THE VIRTUAL CONSTRUCTION SIMULATOR: EVALUATING AN EDUCATIONAL SIMULATION APPLICATION FOR TEACHING CONSTRUCTION MANAGEMENT CONCEPTS

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ABSTRACT

Educating and training students in the architecture, engineering and construction disciplines is challenging. Building and infrastructure projects are becoming ever more complex, necessitating more efficient construction processes to meet increasingly strict cost, time, quality and sustainability requirements. Engineering education that teaches students the dynamic processes inherent in building construction focuses mainly on lectures and case studies supplemented with field trips to construction sites that, while valuable, are often challenged by logistics, safety, and sufficient time for students to witness various construction stages and complexities.

An evolving area of research explores the use of educational computer simulations to enhance construction engineering education and facilitate the development of student problem solving and decision making skills. One current education development initiative at our university, the Virtual Construction Simulator (VCS), explores the value of simulation games in teaching construction concepts such as scheduling, resource management and resource allocation. The VCS is an interactive simulation game developed and implemented in Spring 2010 that engages students in an experiential simulation environment where they plan and develop a construction schedule for a virtual building, make decisions regarding construction methods, resources, and activity sequences, and simulate the construction schedule. We have found that by moving through this virtual stepping process, students assume a more active role in learning the differences between as-planned and as-built construction schedules that result from the factors such as weather, method, and labor productivity.

The researchers assessed the educational value of the VCS through pre- and post- surveys and a student exercise conducted in an introductory course to building and construction management in Spring 2010. Initial results demonstrate the merit of the VCS simulation game as a motivational and engaging learning tool for engineering construction education. This paper discusses the development, implementation, and pedagogical value of the VCS simulation game as a complement to traditional methods for teaching construction scheduling and management.

Keywords: engineering education, construction management, simulation, game theory

1. INTRODUCTION

Educating young engineers in the architecture, engineering and construction disciplines is a challenging task. Planning and managing construction projects is a dynamic process with constant fluctuations and factors that impact performance and educators are continually tasked with equipping students with the construction knowledge and problem solving skills they need to excel. At the undergraduate level, understanding the logic of construction management and managing its concomitant risks is particularly difficult due to the limited practical experience most undergraduates possess at this stage of their education. Teaching students construction scheduling requires detailed and comprehensive understanding of the methods and procedures involved in construction along with the impacts of risk and uncertainty on construction processes. Anecdotally speaking, construction industry superintendents and project managers frequently comment that while newly-hired engineering graduates often excel in computer skills and the use of scheduling applications, they often lack a strong understanding of underlying schedule logics. Traditional methods in teaching construction scheduling, such as lectures, are limited in equipping students with sufficient skills and knowledge of construction complexities and learning that occurs through instructor review and feedback often remains passive. Construction site visits provide valuable learning experiences to supplement course lectures, but are often constrained by time, funding, safety, and logistics. Furthermore, because site visits are by definition limited to short periods, they fail to fully demonstrate complex temporal construction sequences.

The challenge, then, in teaching complex construction concepts lies in involving students in a more active form of learning to enhance knowledge acquisition and retention. Simulation technologies and serious games have been demonstrated to foster active learning through increased engagement as opposed to the passive memorization typical of traditional teaching methods.

2. BACKGROUND

Much research in engineering and construction education has focused on improving students' analytical and decision-making skills. One of the challenges construction engineering students frequently encounter lies in understanding the relationships, logic, and variability underlying complex construction processes and the ability to discern and prioritize important information. It has been argued that traditional educational methods provide students with theoretical knowledge out of context and that construction processes are taught in a way that does not equip students with knowledge applicable in real life situations (Brown et al. 1989; Chinowsky and Vanegas 1996; Dossick et al. 2007; Galarneau 2005). Bridging this gap between theoretical and practical knowledge has long been a primary concern in education (Brown et al. 1989; Galarneau 2005).

