in / out)
Allows different ways to complete the game

Simulates complex processes requiring adjustment of variables by users to obtain desired results or adjusting variables leads to different results
Allows interaction through use of avatars
Avatars are lifelike
Requires interaction with virtual elements within the game
Requires knowledge of game elements beyond mouse prompts, number entry (e.g., combining elements to create new tools, understand complex jargon)
Requires gathering of information in order to complete
Requires synthesis of knowledge to complete or successfully engage elements in the game
The environment within the serious game effectively replicates the real world
NPCs display AI characteristics
NPCs display effective use of AI resulting in dynamic experiences for the user
Offers replay ability with varying results

Table 3. Qualitative rubric questions

Valid responses = 1, 2, 3, 4, 5; rubric scores range from 8 to 40
How interesting was the serious game to play?
How fun was the serious game to play?
How well did the serious game convey a useful systems engineering experience?
How engrossed were you in the story while playing the serious game?
How well did the mechanics of the serious game contribute to conveying the SE experience?
How well did the dynamics of the serious game contribute to conveying the SE experience?
How well did the aesthetics of the serious game contribute to conveying the SE experience?
How appropriate is the Twine gaming engine for creating SE serious games?

Table 4. Replayability rubric questions

Valid responses = True / False; rubric scores range from 0 to 2
Would you play the serious game again?
Would you recommend the serious game to your peers?

Table 5. Free form rubric questions

Valid responses = 1, 2, 3, 4, 5; rubric scores range from 8 to 40
What was the serious game's name?
Who authored the serious game?
What Genre was the serious game a part of?

At what level of Blooms Taxonomy did the serious game fit?

4. Results and Analysis

4.1 Game summaries

Students were very creative in choosing topics, designing, and naming their games. For convenience, in Table 6 we assigned a nickname to each game to enable easier reference in this paper. As can be seen in Table 7, students took on a variety of topics which were interesting to them. More importantly, the students chose topics which they felt were important learning areas for other systems engineers. Of the 14 games, 10 were designed to be played by entry- or junior-level systems engineers. Of the remaining four games, two did not state their intended audience and two were designed for mid-level systems engineers. Some games addressed a very broad topic area (e.g., model-based systems engineering) while others were quite focused (e.g., agile software product owner responsibilities). Due to the nature of the genre chosen (i.e., interactive fiction) for the games and the requirement that each game should be replayable, all the games gave the player an opportunity to practice systems engineering decision-making. Two of the games included decision-making as part of their topic area declaration. Because all of the game developers were affiliated with the United States Department of Defense, the content of their games, the topic areas, and in some cases, the titles of their games reflected this affiliation.

Table 6. Game full titles and nicknames

Full title	Nickname
Zombie Survival “Design a system to combat the zombie invasion”	Zombie
Air Force Test Matrix “Experience systems engineering in support of system flight test”	Matrix
P.Owned “Make decisions to build your character into a product owner”	Owned
The Program Office “Practice all facets of risk management as a program office engineer”	Program
In-Flight Emergency “Experience the decisions of an engineer reacting to an aircraft design flaw”	Emergency
The Haunting of the Life Cycle Management Center “Learn model-based systems engineering principles by exploring the remains of a haunted system development organization”	Haunting
RapidSat “Practice system design trades in the context of a satellite development”	RapidSat
Integration of EO/IR on the B-1B: A Case Study in Integration Trade-Off “Experience the system trades while integrating a new sensor onto the B-1B aircraft”	Integration
Product Owner “Practice implementing the role of the product owner in a scrum process”	Product
NASCAR Challenge: Road to the Daytona 500 “Experience stakeholder requirements definition for a NASCAR racecar”	Challenge

