Integrating Simulation Games into Construction Curricula—The VCS3 Case Study*

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In recent years, in response to higher construction industry standards for project design and delivery under budget, time and safety constraints, technological advances have dramatically changed how design and construction information is represented and managed. To prepare students to respond to these new industry demands approaches to teaching dynamic construction planning and management practices are changing. As a result, simulation games are gaining interest as an approach to providing students with learning experiences better aligned with complex problems in the areas of construction bidding, planning and management. However, while the use of simulation games in teaching construction shows some promising results, it remains sporadic due to high development costs, implementation challenges, and uncertainty of their effectiveness as learning tools. To address this gap, we developed and evaluated a free and open-source construction management game—the Virtual Construction Simulator (VCS)—that involves teaching a more holistic decision making process to planning and managing construction projects. This paper discusses the learning objectives that guided VCS3 development, implementation and assessment, and concludes with findings and recommendations for its broader implementation and future research.

Keywords: engineering education; simulation game; learning assessment; construction management

1. Introduction

Construction management activities, such as planning and scheduling, are inherently complex, often ill-defined and can be resolved using many possible solutions. Determining the best solution involves numerous iterations and frequent solution evaluations. In construction planning, this process includes recognizing tasks and resources needed to complete each of the tasks, and it typically begins by identifying project constraints, goals, construction activities and durations in order to compute the overall project timeline. However, construction plans are subject to constant revisions and adjustments due to unexpected events and complex interactions between resources, labor productivity, or budget. Consequently, construction students learning these processes often struggle to understand the depth and complexity of such fundamental aspects of the field when acquiring the skills necessary to manage inherent project risks, employee safety, or construction quality and responding to schedule changes and delays.

In response, computer simulation games have shown great promise in engaging students to solve complex and ill-defined problems common to the design and construction fields. Simulation games can capture complex relationships between various variables that learners through play can identify and make corresponding decisions. However, developing and implementing these innovative and non-traditional teaching methods in construction curricula remains a challenging process. In the construction education domain, a growing number of simulation game initiatives aim to address topics ranging from high-level organizational management to activity-specific simulation. However, very few of these games have moved beyond the research phase to broad curriculum implementation. Clearly, the potential of simulation games suggests they should be more widely supported in construction education as learning and teaching tools.

To address this challenge, we developed the Virtual Construction Simulator (VCS3), a free and open-source simulation game that holistically introduces scenario-based construction project planning and management. The VCS teaches students to recognize and anticipate how planning and management decisions, as well as external factors, can affect various site productivity metrics and influence changes in construction schedules. Here, we review previous simulation game literature with respect to constructivist and active learning theories and frameworks. We then detail the VCS3 development, including the learning objectives, the learning mechanisms and the game play. The remaining sections describe the implementation process in introductory- and advanced level construction classes to assess student learning gains, attitudes and game usability. Finally, we discuss our findings and the changes made between implementations,

and document our assessment guidelines for instructional support.

2. Why simulation games?

The need for critical thinking education has been identified in the socio-economic shift toward laborers who are required to solve complex problems [1, 2], and teaching students the critical thinking skills that foster reflective judgment has been deemed a primary goal of higher education [3]. Educational researchers and scholars [1, 2], [4–7] generally recognize *critical thinking* as the ability to make decisions to solve complex problems. Furthermore, as opposed to rote memorization, constructivist and experiential learning theories assert that *critical thinking* involves a student's ability to think, analyze, or evaluate, and that knowing "how" is more important than knowing "what" [8]. In particular, Dewey's [4] emphasis on the role of reflective thinking to recognize uncertainties in the problem definition is relevant to construction practice and education. Traditional approaches to classroom instruction have been criticized for failing to capture the ill-defined nature of construction problems characterized by competing goals, multiple solutions, unexpected problems, various constraints and human factors [9]. Thus, many researchers maintain that these approaches do not adequately prepare students with necessary decision making skills for industry tasks [10, 11]. By contrast, simulation games in construction education have been explored to foster the critical thinking process and enable learners to off-load unproductive tasks such as memorizing or calculating, and instead more quickly experiment, identify relationships, and organize information for more meaningful learning.

At their core, simulation games present a simplified model of reality in which students strive to complete tasks governed by rules and constraints [12–14]. While simulation games have existed since the 1970s, they have only recently gained renewed interest due to their ability to accommodate varying learning styles and engage users in personalized teaching and a positive attitude towards learning [15]. Simulation games are based on assumptions informed by theories of *situated*, *experiential*, or *problem-based* learning which argue that learning is more effective when students assume active roles, consider problems from various perspectives and reach conclusions by testing solutions and reflecting on the outcomes of these solutions [16–18]. In particular, *experiential learning* approaches begin when students apply ideas and understand the effects of decisions in order to discern causal relationships and principles that they can then apply to new situations [19]. Conversely, traditional didactic teaching and learning approaches, such as lectures, are grounded in the *information processing* theory in which students receive, assimilate, and infer the information to general principles before they learn how to apply those principles—an approach in which incentives to learn are not clear until the last stage (ibid.).

