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Game-Based Learning for Systems Engineering Concepts

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Abstract

Game-based learning has the potential to improve the education and performance of engineers and decision makers in the systems engineering field. This paper reviews the arguments for the use of educational gaming, with particular attention to the aspects of game-based learning that are well suited to tackling the complex sociotechnical systems engineering problems that currently are trusted only to experts with years of experience. It also describes the development of an educational game, Space Tug Skirmish, designed to be used as a teaching and research tool for systems engineering core concepts.

Selection and peer-review under responsibility of the University of Southern California.

Keywords: *systems engineering education; systems thinking; educational games; game-based learning*

1. Introduction

Systems engineering has long been considered a difficult field in which to train and educate new practitioners. A common belief amongst system engineers is that it takes years of engineering experience before a person is qualified to begin functioning in a systems role[1]. This challenge is largely due to the integrative role of the systems engineer,

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typically requiring deeper understanding of a wide range of areas than provided by a focused education, and the inherent abstractness of high-level systems concepts. For example, the –ilities are often challenging for traditional engineers to understand when they are first exposed to the concept, as they are considered important system characteristics despite not contributing directly to system performance or mission completion. The most common way to achieve familiarity with concepts such as the –ilities has been through work experience, as students can take a year or more to become comfortable working with and understanding these abstract and often confusing topics.

This paper will review the use of games as educational tools, with particular attention paid to the specific advantages of game-based media over traditional methods for the purpose of systems engineering education. The paper will describe the development of Space Tug Skirmish (STS), a game created as a systems engineering concept education and research tool. 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. The paper concludes with a brief discussion of STS and opportunities for further research.

2. Background

2.1. Rise of games as pedagogical medium

Educational gaming and game-based learning is an emerging field that seeks to use the medium of games to make knowledge accessible to a wide range of potential players[2,3]. Games have been shown to be extremely effective tools for learning, particularly due to their ability to create a "system" that players are allowed to test and experiment with, encouraging learning through "failures" that may not be acceptable in a real-world application[4,5,6]. Additionally, games provide a medium for encoding the complexity and emergent behavior that are endemic to many systems engineering problems[4]. This has the potential to target the source of many of the challenges associated with educating new systems engineers using traditional means and, additionally, to assist even experienced systems engineers in rapidly gaining familiarity with new domains and problem spaces[7],[8].

The concept of using games for education and training is not new, with decades of research on the use of games to support learning. Usually games are developed with specific learning objectives in mind, constructed upon mature knowledge, such as scientific principles, historical facts, or mathematical techniques. While the effectiveness of games for pedagogy is still being established[2,9], the rise of interactivity via computer-based games indicates that implementation may be ahead of research[10]. Adoption of games in learning settings rests upon several appealing aspects inherent in the game construct, including abstraction of complexity, guided discovery of behaviors and rules, application and development of skills in the player (i.e. "learning by doing"), appeal and motivation for the player (e.g. win-conditions and "fun"), and ability to shape the context in which the player learns[4,5,6,11].

The concept of "game" can run the gamut across a spectrum of both use (from entertainment to education to training) and implementation (from board games to role playing games to computer games)[12]. The distinction between game and "serious" game arose because of the pejorative notion of games as "light" and not appropriate in a serious environment (e.g. professional context, adult education, etc.)[13]. The label "serious" serves to indicate the game has a "serious" purpose[14]. More recently "purposeful" has been used as a label for games designed to convey a message (e.g. a social message such as "you should conserve natural resources"). Simulations are intended to be realistic depictions of a problem, and are most applicable to training-type games where the player is intended to develop literal skills that are directly transferable to the real world. Games more generally, however have the freedom to abstract the "real" problem so players can have targeted experiences with pedagogical constructs, so long as the skills developed are still transferable to the "real" world. It should be noted that there is a difference between "game-ifying" and developing a game. The former is imposing game-like mechanics and reward systems onto a classical problem (e.g. design of a mechanical structure, with players earning "points" to "win" if they do well[15]), while the latter is developing a compelling experience in the mind of a player through the balancing of story, mechanics, aesthetics, and technology[16]. For the purposes of this paper, game-based learning uses the latter concept of game to support pedagogical aims.