ThunderColt "Resource management, systems science, and systems thinking converge"	ThunderColt
Rocket Scientist Certification Program "Become certified as a rocket scientist by learning systems thinking"	Rocket
Hunting the Wumpus "Learn model-based systems engineering while paying homage to the 1973 video game, Hunt the Wumpus"	Hunting
Where in the SPO is Systems Engineering? "Explore system of systems engineering with a focus on interfaces in a game reminiscent of the famous Public Broadcasting System TV show"	Where

To categorize each game (Table 6), a topic area, the intended audience, and the level of Bloom's Taxonomy is given for each game. Except for the topic area, which we assigned, the students reported the other information in their answers to the free form questions (Table 5). Valid intended audiences included junior, mid, and senior systems engineers. Valid levels of Bloom's Taxonomy (from lowest to highest) included Remember (i.e., recalling facts and concepts), Understand (explaining ideas or concepts), Apply (using information in new situations), Analyze (draw connection between ideas), Evaluate (justify a decision), Create (produce original work). The revised Bloom's Taxonomy for the cognitive domain was provided to the students [58]. Game players did not always agree with the game developers on the targeted educational level of the games. For example, although the game developer designed the game to a single educational level (e.g., Apply), individual game players assessed the game at a variety of other levels (e.g., Analyze and Evaluate). We attribute this situation to the fact that some games apparently straddled multiple levels, but also some game developers and game players may not have understood the distinction between the levels. Of note, all 14 games were assessed by game players at the Apply level; of these, 7 games also being assessed at the Analyze level. This is consistent with the guidance given to each game developer to teach a systems engineering principle and pass on a systems engineering experience. Two of the games were assessed at each level of Bloom's Taxonomy by at least one game player. Interestingly, those two games have identical mid-range cognitive scores, but very different qualitative scores.

Table 7. Game topics, intended audience, and targeted educational level

Nickname	Topic Area	Intended Audience	Bloom's Taxonomy Level
Zombie	System Design	Entry-level	Apply
Matrix	Flight Test	Mid-level	Apply / Analyze
Owned	Agile Software Product Owner	Entry- to Mid-level	Apply
Program	Risk Management	Junior-level	Understand / Apply
Emergency	Systems Engineering Decision-Making	Mid-level	Apply
Haunting	Model-Based Systems Engineering	Junior-level	Apply / Analyze
RapidSat	System Design Trades	Junior-level	Understand / Apply / Analyze
Integration	Integration Trade-Off Decision-Making	Junior- to Mid-level	Apply
Product	Engineering Software as a Scrum Product Owner	Entry- to Mid-level	All
Challenge	Stakeholder Requirements Definition	Unstated	Apply / Analyze

ThunderColt	Resource Management & Systems Thinking	Junior-level	Apply
Rocket	Systems Thinking	Unstated	Apply / Analyze / Evaluate
Hunting	Model-based Systems Engineering	Junior-level	All
Where	System of System Interfaces and Requirements	Junior-level	Understand / Apply / Analyze / Evaluate

4.2 Aggregate assessments of games

The two most important assessments made of the games by the student game players were the games' cognitive viability and their quality. Games with a higher cognitive viability score were deemed to have a greater ability to "encourage higher order thinking" in its players [50]. The valid range for the cognitive viability score was 0 to 20. On the other hand, well-designed games received a higher quality score which could range from 8 to 40. Of course, the ideal game would receive a perfect score of 20 on the cognitive scale and 40 on the qualitative scale. Box and whisker plot analysis (Figure 1 and Figure 2) shows a fair amount of variability in both cognitive and quality assessment for both game sets. The average cognitive score for Game Set #1 was 12.5 indicating fewer opportunities for higher order thinking. Game players varied in their opinion, however, giving scores as low as 7 and as high as 16. The average cognitive score for Game Set #2 was similar at 12.1 with an even greater variability ranging from 2 to 19. For Game Set #1, the average quality score was 28.7 and Game Set #2 was nearly identical with an average quality of 28.6. These scores indicated a high-level of quality according to our rubric. These scores were unexpected as the game developers had only three weeks to develop their game. Like the cognitive scores, variability was high with Game Set #1 players assigning scores from 15 to a perfect 40 and Game Set #2 players assigning scores ranging from 14 to a perfect 40. During the game development period we observed that student attitudes toward computer games varied from "I don't play games" to "Computer games are my thing." This likely explains some of the variation. Additionally, while most students seemed excited at the prospect of creating and playing systems engineering-focused serious games, some students seemed ambivalent at best. We felt this was another source of variation in the cognitive and quality scores. In spite of the lower-than-expected cognitive scores for both game sets, the game players indicated a more than 50% chance they would play the game again and/or recommend it to others. The average replayability score for Game Set #1 was 1.5 and that of Game Set #2 was 1.3. As expected, game player scores varied from the minimum of 0 to the maximum possible score of 2.