The use of educational simulations and serious games is being increasingly explored to address this concern. Educational simulations engage students in a virtual setting where they can visualize, explore, and evaluate their processes and decisions in a safe, accessible and realistic simulated environment. The theory of situated cognition, or situated learning, in which knowledge is seen as interaction within a specific context, has made a significant impact on educational thinking by placing emphasis not on memory, but perception. According to this theory, teaching is tailored to expand learning and skill acquisition through activities (Brown et al. 1989). Computer-based simulations are seen as resources that complement traditional teaching methods and have the potential to bring situated learning into the classroom (Herrington and Oliver 1995).

An educational simulation is generally defined as a simplified model of reality or set of abstract concepts that provide basic information that facilitates student learning and understanding (Dede and Lewis 1995; Sawhney et al. 2000). Simulations are developed around learning situations that contain contextual information mastered through reflection and interaction with the virtual environment (Dede et al. 1999). Learning that occurs in this simulated environment is typically case-based or failure-driven, meaning students attempt several approaches and, when they fail, reflect upon and modify their strategies accordingly, thus engaging in a richer learning process (Dede and Lewis 1995). Aldrich (2003) argues that an ideal learning environment contains elements of both simulations and serious games. While simulation elements facilitate practicing specific skills, game elements create a competitive environment which promotes motivation and engagement, critical aspects of effective learning (Aldrich 2003; Bartles 2003).

Existing simulations developed specifically for teaching construction processes include bidding, schedule review, productivity analysis, resource allocation, risk analysis, and site planning. Of particular interest are situational simulations that afford students opportunities to develop authentic learning environments and explore hypothetical construction process scenarios. Sawhney describes the Internet-based Construction Management Learning System (ICMLS), a discrete event simulation that allows students to test strategies in construction materials, methods, scheduling, estimating, cost, and resource allocation (Sawhney et al. 2000; Sawhney and Mund 1998). Virtual Coach is a situational simulation conceived as a temporally dynamic environment with system-generating random events that require participants to quickly modify and adjust construction decisions

(Mukherjee et al. 2005). Since actual construction projects are characterized by constant operational flux, such as unexpected delays and alterations in site conditions or design, many simulations developed for construction education aim to teach students the variability of these processes and equip them with skills to react, adapt, and modify strategies accordingly (Kim and Paulson 2003; Sawhney et al. 2003). Although these projects have not yet been developed to a level of implementation and assessment, they demonstrate the need for developing contextually rich construction education environments for effective student training.

Research initiated at our University in 2004 focused on developing a 4D learning module – the Virtual Construction Simulator – to immerse students in a 3D model to interactively create a building construction sequence. The main objective of this research was to address the limitations of existing construction teaching methods that employed the critical path method (CPM) method and 2D drawings as their primary educational tools. The VCS 4D learning module sought to integrate schedule creation processes and 3D information review for developing 4D models allowing students to create groups of individual objects, attach activities to these groups, and generate sequences between these activities. Thus, the VCS approach generated a construction schedule directly from a 3D model, eliminating the need for a CPM schedule. Implementation of the VCS in 2006 and 2007 in an upper-level construction management course demonstrated its value in helping students to more easily and effectively create, review and visualize complex construction schedules (Nikolic et al. 2009; Wang and Messner 2007). However, the VCS 4D module was envisioned as only the first step in this research, and does not contain any specific project-based constraints to motivate students to consider the most feasible resource parameters or allow students to revise or modify initial plans based on project progress. The lack of real-time performance feedback limits exploration of alternatives as students receive their schedule evaluations exclusively from the instructor during in-class reviews.

3. CURRENT DEVELOPMENT OF THE VIRTUAL CONSTRUCTION SIMULATOR: VCS-SIMULATION GAME

Actual construction scheduling typically begins by identifying project goals and appropriate construction activities and durations in order to compute the overall project timeline. This is an iterative design process, and the first schedule iteration is rarely viable and typically subject to constant revisions and adjustments. The main reason for this schedule variability is that interconnections between labor, equipment, and other factors such weather or work hours are in constant flux; this variability is rather difficult for inexperienced students to grasp.