2.2. Challenges in systems education and research

A key challenge in using a game-based approach for teaching and studying systems engineering concepts involves the inherent nature of the systems of interest to systems engineering. In particular, the large, complex systems of interest to modern systems engineering researchers often involve many interacting and connected parts, which together result in emergent behavior that may or may not be desirable to system stakeholders. In developing an appropriate game-based implementation, the "system" represented within and by the game must represent no more and no less than the essential complexity that displays the minimum set of constructs that will facilitate learning and transfer of appropriate systems engineering knowledge and skills (K&S). These represent two challenges: essential complexity and representativeness. The former is how well the game exposes players to components, interactions, and emergence, without cognitively overwhelming the player. The latter is how well the game, or game subject, meaningfully represents a "real" system or at least a system that induces transferable K&S.

The project in this paper addresses the question of how game-based media can be used not only to teach systems engineering concepts, but also be used as a research instrument itself[17]. As has been pointed out earlier, games themselves are systems and can be designed to display the features and qualities of interest to systems engineers. Recognizing this, a natural question arises concerning a common data shortage problem in systems research: how can a game be designed as an abstraction of a real system in order to present unique opportunities for research into the *actual* system and associated human behavior? This question will only be partially addressed in this paper, but frames the intended use of the developed game as a testbed for future systems engineering and systems thinking research.

Lastly, an additional challenge in using game-based media for systems engineering education and research is that techniques for game design and efficacy for teaching are still not well-accepted. Implementations of serious gaming have demonstrated efficacy in multi-stakeholder situations, at least anecdotally, promoting human to human discourse and discovery in policy making for socio-technical systems[18,19]. But there are still many competing theories on what makes a good game and how one evaluates not only the outcomes (i.e. what the students have learned) but also the game itself (i.e. whether the game is good at what it was designed to accomplish) [20,21,22].

In spite of these challenges, gaming has the potential to enhance both education and research in systems thinking. Potential benefits include (1) enhancing the systems thinking of both novices and experts, (2) the tailoring of education programs by revealing common weaknesses in the strategies of novices, and (3) improvement in the performance of fielded systems through practice with gaming. This paper intends to motivate further research toward realizing these benefits.

3. Approach for Systems Engineering Game Development

The approach used for this project was to first distill the systems engineering research conducted at the MIT Systems Engineering Advancement Research Initiative (SEAri) down to core concepts. Next, the team leveraged game design and evaluation techniques from the literature in order to compose a purposeful game to simulate a compelling "systems engineering" experience in the mind of the player.

3.1. SEAri research and core concepts

Prior to the summer of 2011, a workshop was held among the students and staff conducting research at MIT SEAri in order to identify a minimum set of concepts reflected across more than ten years of research in value-driven systems design and analysis. The result of this workshop was the identification of six core systems engineering concepts and how they are represented in SEAri research (i.e. SEAri constructs, SC). The six core systems engineering concepts identified are: 1) benefits, 2) "design" choices, 3) resources, 4) uncertainties, 5) time-dependence, and 6) contingent value (illustrated in Fig. 1). These concepts are now described below:

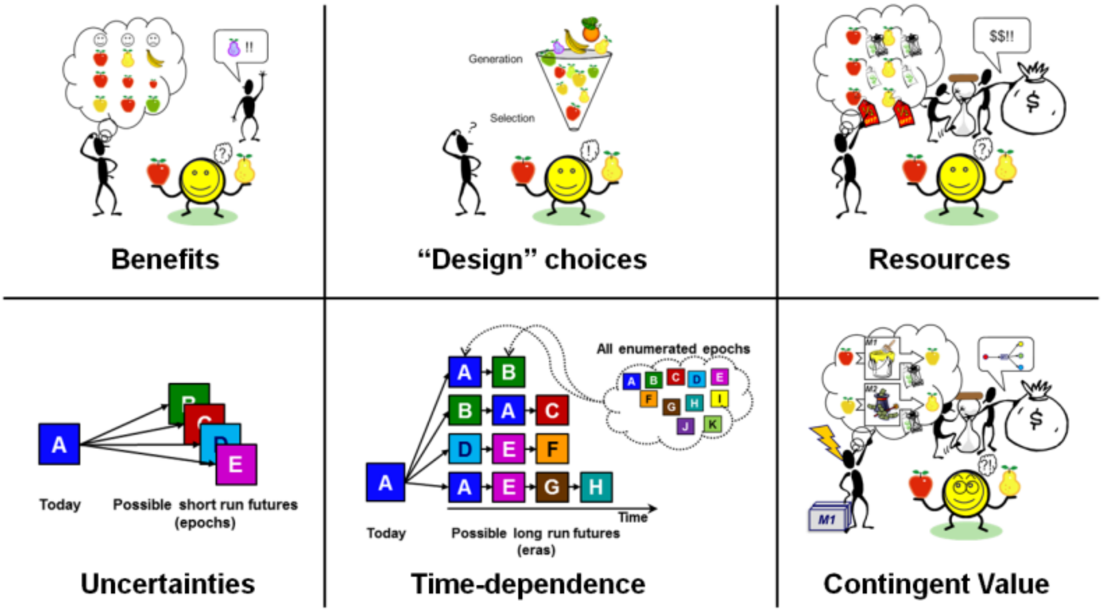

Fig. 1 Six core systems engineering constructs

- Benefits are the perceived positive impacts accrued from a design choice (subjectively defined, varying by person and across time). [SC: utilities by decision maker]
- "Design" choices are the initial and delayed alternatives that are generated and selected. [SC: design variables]
- Resources are the expended currencies required to achieve the benefits, incurred initially, over time, and at the end of life (these may include more than just dollars, such as time, effort, and expertise). [SC: generalized costs]
- Uncertainties are the short run "fixed" context and resource/benefit expectations for a choice; outside of a "designer's" control; looking into the future, many possible short runs exist, one for each uncertain version of reality. [SC: epochs]
- Time-dependence is the long run, time-ordered sequences of the short run, capturing the "path-dependency" of uncertain timelines, allowing for strategy development of "choices" over time. [SC: eras]
- Contingent value describes temporal system properties that represent the ability of a choice to change over time, or not need to change over time, often in response to a revealed "perturbation." [SC: "change-type" ilities]

3.2. Art and science of purposeful game design and analysis

Following the identification of the six core constructs, the project team consulted with the MIT Gamelab (formerly MIT Gambit), which is a research group that "explores the potential of play [as expressed in games]" with a staff that includes researchers and professional game developers interested in "developing games to demonstrate and conduct research."[23] With guidance leveraging Gamelab's extensive expertise developing award-winning games, as well as guidance on the art of game design by Jesse Schell[16], director of the Carnegie Mellon University Entertainment Technology Center, the team developed a project called Space Tug Skirmish, with the goal of encapsulating (at least) the six core systems engineering constructs into a board game medium.

4. Development of Space Tug Skirmish

Space Tug Skirmish (STS) was originally conceived in the summer of 2011 as a potential solution to the challenge of rapidly teaching SEAri research material using the medium of games. Over the years, it had become readily apparent that the lab's graduate students typically required a year of immersion before existing SEAri research methods and terminology began to feel tangible, delaying their ability to contribute effectively with individual research. Given that SEAri's research was also placed at the interface of engineering and upper-management decision making, this slow learning curve was also problematic in demonstrating contributions to potential high-level adopters, particular those with less technical backgrounds. Educational games seemed to offer a great deal of promise as both an effective way of conveying complex ideas and relationships in a short period of time and also a fun distillation of the work that could be used to spark interest.

The summer of 2011 featured a concerted effort towards educational games at SEAri, including multiple weeks of seminars and game prototyping practice, leading into an undergraduate game project designed to leverage current research in tradespace exploration and visualization. While this was occurring, a side project developed attempting to answer a more fundamental need: can we use a game to teach a completely unsophisticated player (no social/technical/systems experience) a basic understanding of system design, particularly the benefits of –ilities (e.g. adaptability, survivability, etc.) given future uncertainty? This question became the catalyst for the central idea behind STS, a card game designed to evoke the tension between designing a system and operating it, all while other players and random uncertainties try to interfere with system goals.

4.1. Overview of gameplay

The basic gameplay of STS revolves around the players, as entrants into the emerging market of rental space tug services that can move objects in low Earth orbit, competing to be the first to make one hundred million dollars. To do this, they control their tug as they alternate between two phases of play, Design and Ops. Each phase has its own set of cards which are only usable within that phase. The two phases have different high level goals: Design phase revolves around playing cards that improve the tug, increasing income or providing useful traits and abilities, while Ops phase is the time in which money can be made and attacks can be directed at opponents. Given limited starting funds, each player will typically alternate between phases multiple times over the course of the game, gradually making money and spending it to further improve their tug. Meanwhile, all players are exposed to uncertainty in the form of the Epoch deck, which reveals new contexts, contracts, and disturbances every round. A brief description of the card types and their connection to the systems engineering constructs are included here:

- Feature – Features are Design phase cards that are attached to your space tug when played, generating a fixed amount of income per turn while in Ops phase.
- Spec – Specs are Design phase cards that are attached to your space tug when played. There are three subtypes of Specs: Propulsion (Prop), Fuel Tank (Fuel), and Manipulator (Manip). Only one spec of each subtype is allowed on each tug. Specs provide the "stats" (power, speed, and energy) that are needed to satisfy Contracts.
- Ility – Ilities are Design phase cards that are attached to your space tug when played. Each Ility provides benefits to the player in the form of new actions or abilities they can perform.
- Features, Specs, and Ilities are the foundation of the Design phase, and map directly into the construct of "design choices": decisions available to the players as they design their space tugs using the cards in their hands. All are accompanied by associated costs scaling with their power level, mapping into the "resources" and "benefits" constructs. The Ilities (and to a lesser extent, the Specs) are also targeted at the "contingent value" construct, as the benefits obtained from these cards are largely determined by significant sources of uncertainty (other players' behavior, the Epoch deck, etc.).
- Attack – Attacks are Ops phase cards that interfere with the other players with actions such as destroying equipped Design cards. Attacks are similar to "disturbances" (described below), but are executed by intelligent adversaries (e.g. other players), and were included to improve gameplay by increasing the interactivity of the players. The threat of Attacks adds to the value of many of the Ilities, which relates to "contingent value."
- Effect – Effects are in both the Design and Ops decks, and are similar to Attacks in that they are played and then discarded, but usually these come with positive benefits to the player who uses them rather than negative impacts to their opponents. Again, these cards are included mostly for gameplay enjoyment, but also generate "uncertainty," as the surprise of an Effect can change the outlook of a game quickly.
- Contract – Contracts are Epoch cards that specify a set of requirements (usually in the form of the three "stats") that, if met by a player's space tug, result in a large reward. Contracts are a key "benefit" to be gained by playing

Specs and also a significant source of "uncertainty", as there is no guarantee that the right Contracts for a player's chosen stats will arise.

- Context – Contexts are Epoch cards that denote modifications to the rules that affect all players as long as they are active. Only one Context can be active at a time, and it is replaced when a new Context is played. Contexts are meant to represent the concept of extended "uncertainties" (shifts), which strongly influence how systems can deliver "benefits" or accumulate "resource" costs.
- Disturbance – Disturbances are Epoch cards that cause one-time effects on all players, rather than consistently affecting the field of play for multiple turns like Contexts. Disturbances are conceptually short-term "uncertainties" that are intended to disrupt the players' plans and force either advance preparations or recovery.
- Persona – The Persona cards are an optional addition to the basic game. If used, each player chooses a Persona at the start of the game, taking their Persona's three cards corresponding to levels one, two and three. Starting the game at level one, the Persona guides the player into a particular playstyle by incentivizing against certain actions. Meanwhile, unlocking levels two and three involve completing midgame objectives, thus incentivizing other actions. Unlocking the higher Persona levels rewards the player with additional powers and abilities that supplement the targeted playstyle. Personas encourage role-playing and situational decision-making skills.

Each card type represents a different potential aspect of system design. Note that the card types are generalized: the potential to expand the STS framework into fields other than satellite design was intentional. A complete version of the Space Tug Skirmish rules can be found as a working paper on the SEAri website (seari.mit.edu).

4.2. Evolution of the game

The development of STS has been largely separated into three distinct endeavors, labeled as versions 1.0, 2.0, and 3.0 (with some small updates between). Each version after the first was designed to add in a new element to assist the stated learning objectives of the game, in addition to balance updates and general gameplay enjoyment improvements. The current version, 3.2, is the result of refined improvements of the original game structure, which are detailed here to illustrate the logic with which the game was created.

