Kim, S., Rybkowski, Z. K. & Jeong, H. D. (2023). Developing and testing computer- and virtual reality-based target value design simulations. *Proceedings of the 31st Annual Conference of the International Group for Lean Construction (IGLC31),* 629–638. doi.org/10.24928/2023/0194

DEVELOPING AND TESTING COMPUTER- AND VIRTUAL REALITY-BASED TARGET VALUE DESIGN SIMULATIONS

Suryeon Kim[1], Zofia Rybkowski[2], and H. David Jeong[3]

ABSTRACT

Knowledge of fundamental lean construction principles and tools is often imparted through the physical playing of serious games and simulations. However, globalization and the emergence of the recent pandemic have created increasing demands for scalability, as well as for diverse player usability and remote implementation of the games. That said, there are challenges associated with transforming existing lean simulations to technology-oriented modes, such as computer- and VR-based formats. For example, while the potential of using advanced formats is promising, it is unclear if these versions offer an equivalent level of learning effectiveness as in-person play. This research reports on the development and testing of different forms of the Marshmallow Target Value Design (TVD) Simulation, including computer- and VR-based formats. Researchers administered and assessed post-simulation questionnaires, and the moderator effect of perceived usability was determined and analyzed. Results show that the computer-based format was more effective than the physical-based format for some TVD principles and that the VR-based format was more effective than the physical-based Marshmallow TVD Simulation for most TVD principles. For the computer-based format, usability moderated learning effectiveness. These results indicate that when developing a computer-based simulation, the usability of the simulation must be considered to ensure maximum effectiveness.

KEYWORDS

Serious games, simulations, target value delivery (TVD), computer-based simulation, VR-based simulation.

INTRODUCTION

Serious games and simulations, primarily designed for educational purposes other than entertainment, play a vital role in the testing and teaching of lean design and construction principles and methods (Bhatnagar et al., 2022; Tsao & Howell, 2015). They impart confidence about lean principles, and by creating a highly immersive environment, they make learning enjoyable. This pedagogical approach promotes engagement and creates links to applicability of instructional content by bridging the knowledge gap between theory and applications (De Freitas & Oliver, 2006; De Freitas & Levene, 2004). Serious games and simulations have been shown to students and practitioners to be effective in imparting lean construction principles

[1] Ph.D. Candidate, Department of Construction Science, School of Architecture, Texas A&M University, College Station, TX, USA, kimsuryeon@tamu.edu, orcid.org/0009-0002-2231-6674

[2] Associate Professor, Department of Construction Science, School of Architecture, Texas A&M University, College Station, TX, USA, zrybkowski@arch.tamu.edu, orcid.org/0000-0002-0683-5004

[3] Professor, Department of Construction Science, School of Architecture, Texas A&M University, College Station, TX, USA, djeong@tamu.edu, orcid.org/0000-0003-4074-1869

and tools—as well as in creating buy-in with participants. In fact the expansion of adoption of lean construction is likely responsible, at least in part, to the illustrative impact of serious games in both academia and industry (Bhatnagar et al., 2022).

Serious games and simulations have been—and still are—typically administered in a physical format, in which in-person interactions, active task involvement, and hands-on experience are maximized; these qualities been shown to improve learning (Rybkowski et al., 2021). However, as adoption of lean construction has expanded, projects have also become increasingly globalized to include multi-cultural stakeholders; pedagogical environments have become diverse and advanced, leading to the need to enhance scalability of serious gaming. The emergence of the global COVID-19 pandemic also heightened the demand to take gaming into digitized and remote formats (Rybkowski et al., 2021). Virtual formats offer the potential to accommodate varied geographical regions with greater accessibility. They also enable users to become highly immersed in the educational process (Schroeder et al., 2020).