Building upon the initial VCS 4D learning module, the current VCS development phase takes a more active approach to learning by incorporating simulation and serious games attributes. Immediate feedback along with rules and variability allows students to test construction options and observe progress over time, thus actively managing factors that impact construction schedules and allowing personal understanding of processes to develop. The VCS simulation game introduces project-based constraints, construction methods, costs, resource allocation, labor productivity, and weather as critical factors in creating and reviewing construction schedules. Typically, when students schedule resources they tend to assume both maximum efficiency and minimal changes to their initial schedule. The VCS game enables students to explore various tradeoffs when choosing construction methods or allocating resources to manage cost, duration, quality and safety. Through the VCS simulation game application, students can observe the differences between as-planned and as-built schedules resulting from actors such as weather or labor productivity. Thus, the VCS game affords incentives for students to examine project sequencing logic or optimize efficiency of all available project resources through immediate feedback of project management decisions.

To demonstrate the dynamic nature and the complexity of managing construction processes, the VCS application was developed around a small-scale pavilion project. This project included detailed construction methods for each of its building elements, including cast in place foundations, slabs, wood columns, beams, trusses, sheathing, and shingles. To construct the pavilion, students select the construction methods for each building element, plan crew sizes, and develop the sequence of activities. After developing the as-planned schedule, students run the construction simulation to make day-to-day decisions regarding resource allocation and observe the progress of their planned as-built schedule. Figure 1 shows the VCS simulation game user interface for project planning and simulation.

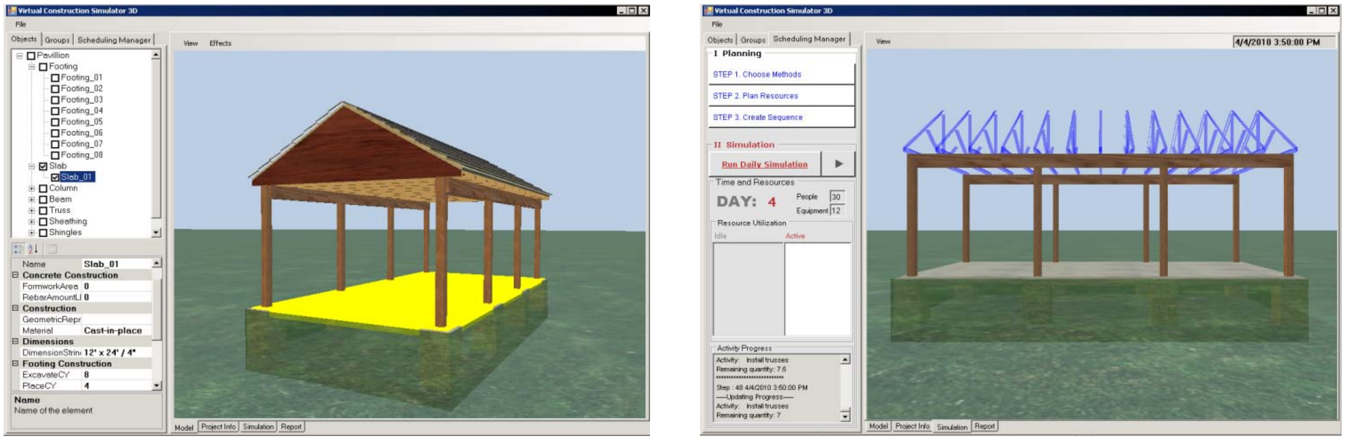


Figure 1: VCS user interface: Navigable 3D view of building elements (left) and the simulation progress (right)

A significant difference between previous VCS 4D learning module and the current VCS simulation game iteration is that students do not directly create activities or calculate their own activity durations when developing a construction schedule. Instead, activities are automatically created from the selected construction methods attached to grouped building elements, while the activity duration is calculated using the crew's daily output for the chosen method and the appropriate building element quantities embedded in the model. This enables students to test different scenarios in which construction method selection and resource allocation directly affect activity durations and schedule productivity.