4.2.1. Changing from Version 1.0 to Version 2.0

Version 1.0 was the first "complete" printing of STS, and featured many of the hallmarks of the game today, particularly the various card types and the purposes of the Design and Ops deck. Version 1.0 contained Features, Specs, Ilities, Effects, and Attacks in essentially the same form as they are now. The Epoch deck did not exist in Version 1.0, but Contracts were located in the Ops deck, to be played and met in Ops phase. Contracts were also tied directly to particular Spec cards rather than the stat system. Version 1.0 was playtested extensively by a small team of graduate students over the course of six months. At this point in the design process, the main concerns of playtesting were balance (are the variety of strategies with which people play similarly likely to win?) and the inclusion of the relevant core concepts within the game mechanics. It became apparent early on that investing in Features was a considerably more consistent winning strategy than building Specs, as the combination of circumstances necessary to win a Contract (draw the Contract AND the matching Specs) was simply too rare to be a winning strategy. This was also deemed to be counterproductive on the "fun" side, as playing large amounts of Features and simply accumulating income made for relatively boring games. Additionally, the team was concerned that the "uncertainty" concept was not clearly represented in the game mechanics, at least comparatively against the others. Although drawing cards randomly out of a large deck adds significant uncertainty to the game, it was considered too abstract a lesson and there was concern that it might be viewed simply as a "way to play card games," rather than an important aspect of system design and the Space Tug story.

Version 2.0 set out to resolve both of these problems with the creation of the Epoch deck: a game element designed to explicitly represent the uncertainty which can have dramatic effects on system value (both the Space Tug itself, and the cards in a player's hand that represent future options). The Epoch deck was set to reveal a new uncertainty after every round, in order to force the game to change state and break up the "income wars" of Version 1.0. Contracts were moved from the Ops deck to the Epoch deck for two reasons. First, having Contracts in the

Epoch deck and not drawn/played by the players matched the flavor of the game significantly better, since Contracts were intended to be Space Tug service orders from outside parties. Second, it also removed the possibility that an opponent would draw a Contract matching your Specs, thus preventing you from earning the reward, which was a serious barrier for a profitable Spec-centric game plan. Context and Disturbance cards were also added into the new Epoch deck to represent these different types of uncertainty relevant to system designers. Additionally, they were designed to clarify that the "uncertainty" concept is not strictly related to negative outcomes. Version 1.0 displayed uncertainty only in downside (not-useful draws, opponent attacks, etc.), but the Contexts and Disturbance cards were purposefully split approximately 50-50 between positive and negative consequences, allowing players to practice both defending against negative uncertainties and exploiting positive uncertainties.

4.2.2. Changing from Version 2.0 to Version 3.0

Version 2.0 was playtested by a larger group of students over more than a year. The Epoch deck was determined to be a success at both representing the considerable effects of uncertainty and supporting the Spec-centric playstyle. The attention of the playtesters turned once again to balance, but with additional emphasis on the use of STS as a learning tool. Significant time was spent breaking down STS with a variety of "serious" game frameworks and models, to ensure that the game's message was clear and shared between all of its elements.

STS was created with relatively few frills, as it was intended to be a simple card game that focused mostly on mechanics in order to convey its message. However, that was not intended to replace intelligent deployment of the other three of Schell's four aspects of game design: technology, aesthetics, and story[16]. Early efforts in Version 3.0 development included a deconstruction of the mechanics and technology of STS with respect to aesthetics, story, the core concepts, skill versus chance, and connections to other SEAri-related concepts. The resulting breakdown is included in Appendix A. Of particular note are the strong matching of at least one core concept to each game mechanic and the balance between skill and chance.

Another effort at breaking down STS into its main components was performed using Mitgutsch's Serious Game Design Assessment Framework[24]. This design assessment framework was created explicitly for serious games, looking for a means to promote not only coherence but also cohesiveness in creating an experience that comports a specific, targeted lesson. This framework encompasses six main aspects: aesthetics, fiction, mechanics, framing, content, and the key "serious" aspect, purpose, defined as the intersection of the aim and impact of the game. A summary of key items discussed in the breakdown of STS using this framework is shown in Fig. 2.

This diagram shows that the mechanics of STS are the strongest aspect of the game from a cohesiveness standpoint, with strong connections to nearly all other aspects. Also the game's aesthetics are the weakest aspect, which is to be expected given lack of graphic design experience available for the project. Overall, STS performed fairly well when evaluated using this framework, particularly given the unavoidable limitations on aesthetics, but the team was interested in improving the fiction and framing of the game. It was determined that the implementation of the Persona system, a previously imagined extension to the basic game (shown in red), would succeed in this goal, as well as reinforcing the fiction-mechanics, fiction-framing, and framing-purpose cohesive connections.