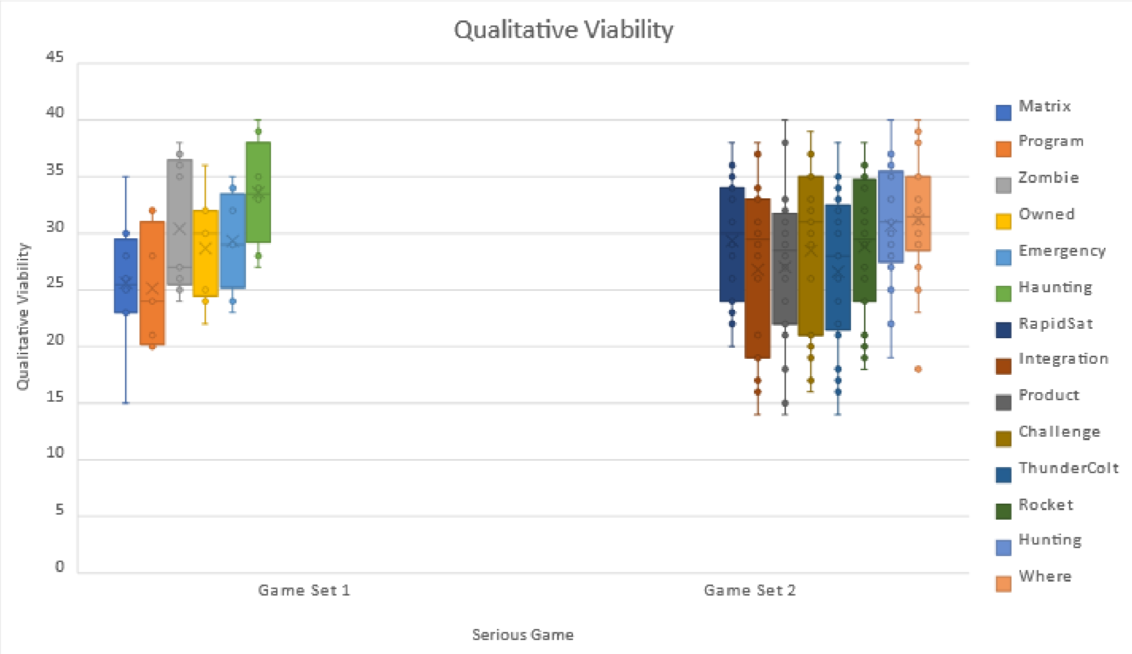

Figure 1. Qualitative viability scores

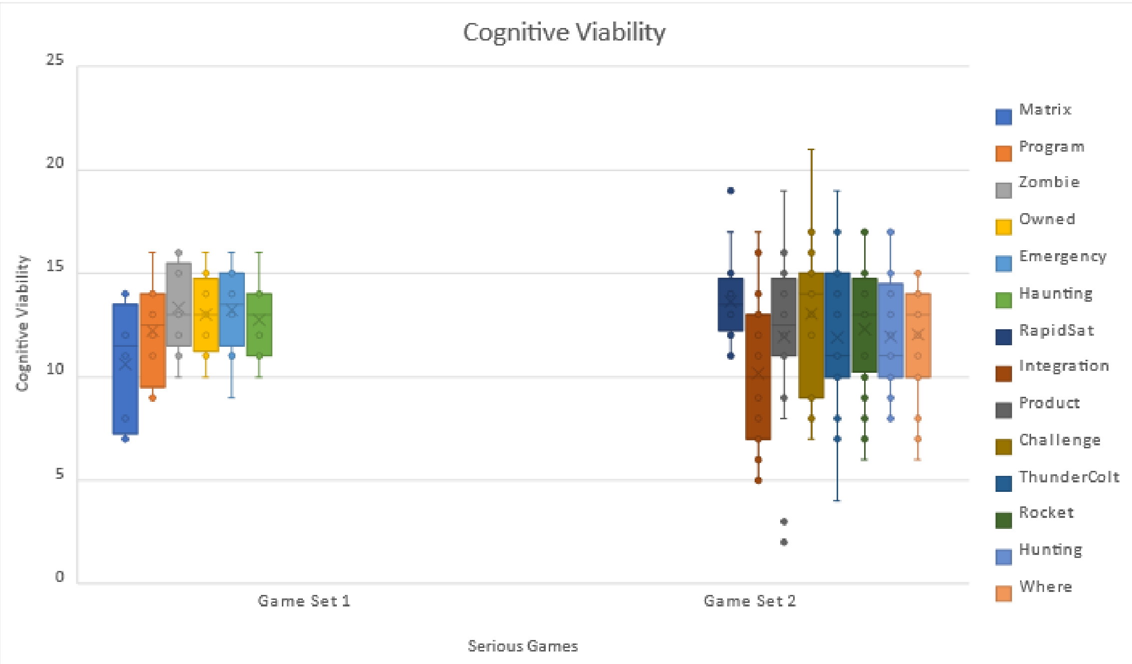

Figure 2. Cognitive viability scores

The scatter plot in Figure 3 shows each game plotted with respect to its qualitative and cognitive scores. To improve readability of the plot both the quality and cognitive axes are truncated around the actual quality and cognitive scores for each game. The optimality point beyond the top-right corner of the graph (i.e., a quality score of 40 and a cognitive score of 20). There is some clustering of the qualitative / cognitive data as well as some outlier data points.