Activity duration and cost data is generated within the simulation using information from the RS Means Database, a commonly accepted cost and production data source, stored and retrieved from Access database. Automated cost and schedule computation eliminates the need for manual calculation to further motivate students to explore alternatives for the most optimum solution. Through repetition and practice, students build their own understanding of the relationships between variables, instead of relying only on instructor-provided information. The immediate feedback encourages students to identify questions and enriches in-class discussion following the activity.

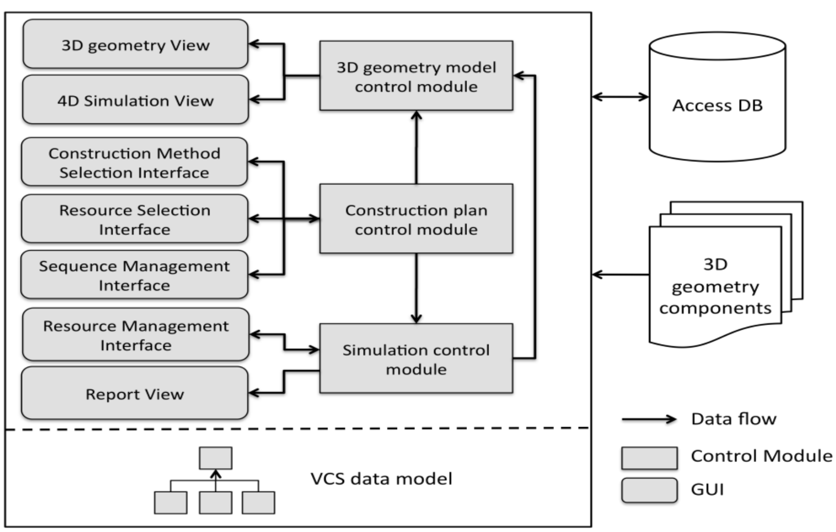
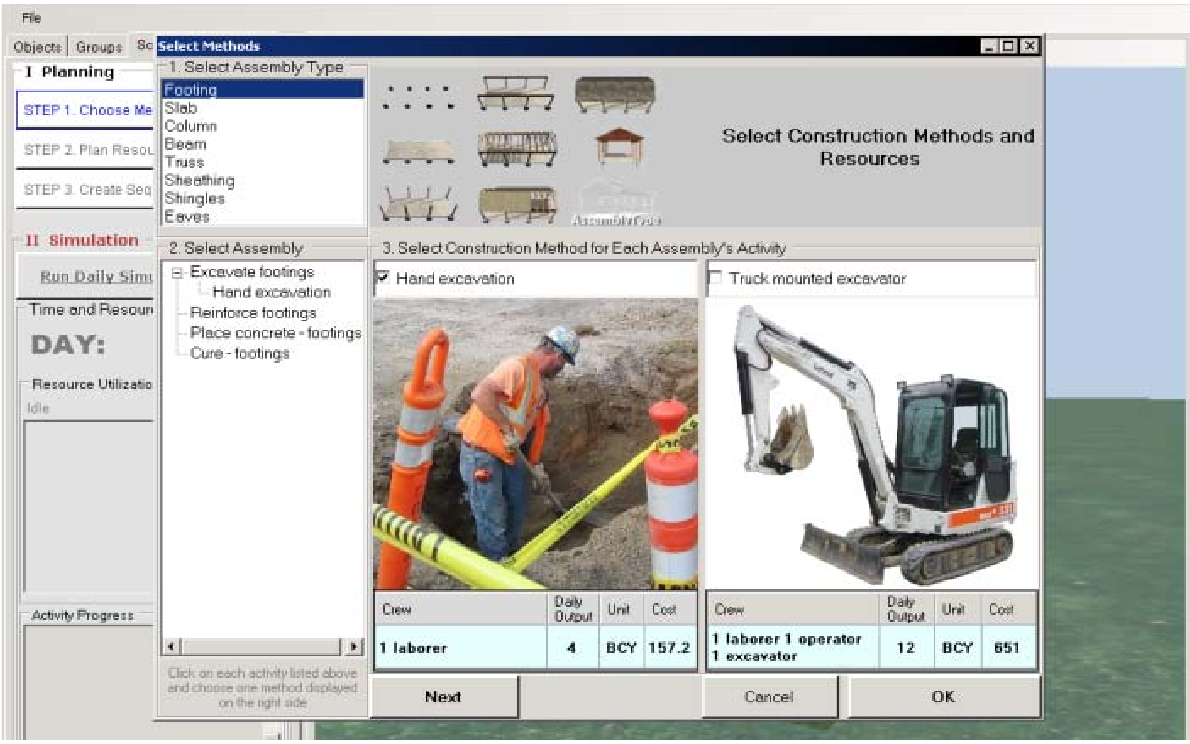
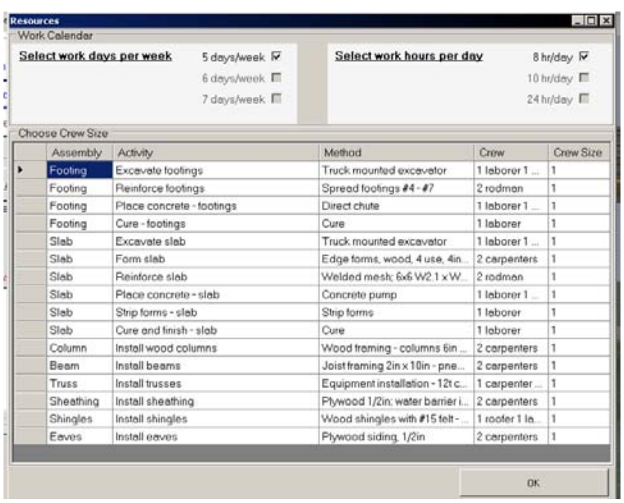