The Persona system was originally conceived as a way to include avatars in STS for the players, as avatars (or other forms of player representation) are considered useful game design elements for increasing player immersion and investment[16]. Eventually however, it became clear that the Personas were a perfect opportunity for including additional learning opportunities in the game in a way that would simultaneously promote replay value. Personas were therefore implemented in Version 3.0. Essentially, the Persona cards benefit the game on four levels. First, as an avatar that players can choose, the Persona increases investment. Second, the midgame objective of leveling up the Persona provides intermediate goals and satisfaction for the players, keeping the game fun and interesting throughout. Third, the variety of Personas increases the game's replay value by differentiating games through asymmetry. And finally, the Personas offer a way for SEAri to control and guide players into exposure to specific learning objectives: since each Persona has a particular promoted playstyle, players are incentivized to playstyles (and the corresponding challenges and lessons) that they might normally avoid or never consider.

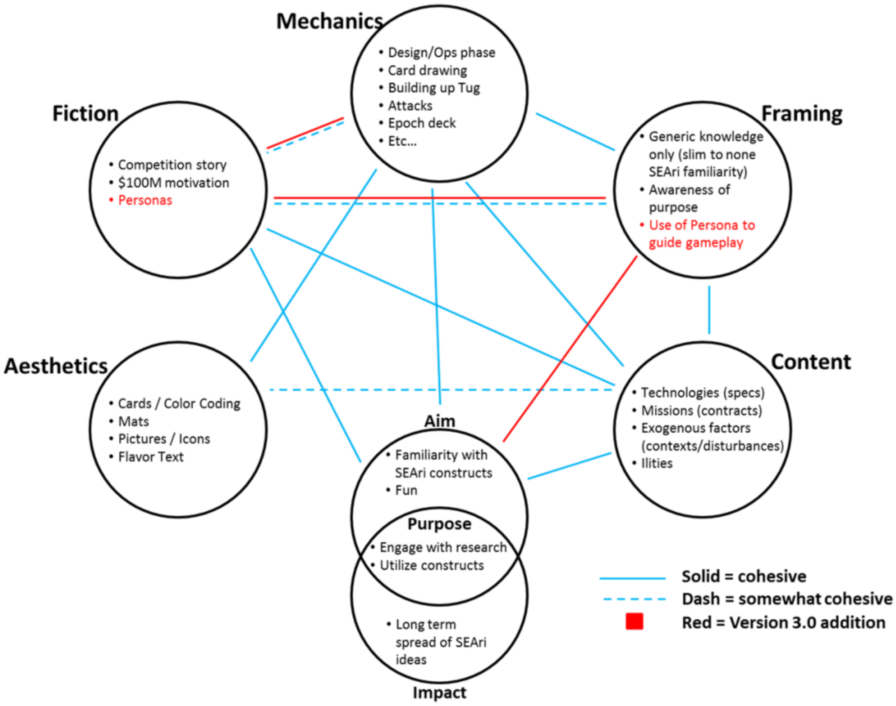

Fig. 2. A breakdown of Space Tug Skirmish with the Serious Game Design Assessment Framework[24]

The last major change to emerge from Version 3.0 development was the rework of Specs and Contracts to use the "stats" system. The original Contracts required a particular set of Specs; this is considered counterproductive by value-driven systems engineering as it implies the importance of form-dependent solutions, making assumptions on the best type of system to complete the task. In SEAri research (and other value-driven work), emphasis is placed on avoiding form-dependence, instead focusing on outcomes. Contracts were reworked into their current form to replace Specs with stats. Specs were then assigned stats according to their cost and flavor, creating a richer space with many potential solutions to any given Contract. The key outcome of this change was to make STS more consistent with a value-driven perspective, reducing the potential for mixed messages to confuse the player.

5. Discussion

It turned out that STS was actually fun to play and students would spontaneously play for hours most Fridays during the semester. Informally interviewing students revealed that each of them tended to have a preferred playstyle in the game, which suggested stable strategies for managing the uncertainty and dynamics in the game. These strategies informed the development of the mentioned Personas in order to encourage players to try out different playstyles and become exposed to the associated lessons. The emergence of these stable strategies, however, also suggested that the game itself was displaying the properties of being a system, as mentioned earlier. This suggested that collecting data on the game itself could provide an opportunity for learning about systems and human strategy development vis a vis the six systems engineering constructs. Initial data collection involved tracking of metrics, such as player budgets, cards in hand, state of the game mats, and cards played each round, as well as observation of the player's affect and socialization. It soon became clear that data collection was onerous and interfered with actual gameplay. The collection of data about strategies employed by players of varying experience has the potential to be utilized to uncover both productive and unproductive patterns of systems decision making. In order to facilitate data collection on player behaviors, a project was undertaken in the summer of 2013 to implement STS as an online-multiplayer computer game, with the primary purpose of facilitating data collection. That activity is still underway and experiments conducted with digital STS will be addressed in a future paper.