While there are growing efforts to transform lean serious games and simulations into advanced learning environments, such as computer- and virtual reality (VR)-based formats, several areas must still be addressed. Firstly, there is a need to know whether different learning environments can promote the same amount of knowledge retention and learning effectiveness. Although there is a prevalent belief that learning with serious games and simulations offers similar cognitive effectiveness, differences in format may be significant in their capacity to provide effective learning (Ypsilanti et al., 2014). Furthermore some researchers have concluded that computer-based serious games and simulations do not always offer a positive impact on learning (Erhel & Jamet, 2013; Liu et al., 2020). Second, computer- and VR-based formats require a certain level of technological familiarity which significantly influences users' attitudes toward active involvement (Davis, 1989; Idris et al., 2015). The success of learning lies in actual involvement in the process, and users' negative attitudes may hinder them from learning (Tsai et al., 2015; Ypsilanti et al., 2014). To systematically investigate those areas, the development and testing of serious games and simulations in different formats are needed.

This research aims to develop and systematically test two formats of simulations: a computer (keyboard)-based Marshmallow TVD Simulation and VR (headset)-based Marshmallow TVD Simulation, which mimic the physical Marshmallow TVD Simulation's overall concept, framework, and rules. Two valid research questions, which will contribute to the current body of knowledge, were explored: (1) Are there differences in knowledge retention for physical- vs. computer- vs. VR-based formats? and (2) What is the effect of perceived usefulness and usability on knowledge retention for computer- and VR-based formats?

BACKGROUND

MARSHMALLOW TVD SIMULATION

Target Value Design (TVD) is one of the most effective lean processes that adapt the target costing concept to the peculiarity of the construction industry (Zimina et al., 2012; Engebø et al., 2021; Jacob et al., 2021). TVD is a management practice that aims to deliver a project within a specified allowable budget by promoting innovation throughout the project life cycle, increasing value and eliminating waste, and continuously improving a project's design in order to reach desired goals, thereby satisfying the client's values (Alves et al., 2017; Rybkowski et al., 2016; Zimina et al., 2012). Target Value Design is an adaptation of Target Costing for construction project delivery (Ballard, 2011; Zimina et al., 2012), constituting the design phase of Target Value Delivery (Hill et al., 2016).

The Marshmallow TVD Simulation is one of the full-blown lean simulations designed for practicing the TVD process. It simplifies traditional and TVD processes so participants can intellectually grasp the TVD framework (Rybkowski et al., 2016). The simulation consists of two rounds. In each round, participants build a tower that can hold a marshmallow at the top with supplied materials (e.g., drinking straws, uncooked spaghetti noodles, coffee stirrers, bamboo sticks, masking tape, and a marshmallow). The tower should be at least 60 cm (approximately 2 feet) tall and free-standing (i.e. not taped to the table). During Round I, participants build a tower without awareness of the unit cost of each material. After the first round is finished (within approximately 20 minutes), they count and report the unit amount of each material they chose to use to build their tower so that a typical Market Cost (an average of all towers) is established. Target Cost is then set to be 20% lower than the Market Cost, and an even lower "stretch goal" (Allowable Cost) is declared by each team. During Round II, participants again build a tower, but this time within the Target Cost (and potentially even their individually declared Allowable Cost). At the start of this round, they are given information about the unit cost of each material Amounts reached per team are collected on a spreadsheet and projected on a wall for all to see and discuss following play (Munankami, 2012; Rybkowski et al., 2016).

The Marshmallow TVD Simulation is a good candidate to be developed and tested in various modes, including physical-, computer-, and VR-based formats. Firstly, it requires a sense of spatiality. One of the requirements of the tower is that it must be free-standing, which means it must resist gravity. Computer- and VR-based formats can simulate gravity using three-dimensional software programs such as Unity™. Also, the 3D-format simulates reality, offering the opportunity for flexibility and therefore variety in tower design. Additionally, the simulation software can rapidly calculate total cost based on the fixed unit cost of user-selected materials. Finally, computer- and VR-based format simulations can be augmented with add-ins.

Research Question Development

This research involved development and testing of computer- and VR-based simulations of the Marshmallow TVD Simulation. Simulation development required transformation of the physical simulation. Testing and analysis of the learning effectiveness of the two simulations required determining the moderator effect of perceived usefulness and usability of the advanced formats. Two research questions were posed:

Research question 1. Are there differences in knowledge retention for physical- vs. computer- vs. VR-based formats?

Learning effectiveness refers to the extent to which a goal or task can be achieved. This research investigated whether the different simulation formats affect a users' knowledge retention. It was investigated by evaluating instructional content after playing the simulations.