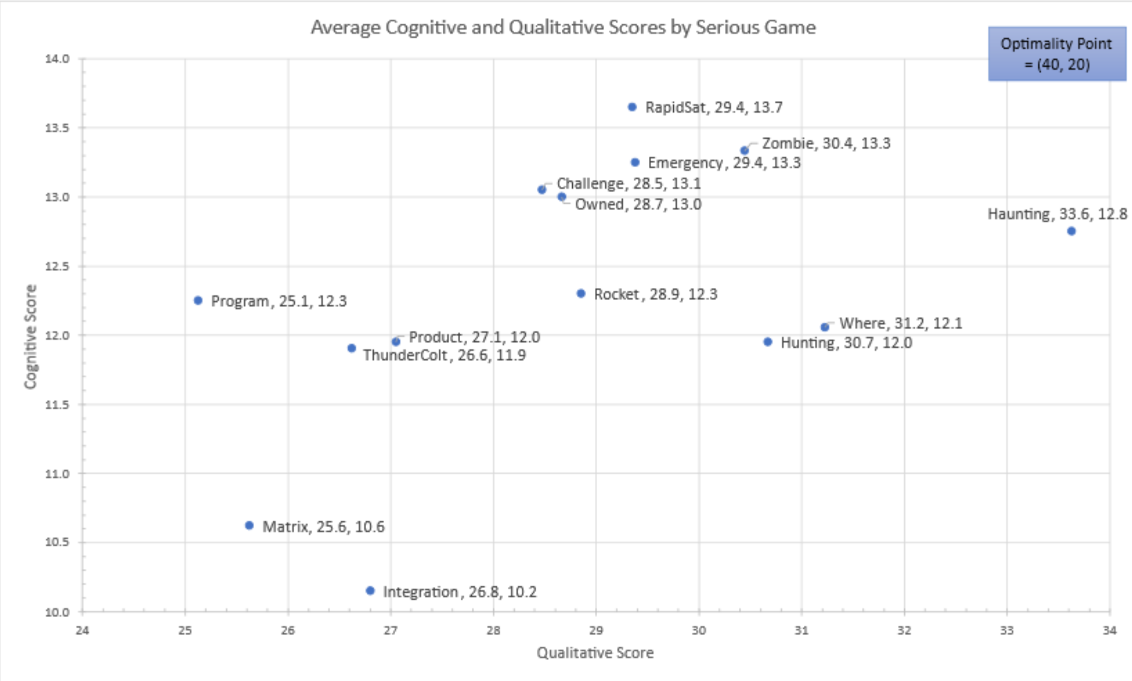

Figure 3. Cognitive and qualitative scores by serious game

4.3 Detailed assessment of games

According to the Video Game Higher Order Thinking Evaluation Rubric used to assess cognitive viability of each game, a score of 9 – 13 indicates the lower range of cognitive viability (i.e., few opportunities for higher order thinking). All fourteen games fell in this range. Although this might seem disappointing to those hoping for proof that interactive fiction systems engineering serious games provide a greater opportunity for higher order thinking, it is important to point out that each game was effectively designed to this level of cognitive viability. This is made clear when noticing that all fourteen games were designed to the Apply level of Bloom's Taxonomy, which is just above Remember and Understand. This indicates that the game designers purposely focused more on conveying principles of systems engineering sprinkled with some opportunity to explore how they are applied. For example, game players were given the opportunity to design a system, build a product backlog, or interpret the behavior of in-game characters. In general, the games were not designed to teach higher order thinking captured at the Analyze, Evaluate, and Create levels of learning which would ostensibly give the game player an opportunity to differentiate, compare, contrast, argue, critique, or even innovate something new. Although some students assessed some of the games as providing learning opportunities at higher levels of Bloom's Taxonomy, because they did not only assess a game either starting at or only at Analyze, Evaluate, or Create, we deduce that they only saw snippets of opportunity for higher order learning, but did not feel any of the games strictly existed at those levels.

The games assessed highest with respect to cognitive viability include Owned, Challenge, Emergency, Zombie, and RapidSat which formed a cognitive cluster ranging from 13.0 to 13.7. The ten top-scoring questions on the cognitive rubric for each game set are captured in Table 8. There is 90% commonality (marked with an asterisk) between the game sets (although the questions are not all in the same order). These top scoring questions reflect the requirements placed on the game designers (i.e., teach a systems engineering concept, impart a systems engineering experience, include a storyline, make the game replayable, etc.). Cognitive questions such as "Require synthesis of knowledge," "Offer simple puzzles," and "Offer meaningful interaction" also indicate the game designers' focus on the Apply level of Bloom's Taxonomy. Differences between Game Set #1 and Game Set #2 can be explained in a variety of ways; for example, the designers in Game Set #1 were younger and appeared to have a stronger desire and ability to use graphics and sound in their games whereas the older designers in Game Set #2 tried to capture the complexity of real life based upon their more extensive systems engineering experiences.