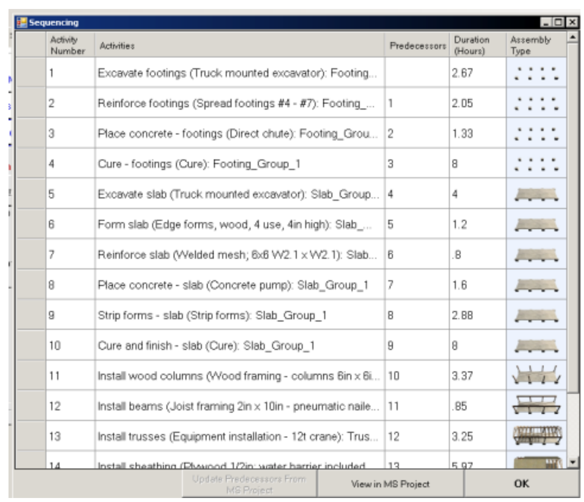
Figure 2: The System Architecture of VCS simulation game

Figure 2 charts the system architecture and the data flow path between VCS game application components. Major elements include the VCS application, the Access database, and a 3D game engine. The VCS application itself is comprised of three core control modules: the three-dimensional geometry module, the construction planning module and the simulation module. The Microsoft XNA game engine was employed to display geometric models of the pavilion building elements modeled in 3ds Max Design Studio. Information about building elements, quantities, construction methods, and resources is retrieved and stored in Microsoft Access database. An object- oriented programming paradigm was used to represent objects such as building elements, construction methods, resources, and functions needed for communicating with the database and for calculating construction simulation progress.