Knowledge retention was measured regarding: (a) mutual respect and trust; (b) mutual benefit and reward; (c) collaborative innovation and decision-making; (d) early involvement, (e) early goal definition; (f) intensified planning; (g) open communication; (h) appropriate technology; and effectiveness of the (i) organization and leader. These characteristics represented fundamental TVD principles intended to be conveyed through the Marshmallow TVD Simulation (Munankami, 2012), and were adopted for the consistent assessment of the three different simulation formats.

Research question 2. What is the effect of perceived usefulness and usability on knowledge retention for computer- and VR-based formats?

As computer- and VR-based formats adopt advanced technologies, a users' attitude toward technology works as an essential factor in learning effectiveness. Serious games and simulations should be usable regardless of a user's personal characteristics (Jordan, 1998). Two elements, perceived usefulness, and usability, determine the users' attitude toward the technology (Davis, 1989). This research hypothesized that these qualities moderate knowledge retention in computer- and VR-based simulations, as shown in Figure 1.

Perceived usefulness refers to the degree to which a user believes using a particular technology and system will enhance their performance. Usability refers to the level of comfort users feel and how confident they are with the simulation's capacity for them to reach specified goals (Davis, 1989). These qualities are determinants of a good user experience (Diefenbach et al., 2014; Jordan, 1998) and they help guarantee the success of learning effectiveness in computer- and VR-based formats (Pal & Vanijja, 2020).

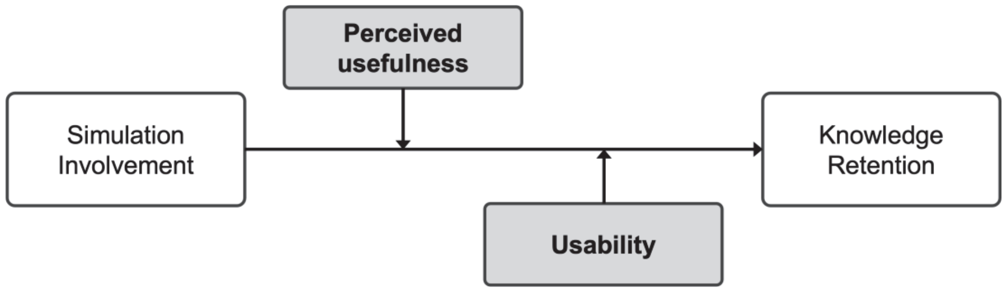


Figure 1: Conceptual Diagram for Research Question 2.

SIMULATION DESCRIPTION

COMPUTER-BASED MARSHMALLOW TVD SIMULATION

This research developed computer- and VR-based formats of Marshmallow TVD Simulation using Unity™. The 3D-software is often used for gaming and can: imitate the properties of materials with some sense of reality; simulate physical characteristics including movement and gravity; provide a user-friendly user interface; and allow multiple networking (Unity User Manual, 2020). The rules and goals of the physical format of the Marshmallow TVD Simulation were transformed into computer- and VR-based formats. Figure 2 shows how key scenes in each format were realized.

The computer-based format requires a three-button mouse (e.g. two buttons and a wheel), as well as a keyboard. Users can select objects in the scene, rotate, place, and delete the object, turn the camera, and zoom in and out with the mouse and keyboard. The computer-based format also provides a graphical user interface that allows users to interact through graphical icons in the scene.

VIRTUAL REALITY MARSHMALLOW TVD SIMULATION

The VR-based Marshmallow TVD Simulation requires users to wear a VR headset and operate controllers. There are two buttons in each controller: the grab button and the trigger button. Grab buttons are located near a user's palm and allow them to grip and release an object. Trigger buttons are operated by index fingers and enable users to activate functions such as a "gravity test" in the VR environment. To a large extent, motions and actions are similar to playing in a physical environment, so users can intuitively understand their manipulations. In the VR-based format, the following were included: a graphical user interface, a panel itemizing materials, costs, and test/return buttons.

SIMULATION TESTING

A post-simulation questionnaire was conducted to investigate the two research questions. Students majoring in construction science, architecture, and civil engineering were recruited; 32 and 26 responses were collected in computer- and VR-based formats, respectively.