Table 8. Highest scoring cognitive viability questions by game set

Game Set #1	$\bar{x}$	σ	*Game Set #2*	$\bar{x}$	σ
*Has a storyline	0.97	0.14	*Has a storyline	0.97	0.16
*Offers meaningful interaction, such as dialogue with NPCs	0.93	0.24	*Requires the player to assume a role in the game, rather than simply play	0.96	0.21
*Allows different ways to complete the game	0.93	0.24	Simulates complex processes requiring adjustment of variables by users to obtain desired results or adjusting variables leads to different results	0.84	0.36
*Offers replay ability with varying results	0.95	0.20	*Allows different ways to complete the game	0.84	0.37
*Requires player to assume a role in the game, rather than simply play	0.91	0.28	*Offers simple puzzles	0.81	0.39
*Requires synthesis of knowledge to complete or successfully engage elements in the game	0.89	0.31	*Requires synthesis of knowledge to complete or successfully engage elements in the game	0.82	0.38
*Requires gathering of information in order to complete	0.87	0.33	*The environment within the serious game effectively replicates the real world	0.81	0.39
*The environment within the serious game effectively replicates the real world	0.77	0.42	*Requires gathering of information in order to complete	0.81	0.39
*Offers simple puzzles	0.73	0.45	*Offers replay ability with varying results	0.82	0.38
Uses graphics & sound	0.73	0.45	*Offers meaningful interaction, such as dialogue with NPCs	0.77	0.42

According to the Qualitative Rubric, a score of 25 – 32 represented high quality, and games scoring 33 – 40 were superlative with respect to mechanics, dynamics, aesthetics, education, and entertainment. The games scoring the highest on the cognitive index also scored the highest on the qualitative index (i.e., scores ranging from 28.5 to 29.4) (Table 9), with the addition of one additional game, Haunting which scored the highest on the quality index and edged into the superlative quality category with a score of 33.6. Because the highest-rated cognitive games were also of the highest quality, we infer that there is a relationship between the two indices. There was 66% commonality between game sets with respect to top-rated quality questions. The first three questions were even in the same order between game sets. The younger developers in Game Set #1 were more interested in the dynamics and aesthetics of the games while the older game developers from Game Set #2 differentiated themselves by showing in interest in the games being fun and having good mechanics. Game developers from both groups scored all questions above average (i.e., above 3). Game Set #1 developers average scores ranged from 3.5 to 3.8 while Game Set #2 developers were a bit more critical and rated their games from 3.2 to 3.8. Both sets of developers recognized the Twine interactive fiction gaming engine as an above-average tool for creating systems engineering serious games. The score for this question was the third highest for both groups of game developers. We believe that if the game developers had more time to develop their games that the quality scores would have been higher. The students developing the games reported that they were very pressed for time to learn the Twine gaming engine and develop high quality games.

Table 9. Highest scoring qualitative viability questions by game set

Game Set #1	$\bar{x}$	σ	*Game Set #2*	$\bar{x}$	σ
How interesting was the serious game to play?	3.67	1.11	How interesting was the serious game to play?	3.82	1.00
How well did the serious game convey a useful systems engineering experience?	3.75	0.83	How well did the serious game convey a useful systems engineering experience?	3.73	1.11
How appropriate is the Twine gaming engine for creating SE serious games?	3.85	0.91	How appropriate is the Twine gaming engine for creating SE serious games?	3.64	1.13
How engrossed were you in the story while playing the serious game?	3.59	1.02	How fun was the serious game to play?	3.54	1.18
How well did the dynamics of the serious game contribute to conveying the SE experience?	3.55	0.91	How engrossed were you in the story while playing the serious game?	3.54	1.02
How well did the aesthetics of the serious game contribute to conveying the SE experience?	3.55	0.98	How well did the mechanics of the serious game contribute to conveying the SE experience?	3.54	1.13

Replayability was assessed on a scale of zero to two. The average replayability score for Game Set #1 games was 1.47 and for Game Set #2 was 1.27 indicating a greater than 50% likelihood that they would play the games again or recommend them to others to play. Variances were high at 0.53 and 0.74 respectively indicating that whether a game is worth replaying or recommending to others may be subjectively based upon the game player's personality. A correlation analysis indicates that quality & replayability were highly correlated ($\rho = 0.91$) while quality & cognitive and cognitive & replayability were less correlated with each other but had nearly identical correlations ($\rho = 0.49$ and $\rho = 0.50$). For example, Haunting had a nearly perfect replayability score of 1.9 and was the highest scoring game with respect to quality (33.6). Similarly, Zombie, obtained a perfect replayability score and was fourth on the qualitative scale. Although this may seem a disconnect, games scoring in second, third, and fourth place on the qualitative scale were in a tight cluster with less than a single point differentiating them. Student game players indicated that these high-quality games were just really fun to play.