From the educational and cognitive psychology view, learning is comprised of cognitive, metacognitive, and motivational components [20]. The *metacognitive* aspect is particularly interesting as it is context based, and entails a realistic problem-based situation to learn how, when and what skills to apply to particular problems [20, 21]. Research in education argues that problem solving activities situated within the context are crucial for learning more effective domain-specific strategies compared to general problem solving strategies [22–24]. Furthermore, domain-specific strategies are gradually acquired through experience, which allows experts to recognize problem types and apply familiar strategies [11, 25–27]. Jaafari et al. [28] illustrated that in construction planning, the mental framework to visualize construction processes and to determine the feasibility of decisions made is acquired through experience on actual projects, an advantage that students typically lack. As a result, students should engage in problem solving activities in which they learn to identify problems, determine constraints, and generate and evaluate multiple solutions to inform their decisions [29, 30]. Two major themes promoting the use of simulation games in education are (1) their motivational power to engage the learner, and (2) an active process of learning by doing [31–33].

Because actual construction projects are characterized by frequent alterations, such as unexpected delays and changes 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 [34, 35]. The current literature reports two main groups of computer-based simulation environments in construction education (Table 1). The first group focuses on simulating managerial activities at the organizational level, such as bidding, marketing, or company management; the second simulates decisions at the project- or activity-level, such as scheduling or managing site resources. More recent efforts seek to integrate information from BIM models into game engines [36, 37], teach safety training [38] and lean and sustainable principles [39]. The list suggests that most simulation games are team-based, and that project-level games mostly focus on specific project type [40, 41]; or activity type [42–44]. Furthermore, few games on this list are widely

Table 1. List of computer-based construction simulation games and learning features for managing organizations and projects

Simulation game	Objective	Role	Team play	Sim. Period	Performance indicator/assessment	Reference
Organizational level						
Construction Mgmt Game	Competitive bidding, selecting subcontractors	GC	Team of 5	3 years at 3-month periods	Highest relative gain at the end of simulation	Au et al. 1969
CONSTRUCTO	On-site construction management training	-	Team	Quarters	Financial expenditures and construction progress	Halpin and Woodhead 1970
AROUSAL	Bidding, staffing, finance	Senior Management	Team of 4	8 quarters/ 2 years	Presentation of the company performance	Lansley 1982
SuperBID	Bidding, management	GC	Team/ Individual	Quarters	Actual project cost Maximum ROI	AbouRizk and Sawhney 1994
Contract and Construct	Bidding, selecting contractors, management	PM	Team	94 weeks	Cost, time, safety Debriefing	Martin 2000
C3M	Competitive bidding to gain market share	GC	Team of 4	12 quarters	Profit and market share	Nassar 2003
B.I.G. – Build. Industry Game	Bidding, business strategy	GC	Team/ Individual	2-month cycles	Profit, financial records	Johnston et al. 2003
MERIT	Running a construction company	Board of directors	Team of 6	8 quarters/ 2 years	Turnover, company value, contract completion	Wall and Ahmed 2008
Project level						
Parade of trades	Trade coordination	CM	Team	n/a	Duration Trade workflow	Choo and Tommelein 1999
VIRCON	Pre-bid construction planning and cost	GC/CM	Team	n/a	Cost and duration estimates	Jaafari et al. 2001
ICMLS	Schedule/cost plan for a concrete placement	PM	Team	n/a	Cost and duration estimates	Sawhney et al. 2001
Virtual Coach	Resource allocation	CM	Individual	36 weeks	As-built duration and cost	Rojas and Mukherjee 2005
Simulation Model	Construction of a rock and clay dam	Contractor's PM	Teams of 3	n/a	Class presentation Self-report questionnaire	Al-Jibouri et al. 2005
CAL excavation game	Excavation, surveying, safety and overtime	CM	Team	n/a	Time, cost, quality	Sherif and Mekkawi 2010
LEAPCON	Lean management of high-rise interior finishing	GC (PM, QC, crane op)	Team of 4	11-minute cycles (11)	Apartments complete, cash flow, quality	Sacks et al. 2007
VICE-bridge	Construction	Arch./GC	Team/ Individual	n/a	Time and cost of completion	Goedert et al. 2011

available [41, 42] and provide instructional support for class implementation [45, 46].