Following play, participants were asked to score on a scale of 1 (lowest) to 5 (highest) their perception of the simulation's ability to impart the following key TVD concepts: (a) mutual respect and trust; (b) mutual benefit and reward; (c) collaborative innovation and decision-making; (d) early involvement of key partners; (e) early goal definition; (f) intensified planning; (g) open communication; (h) appropriate technology; and effectiveness of (i) organization and leadership. These data were compiled and compared to identify whether there are statistically significant mean differences between various formats. Previous experimental data from Munankami (2012)'s physical format were used as a control group for the first research question. For the second research question, participants were asked about their perceptions of the simulations. They evaluated the perceived usefulness and usability of the simulations.

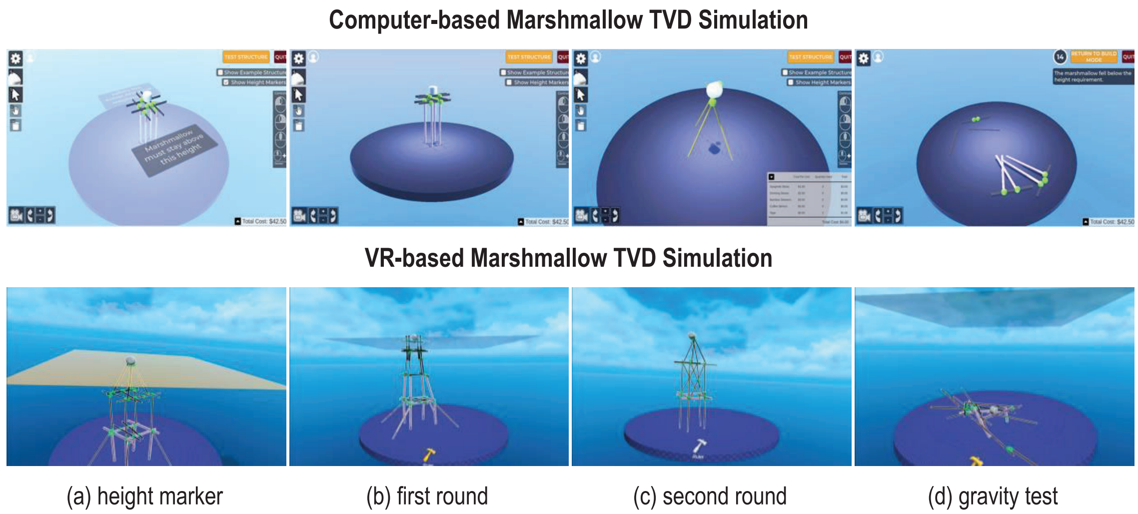


Figure 2: Computer (keyboard)- and VR (headset)-based Marshmallow TVD Simulations

ANALYSIS AND RESULTS

RESEARCH QUESTION 1. ARE THERE DIFFERENCES IN KNOWLEDGE RETENTION FOR PHYSICAL- VS. COMPUTER- VS. VR-BASED FORMATS?

A one-way analysis of variance (ANOVA) was conducted to investigate whether the computer- and VR-based Marshmallow TVD Simulations show a similar or even better understanding than physical simulation.

From the ANOVA, a significant effect of different simulation formats was observed on seven out of nine TVD principles; (a) mutual respect and trust [$F(2, 103) = 6.286$, $p = .003$], (b) mutual benefit and reward [$F(2, 103) = 3.367$, $p = .038$], (c) collaborative innovation and decision-making [$F(2, 103) = 4.967$, $p = .009$], (e) early goal definition [$F(2, 103) = 14.629$, $p < .001$], (f) intensified planning [$F(2, 103) = 8.613$, $p < .001$], (g) open communication [$F(2, 103) = 4.739$, $p < .011$], and (i) organization and leader [$F(2, 103) = 3.763$, $p = 0.026$].