In terms of assessment, STS appears to be successful in at least two aspects. First, new students claim to have grasped the systems engineering concepts embedded in the game and are comfortable applying those concepts in new contexts (e.g. their research on real systems). Second, as described earlier, STS itself has good coverage across the serious game design assessment framework, implying that the game itself is, at the very least, cohesive and coherent in presenting its educational purpose. Further work applying more formal assessment techniques (e.g. experimental verification that knowledge of the game transfers to mastery of systems engineering concepts) will be pursued in the future. For now, STS holds promise in at least exposing graduate students to core systems engineering constructs in a meaningful way, which results in improved and accelerated basic understanding, while engaging the students in an activity they want to pursue in their free time.

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Appendix A. Space Tug Skirmish Mechanics Deconstruction

Good game design balances four game aspects: Story, Mechanics, Aesthetics, and Technology[16]. The cards and mats are the technology in STS, with associated artwork comprising the aesthetics. Game play emerges through mechanics, which provides opportunity for lessons, as described in Table I. The core concepts in STS include the six constructs: Design (choices), Cost (resources), Utility (benefits), Epoch (uncertainty), Era (time-dependence), and Ilities (contingent value), as well as Perturbation, Options, Timing, Budget, Strategy, and Social elements.

Table I. STS mechanics mapped to lessons and aspects of game design (continued on next page)

STS Mechanic	Core Concepts	Other Concepts	Skill vs. Chance	Other Aspects
Design Phase	DESIGN, COST Make *choices* about what to build, subject to *costs*		SKILL Decision making is skill based, improves over time	STORY This is the “planning” phase of the Space Tug business
Ops Phase	UTILITY, ERA Gather *utility* over *uncertain life*		CHANCE Uncertainty dominates ops phase	STORY The “working” phase
Launch/Recover	COST, UTILITY, ERA Tradeoff *utility* of more time in ops vs. improvement in design subject to transition *costs* and *uncertainty* evolution	TIMING	SKILL Launch/recover can’t be interrupted, game sense of when to execute should improve	
Epoch Shift	EPOCH, ILITY, ERA, DESIGN *Epoch* context changes regularly, *evolving* over time. *Choices* about *Ilities* represent the best way to control these effects	PERTURBATION	CHANCE Most random aspect of game: requires acknowledgement of inability to control all circumstance	STORY Where “our” story is told: teach players about coping with this problem
Initial Constraint: $30M	DESIGN, COST Make intelligent *choices* with limited *funds*	BUDGET	SKILL Practice makes perfect	
Card Draw / Initial Hand	DESIGN Make intelligent *choices* with limited selection		CHANCE / SKILL Largely random, but skill involved in playing what you are dealt	

STS Mechanic	Core Concepts	Other Concepts	Skill vs. Chance	Other Aspects
Income	DESIGN, UTILITY *Design* system to maximize *utility* in ops, via a variety of means		SKILL Experience lends itself to smart decisions	STORY Making $ is the stated goal
Destroy, Disable, Repair	DESIGN, ILITY *Choose* how to mitigate damage, with *ilities* as a primary technique	SOCIAL, OPTIONS, PERTURBATION	SKILL Experience lends itself to smart decisions	
Hand Management (limit, discard)	DESIGN, ERA As *uncertainty evolves*, maintain potential *choices*	STRATEGY, OPTIONS	SKILL Experience lends itself to smart decisions	