5. Conclusion

Systems engineers spend many years attempting to accumulate the experience required to perform their duties, but as junior- and mid-level systems engineers may still never have an opportunity to learn important aspects of their domain. For example, they may struggle to gain the experiences required to deal with a product failure as a chief engineer and may rely heavily upon mentors throughout their careers to try to gain missing knowledge required for them to perform well in these difficult situations. This lack of a complete repertoire of systems engineering experience highlights the need to provide a way for new, mid-level, and even senior systems engineers opportunities to gain necessary systems engineering experience in ways other than waiting for the right jobs to come available or hoping to gain experience through mere happenstance. A way to convey large amounts of important systems engineering experience in efficient ways is needed and this method of accumulating systems engineering experience should also be motivating. We surveyed existing systems engineering games, finding that they were relatively few in number, were not widely disseminated, and were largely focused on requirements management. We also surveyed the use of interactive fiction in providing experiential education reporting that many domains are using interactive fiction to educate, especially in the medical sciences fields. We also surveyed methods of assessing the cognitive viability and quality of serious games finding that the Video Game Higher Order Thinking Evaluation Rubric is appropriate for assessing cognitive viability and our own qualitative assessment rubric is appropriate for assessing serious game quality.

We postulated that serious systems engineering experiential games, of the interactive fiction genre, built using the Twine gaming engine, may be a way to quickly generate games which impart systems engineering experience in an entertaining, useful, and replayable way. 31 students in two groups over a one-year period created 14 systems engineering interactive fiction serious games using the Twine gaming engine as part of a capstone graduate course in advanced systems engineering at the United States Air Force Institute of Technology. Students were given approximately three to four weeks to learn the Twine gaming engine and construct their game which conveyed a systems engineering experience and taught a systems engineering principle. The games were creative and covered a wide range of systems engineering topics. Most were built at the Apply and Analyze levels of Bloom's Taxonomy and were designed to be played by Entry- through Mid-level systems engineers. The average cognitive score for both game sets were similar (12.5 and 12.1) indicating fewer opportunities for higher order thinking. This score aligned with the design-to level of Bloom's Taxonomy. Game Set #1 and #2 also had similar quality scores (28.7 and 28.6) indicating a high level of quality according to the rubric. Game replayability scores between the two game sets were similar (1.5 and 1.3) indicating that players had an above average desire to replay the games or share them with colleagues. We found that there was a strong correlation between game quality and replayability (0.91) with less correlation between cognitive viability and replayability (0.50) indicating that students demand excellence and value in systems engineering serious games.

The first known interactive fiction systems engineering serious games created for this research show promise as a mechanism for sharing important systems engineering experiences in an entertaining and efficient way. These types of games built using the Twine gaming engine can be created quickly, as demonstrated by the four-week turnaround time. Our research indicates that junior- through senior-level systems engineers all enjoyed creating and playing interactive fiction serious games focused on teaching systems engineering principles and sharing systems engineering experiences. Possibly the greatest implication of our research is the discovery that these interactive fiction-based serious games allow systems engineers to learn, practice making decisions, and explore options in non-threatening, enjoyable, and challenging ways. We plan to continue our research focusing on developing methods for building advanced systems engineering interactive fiction games which address the higher levels of Bloom's Taxonomy to improve cognitive viability. We also plan to investigate other gaming engines, or combinations of gaming engines which might result in higher quality games which offer greater opportunities for enjoyable and challenging learning.

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Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work in this paper.

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