(a) *Construction method selection*





(b) *Resource allocation* (c) *Sequencing construction activities*

Figure 3: Graphical User Interfaces for construction planning

A sequence of graphical user interfaces (GUI) in the construction plan control module allows the user to make informed decisions when selecting construction methods, crew sizes and construction sequence. The *construction method selection* GUI displays available methods for each activity with corresponding crew types and daily costs so students can readily understand and compare construction methods (Figure 3a). The list of activities and their proposed methods are displayed for each work package type such as footings, slab, or columns. Activities are automatically generated and attached to either individual element or a group of building elements of the same type when a particular method is selected. The *resource allocation* GUI allows users to select crew sizes for each construction method and calculates as-planned durations (Figure 3b). Similarly, the *activity sequence* GUI allows users to develop activity sequences either by typing in the activity predecessor's number manually (Figure 3c) or loading Microsoft Project activity list and duration information. The predecessors data can then be updated in the VCS application.

The simulation control module calculates daily schedule progress based on scheduled construction activities and the type and number of human resources and equipment allocated. During the simulation, the user is prompted to allocate "hired" resources for each starting activity. After completing the daily simulation, the user can review daily and cumulative construction progress on the *reporting* GUI, showing weather data, construction progress, resource utilization information, and daily and cumulative costs. The simulation process then moves forward until the project construction is complete.

4. VCS IMPLEMENTATION

The VCS game simulation was tested in Spring 2010 in an introductory building and construction management engineering course of eighty-six students. A two-hour practicum session was used for the exercise, during which students were asked to develop and simulate the project sequence using the VCS application. The competitive aspect of the exercise asked students to test and report how fast they could build the pavilion under given constraints, including budget and available resources. Prior to the exercise, students were trained to use the VCS application. To generate the construction sequence, students move through the construction process by grouping building elements into work packages, choosing a construction method for each element type, choosing crew size, and sequencing generated activities. Following this planning stage, students enter the simulation mode and move through daily simulation cycles in which they determine daily site resources and observe progress through daily summary reports. The as-planned schedule serves as a guideline to the overall schedule duration; students can accelerate activities by "hiring" more resources during the simulation as needed.

Data collection was done through pre- and post-survey questionnaires measuring the level of learning, motivation, and students' perception of the simulation experience and application. Demographic information such as academic standing and previous experience with computer games was collected to improve the accuracy of the analysis. The level of knowledge in construction concepts was measured with open-ended questions and compared to determine if any change in learning occurred as an effect of the simulation experience. The level of motivation and students' perception of the assignment was also measured. Lastly, a series of both open-ended and closed questions measured learning experience from the student perspective and feedback on the application, user interface, system functionality and useful features for future development and improvement of the VCS simulation game.

5. RESULTS

Eighty students from two class sections completed the VCS activity and both surveys. Both class sections were taught by the same instructor. The average age of the participants was 21; there were 73% male and 23% female students. While completing the simulation exercise was a class requirement, participation in the research study including observations and surveys was voluntary and did not affect student grades.

1.1 Motivation

Research in education has recognized motivation as a driving force behind the learning process. Motivation is broadly defined as the willingness to engage in a specific task and invest time and effort in an experience (Garris et al. 2002; Gee 2003; Squire 2006). This study focuses on exploring the effect of simulation games on the level of student motivation and the relationship between this motivation and learning. The hypothesis was that the level of student motivation would score higher after using the VCS simulation game. Motivation was measured using an 11-item scale adapted from the On-Line Motivation Questionnaire (Boekaerts 2002). In addition to asking students how they felt immediately before and after the simulation experience, questions such as "how *useful* do you consider this assignment?", "how much *effort* do you plan to put into this assignment?" and "how *important* do you find to perform well on this assignment?" sought to measure students' motivational orientation and perception about the importance and interest in the task that could have impacted their performance.