References

1. Davidz H, Nightingale D, and Rhodes DH. "Enablers and Barriers to Systems Thinking Development: Results of a Qualitative and Quantitative Study." *3rd Conference on Systems Engineering Research*. Hoboken, NJ; March 2005.
2. Randall JM, Morris BA, Wetzel CD, and Whitehill BV. “The Effectiveness of Games for Educational Purposes: A Review of Recent Research.” *Simulation & Gaming* 1992; **23**(3):261-276.
3. National Research Council. *Learning Science Through Computer Games and Simulations*. Committee on Science Learning: Computer Games, Simulations, and Education. Honey MA and Hilton ML, Eds. Board on Science Education, Dividsion of Behavioural and Social Sciences and Education. Washington, DC: The National Academies Press; 2011.
4. Squire K. *Video Games and Learning: Teaching and participatory culture in the digital age*. 1st ed. New York: Teachers College Press; 2011.
5. Perkins D. *Making Learning Whole: How seven principles of teaching can transform education.*. San Francisco: Jossey-Bass; 2009.
6. Gee JP. *What Video Games Have to Teach us About Learning and Literacy*, New York: Palgrave Macmillan; 2007.
7. Lamb CT and Rhodes DH. "Collaborative Systems Thinking: Uncovering the Rules of Team-Level Systems Thinking." 3rd Annual IEEE Systems Conference.Vancouver, Canada; March 2009.
8. Huang A and Levinson D. “To Game or Not to Game: Teaching Transportation Planning with Board Games.” *Transportation Research Record: Journal of the Transportation Research Board* 2011; **2307**: 141-149.
9. Backlund P and Hendrix M. “Educational Games – Are they Worth the Effort? A literature survey on the effectiveness of serious games.” 5th Int’l Conf. on Games and Virtual Worlds for Serious Applications, September 2013.
10. Wolfe J, and Crookall D. “Developing a Scientific Knowledge of Simulation/Gaming.” *Simulation & Gaming* 1998; **29**(1): 7-19.
11. Arnab S, Berta R, Earp J, de Freitas S, Popescu M, Romero M, Stanescu I and Usart M. “Framing the Adoption of Serious Games in Formal Education” *Electronic Journal of e-Learning* 2013; **10**(2):159-171; available online at www.ejel.com.
12. Aldrich C. *The Complete Guide to Simulations & Serious Games: How the most valuable content will be created in the age beyond Gutenberg to Google*. San Francisco: Pfeiffer; 2009.
13. Derryberry A. “Serious Games: Online Games for Learning,” Adobe White Paper [online]: http://www.adobe.com/resources/elearning/pdfs/serious_games_wp.pdf (accessed 20/04/2011); 2007.
14. Djaouti D, Alvarez J, Jessel JP, and Rampnoux O. “Origins of Serious Games.” [online]: http://www.ludoscience.com/files/ressources/origins_of_serious_games.pdf (accessed 14/11/2013); 2011.
15. Ebner M and Holzinger A. “Successful implementation of user-centered game based learning in higher education: An example from civil engineering.” *Computers & Education* 2007; **49**: 873-890.
16. Schell J. *The Art of Game Design: A book of lenses*. 1st ed. Burlington, MA: Elsevier; 2008.
17. Wang AI, Ofsdahl T, Morch-Storstein OK. “*Collaborative Learning through Games – Characteristics, Model, and Taxonomy*.” [online]: http://www.idi.ntnu.no/grupper/su/publ/alfw/CollaborativeLearningThroughGames.pdf (accessed 13/11/2013); 2009
18. De Heer J, de Groot T, and Hrynkiewicz R. “Serious Gaming is Serious Business in Urban Planning.” Third Int’l Conf on Infrastructure Systems and Services: Next Generation Infrastructure Systems for Eco-Cities (INFRA). Shenzhen, China; November 2010.
19. De Caluwe L, Geurts J, Kleinlugtenbelt WJ. “Gaming Research in Policy and Organization: An Assessment from the Netherlands.” *Simulation & Gaming* 2012; **43**(5): 600-626.
20. Kriz WC, and Hense JU. “Theory-oriented Evaluation for the Design of and Research in Gaming and Simulation.” *Simulation & Gaming* 2006; **37**(2): 268-283.
21. Dondlinger MJ. “Educational Video Game Design: A Review of the Literature.” *Journal of Applied Educational Technology* 2007; **4**(1):21-31.
22. Hense J, Kriz WC, and Wolfe J. “Putting Theory-oriented Evaluation into Practice.” *Simulation & Gaming* 2009; **40**(1):110-133.
23. http://gamelab.mit.edu/about/ [online] (accessed 14/11/2013); 2013
24. Mitgutsch K and Alvarado N. “Purposeful by Design? A Serious Game Design Assessment Framework.” *Proceedings of the International Conference on the Foundations of Digital Games* (FDG ’12). ACM. New York, NY, 2012; 121-128.