A Tukey HSD test was used for post hoc comparisons of the seven TVD principles to compare each of the different formats to every other format; that is, the test compared understandings of TVD principles from physical- and computer-based, physical- and VR-based, and computer- and VR-based formats. Overall, results indicated that the mean score for the VR format was significantly different from the computer-based format, implying that the VR simulation can more effectively impart the principles of TVD than the physical simulation. The computer- and VR-based formats did not significantly differ in conveying TVD principles except for (e) early goal definition. Early goal definition was most effectively imparted in the VR-based version, followed by computer-based and physical formats (Table 1).

Two TVD principles, including (d) early involvement of key partners and (h) appropriate technology, did not show statistically significant differences. The result means that those two principles can be imparted effectively regardless of the simulation format used. In summary, the VR-based format is superior to other formats in imparting fundamental TVD principles. Some principles can be effectively imparted regardless of the simulation formats, others can be more effectively transferred to a VR-based format. Computer-based and physical-based formats showed very similar levels of effectiveness.

Table 1: Result of Tukey HSD Test

TVD Principle	Mode (I)	Mode (J)	Mean Difference (I - J)	Std. Error	Sig.
(a) Mutual respect and trust	VR	Physical	.579	.164	.002
(b) Mutual benefit and reward	VR	Physical	.442	.173	.032
(c) Collaborative innovation and decision-making	VR	Physical	.492	.156	.006
(e) Early goal definition	VR	Physical	.752	.152	<.001
	Computer	Physical	.552	.142	<.001
(f) Intensified planning	VR	Physical	.686	.166	<.001
(g) Open communication	VR	Physical	.489	.159	.008
(i) Organization and leader	VR	Physical	.556	.207	.022

(Note: Only statistically significant results from the Tukey HSD test are included above.)

Research Question 2. What is the Effect of Perceived Usefulness and Usability on Knowledge Retention for Computer- and VR-Based Formats?

A moderation analysis was used to determine whether the relationship between users' involvement and knowledge retention was influenced by or moderated by usability and usefulness. Four moderation analysis models were created for this research: (1) usability's moderator effect in computer-based format mode; (2) usability's moderator effect in VR-based format; (3) usefulness's moderator effect in computer-based format; and (4) usefulness's moderator effect in VR-based format. Among the four models, the usability's moderator effect in computer-based format showed statistically significant results, as shown in Table 2. The results indicate that the usability of a computer-based format reduces the positive relationship between users' involvement and their understanding of TVD principles ($R^2 = .311$, $F(3, 28) = 4.499$, $p = .043$).

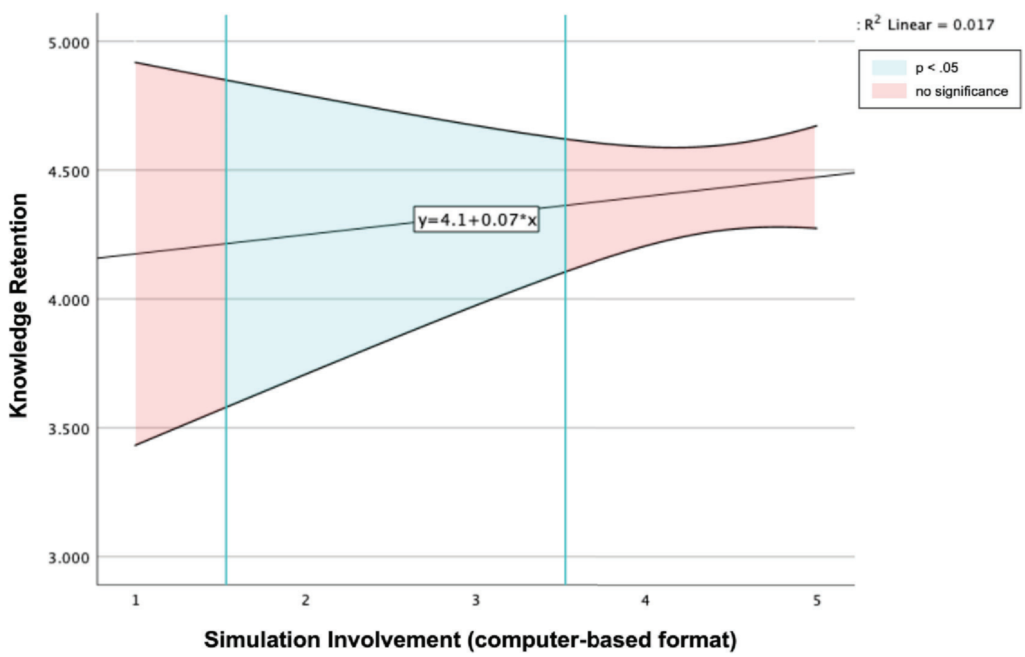
Johnson-Neyman interval further investigated the range of usability where the moderator effect is statistically significant. As a result, the moderator effect of usability on the relationship between the involvement and understanding of TVD principles was significant, from 31.25% to 68.75%; if further increased, there is no moderating effect of usability (Figure 3). The result implies that if the usability is between 31.25% and 68.75%, the effectiveness of the computer-based format can decrease even though there is a positive correlation between the users' involvement and their understanding of TVD principles.