Two new scales were created combining the items before and after the simulation. Both scales incorporated similar questions on emotional state (such as feeling nervous, worried, enthusiastic, annoyed, and confident) and learning intent items (such as intent to perform well, task utility, and amount of effort invested in the task). The reliabilities of these two scales were α=.73 for the pre test α=.82 for the post test. Paired sample t-tests demonstrated that the motivation level after the simulation exercise (M=3.25, SD=.41) was significantly higher than the motivation level prior to the simulation exercise (M=2.97, SD=.36), $t(80) = 4.40$, $p<.001$.

1.2 Learning

Short open-ended questions were included in both pre-test and post-test surveys to determine changes in learning that occurred as an effect of the simulation game. This open-ended format was deemed the most appropriate for students to reflect on specific construction issues that pertained to general construction management domains and were relevant to the simulation exercise. One question asked students to list factors they thought could affect construction activity duration and subsequently rate the difficulty of managing these factors. Both qualitative and quantitative data analyses methods were used to determine differences in student understanding of factors that impact construction activity duration before and after the simulation exercise. Identified factors were analyzed and grouped into categories and the average rating of each group was calculated. Table 1 shows the list of factors with average ratings before and after the simulation.

Table 1: Comparison of the responses to an open ended question before and after the simulation.

Factors that impact construction activity duration	**Difficulty to control the factor**	
	before	*after*
Schedule (overlapping activities)	**1.8**	**2.4**
Labor size	2.8	2.2
Labor productivity (experience)	**2.2**	**3.5**
Weather	4.9	4.9
Budget	4.7	4.0
Equip/Mat. Avail	**3.5**	**1.7**
Random events	3.5	--
Safety/Quality	2.5	--
Construction Method	--	1.5
Other (change order, site logistics)	3.2	--

The data comparison revealed that students listed more general factors pre-simulation that were categorized as *schedule*, *labor size and productivity*, *material and equipment availability*, *weather*, *budget* , *safety and quality*, and *random events.* Factors that were mentioned only once were grouped as *other*. One major variation among responses was the increased frequency of fewer factors with more detailed descriptions after the simulation. Three factors showed the most noticeable shift in ratings based on the simulation experience. *Labor productivity* became more frequently cited and perceived as more difficult to control after the simulation experience (*M*=3.5) compared to pre-simulation (*M*=2.25). Likewise, the factor *schedule* initially averaged *M*=1.8 but became more frequently mentioned as the amount of overlapping activities with a slightly higher rated difficulty of control (*M*=2.4) post-simulation. Equipment and material availability remained a frequently cited factor with a much lower difficulty rating after the exercise (*M*=1.75) compared to before the exercise (*M*=3.5). Interestingly, *random events* such as labor strike or equipment failure, as well as *quality* and *safety* were entirely absent in the post-evaluation survey. These results indicate a slight shift of attention to factors emphasized by the simulation game, and could explain the higher-rated difficulty of managing labor productivity as students became aware of the varying productivity based on the labor experience (the learning curve) and the weather. Similarly, scheduling overlapping activities appeared to be more challenging post-simulation, which may be due to embedded activity constraints within the simulation that prohibited certain activities to start before others were complete (e.g. columns cannot be installed until slab has cured for a certain amount of time). Conversely, equipment availability and material delivery as constant factors in the simulation were not perceived as a challenge compared to pre-simulation surveys.

The second open-ended question asked students to think about measures they would suggest for accelerating the schedule in the event of delays and to list the most likely effects of these selected measures. As with the previous question, qualitative analysis showed a similar trend, with post-simulation responses reflecting more of the simulation experience. While the proposed measures to accelerate the schedule did not differ as much, the explanation of the most likely effects became more detailed and relevant to the simulation experience. For example, cost increase as a function of increasing crew size became related to resource management challenges and increased cost of idle resources on site. These results suggest the potential for the simulation to focus student attention on specific issues and offer an opportunity to develop different scenarios based on learning objectives.