Previous studies have reported that the success of serious games and simulations lies in the active involvement of users playing them, and the more actively and intensively involved the learning process, the better the understanding that emerges (Ropes, 2013; Ypsilanti et al., 2014). However, depending on the usability of the serious games and simulations, specifically in the computer-based format, effectiveness can be changed. Thus, it is crucial to improve the usability of the computer-based simulation to guarantee the maximum level of learning efficacy.

Table 2: Moderation Estimates

	Coeff	SE	t	p	LLCI	ULCI
(1) Usability's moderator effect in the computer-based format						
Involvement	1.629	.741	2.198	.036*	.111	3.147
Usability	1.634	.717	2.280	.031*	.166	3.102
Involvement × Usability	-.334	.158	-2.121	.043*	-.657	-.011
(2) Usability's moderator effect in the VR-based format						
Involvement	1.107	1.122	.987	.334	-1.220	3.434
Usability	1.117	1.100	1.015	.321	-1.165	3.400
Involvement × Usability	.272	.240	1.134	.269	-.770	.226
(3) Usefulness's moderator effect in the computer-based format						
Involvement	.740	.527	1.404	.171	-.340	1.820
Usefulness	.769	.544	1.412	.169	-.347	1.885
Involvement × Usefulness	-.143	.114	-1.252	.221	-.377	.091
(4) Usefulness's moderator effect in the VR-based format						
Involvement	.320	.901	.355	.726	-1.549	2.189
Usefulness	.409	.927	.442	.663	-1.513	2.332
Involvement × Usefulness	-.040	.196	-.204	.840	-.445	.366

*(Note: * signifies statistically significant relationship.)*



Note: X-axis indicates the level of simulation involvement (1: least involved, 5: actively involved). Y-axis indicates users' knowledge retention (1: very low understanding, 5: very high understanding). Usability has a moderator effect in the range highlighted in blue (involvement 1.56 – 3.41).

Figure 3: Johnson-Neyman Plot - Usability's Moderator Effect in Computer-based Format

DISCUSSION AND CONCLUSION

This research investigated the effectiveness of different simulation formats, namely physical-, computer-, and VR-based formats, on a users' knowledge retention. Computer- and VR-based formats of Marshmallow TVD Simulations were developed and used to investigate two research questions.

Empirical results indicated that the VR-based format is superior to other formats in imparting fundamental TVD principles, while some TVD principles, including early involvement of key partners and appropriate technology, can be imparted effectively regardless of the simulation format. Physical- and computer-based formats showed similar effectiveness in imparting TVD principles except for early goal definition. In addition, the usability of a simulation can moderate the learning effectiveness of the computer-based format. From this we learned that developers need to guarantee a high level of usability, specifically when engaging users in a computer-based format.

This research provides insights that can be instructive for future serious game and simulation developers. Simulation developers, especially those who intend to develop a computer-based format, should take care to improve usability to maximize learning effectiveness. This research identified the relatively unexplored area of moderator effectiveness for perceived usefulness and usability. By extending the results to other serious games and simulations, different modes can be adopted to be effective for a wider range of participants.

ACKNOWLEDGMENT

The authors would like to acknowledge the Texas A&M University's Construction Industry Advisory Council (CIAC) for financial support of this research.

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