The survey results of student perception revealed an overall positive attitude toward the use of the simulation game, a sense of engagement and learning gains. Generally, students rated the simulation experience as applicable, relevant, engaging, enjoyable, and helpful in better understanding scheduling processes. Students reported that the most important lessons learned from the simulation related to developing a **bigger picture** of the scheduling process and a more *hands on experience with scheduling*; the importance and challenges in good **schedule coordination** and the *constraints in order of activities*; the efficient use of **resources** and the *balance between production capabilities and cost*; and that **changes and delays** are part of the process and the need to *account for them on a project.* The greatest challenges students reported included delays caused by the weather, managing to avoid idle resources, and the coordination of concrete pour activities to enable subsequent activities.

6. DISCUSSION

This implementation of the VCS simulation game demonstrated its value in providing a visual, interactive, realistic and engaging learning experience. Student evaluation of the experience as engaging, enjoyable, and fun is consistent with broad research findings that conclude simulation games are generally perceived as more interesting than lectures and other formats of traditional teaching methods. Student motivation level measured post-simulation reflected that this perception increased significantly after the simulation. Although research on whether higher motivation levels lead to more effective learning is still somewhat limited, educators generally prefer motivated learners as more open to the new learning experiences. Consideration of other factors such as gender, learning preferences and time spent on tasks will provide more insight in the nature of this relationship.

Comparisons of learning outcomes pre-and post-simulation indicated the potential of the VCS simulation game to influence and shift student attention to specific content advanced by the simulation. In this phase, the implementation of factors such as construction methods, weather, and varying labor productivity increased and focused the awareness of these factors following the simulation exercise. This information can be very useful when considering different learning scenarios in the following stages of the development and implementation when additional factors such as random events, safety, and quality are included.

Information retention is another important issue when implementing simulations and educational games. However, information retention was not tracked in this study due to limitations of class structure. The VCS simulation exercise was introduced as external to course content and was tested in a discrete two-hour practicum time allotted for the study. Results of learning outcomes would benefit more from a structured simulation exercise embedded within class content and aligned with the learning objectives of the class instructor. For future research a series of tests extended temporally would be beneficial in evaluating the long term effect of the simulation on learning and the retention of information. The more distributed implementation would also allow for additional tracking and comparison of the simulation game effectiveness with the standard approaches to teaching construction scheduling.

This study may not have fully captured the effects of the simulation game on learning given the quasi-experimental nature of the study and a pre- and post-test method used to measure concepts. Sensible incorporation of learning objectives into class content along with the post-simulation debriefing and discussion with students would provide additional insight and reinforce the learning process.

7. CONCLUSION

In education, simulation games are gaining ground for their value in encouraging problem solving, exploration, and creative thinking, all of which are necessary for real world challenges. At the same time, developing appropriate assessment methods to evaluate the effectiveness of simulation games remains incomplete. The development of the VCS simulation game sought to address existing challenges in teaching students the dynamic nature of construction through active learning whereby students iterate construction processes to identify problems, make decisions and observe the effect of those decisions. Results of this study demonstrate the benefits of the VCS in helping students to form a more holistic view of construction scheduling and increase student interest and motivation in learning about construction processes, cost and time tradeoffs, and inherent management challenges. Based on project goals, the VCS simulation game allows students to explore different strategies of construction process optimization and to observe these processes in real time. This immediate feedback shifts the student’s role from passive to active learner, complements instructor feedback, and creates opportunities to raise more questions and richer in-class discussions.

Based on these results, the VCS will be improved and further developed to incorporate additional educational and structural factors. With an elaborate dataset, the effect of gender differences and learner preferences can be further explored to enhance the effectiveness of the VCS as a teaching tool. Using strategies such as role-playing and self-evaluation, game-based simulations in construction engineering education can provide students with opportunities to learn construction concepts through practical experience.

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