These studies demonstrate an increasing interest in developing contextually rich construction education environments for students. Yet, one of the remaining issues in understanding the educational benefits of simulation games and best practices for their use is still rather limited implementation and the lack of a structured, objectives-driven approach to defining, developing and evaluating educational simulation games. The literature further reveals that the game design typically overlaps with the use of games, and thus the method of their development remains largely overlooked in education games research [15]. Challenges that still hinder the broader adoption of simulation games within curricula include the lack of understanding of clear learning objectives that inform game design and assessment, as well as the instructional support for the non-gamer educators to successfully implement simulation games in classrooms. Assessment methods are often contested because simulation game learning approaches generally involve more complex processes of solving ill-defined problems. While simulation games offer learners the means to monitor their own performance through metrics such as levels completed, cost, or time for example; a successful outcome, or even failure, are not the only indicators of the learning process. Therefore, measuring learning gains from simulation game approaches differs from that of traditional assessment, as the trial-and-error approach and learning

through failure are integral and powerful facets of the learning process.

On the other hand, successful implementation of simulation games also hinges on engaging the instructor in the learning process. Though educational simulation-games support learning by providing in-game performance feedback, their effectiveness still depends on an instructor's ability to understand the role of the game in reinforcing the learning process. Debriefing and scaffolding are recognized as critical pedagogical elements of the game-based learning; the instructors' role is to ensure that students meet the specific learning objectives [15, 47, 48]. As instructors are not necessarily game developers, they may be unfamiliar with game-based learning and limited by the general lack of instructional support for using simulation games. The greatest criticism of the constructivist approach is the lack of detailed and systematic development of instructional design guidelines and translation of the constructivist views inside classrooms. Providing instructors with necessary materials, guidelines, technical, instructional and assessment support is thus equally important to ensure the broader adoption and adaptation within curricula.

3. The virtual construction simulator (VCS) game—case study

To address some of the challenges to broader adoption of simulation games in construction cur-
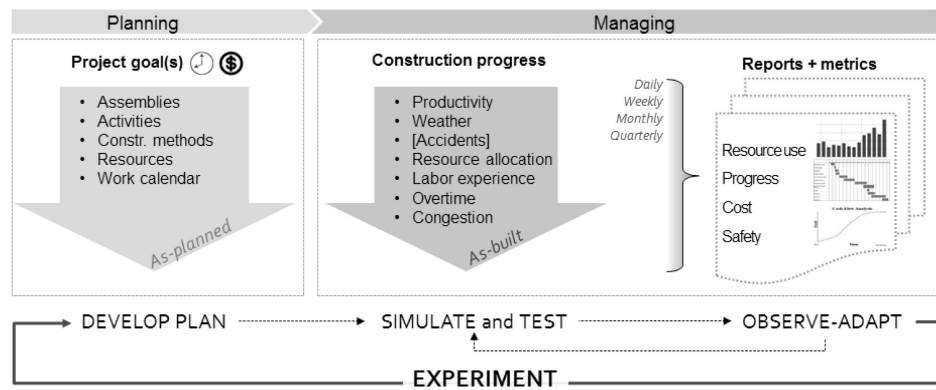
Fig. 1. The VCS3 learning process.

ricula, we developed the free VCS3[1] game as a compelling and holistic learning experience for the dynamic construction planning and management. The pedagogy of the VCS game extends the specialized focus of existing construction games to support flexible and custom scenarios for individual learning of how the decisions and dynamic factors affect the construction progress. We documented this process through a set of development, implementation and assessment guidelines for instructors discussed in the following sections.

3.1 Design

3.1.1 Learning objectives

The primary objective of the VCS3 simulation game is to engage students in a holistic understanding of the dynamic nature of construction projects as they are influenced by both planning and managerial decisions and outside influences. Specifically, the goal of the game is to guide students through the many common decisions and considerations typical in (1) planning project construction and (2) responding to changes during construction duration as they are affected by resource management decisions, varying labor productivity levels, and unforeseen influences such as adverse weather conditions, lack of employee experience, overtime cost overruns, or construction congestion. As a result, our learning objectives for the VCS3 game aim to allow students for a given project scenario to be able to:

1. Identify project constraints such as client goal(s), budget, resources, and time;
2. Develop resource-efficient construction sequence to meet the project goals by comparing construction methods in terms of cost, resources, and daily output;
3. Determine daily resource needs and efficiently manage and allocate resources on site;

4. Recognize and adapt to changes to the construction plan and factors affecting the overall schedule (i.e. the difference between as-planned and as-built);
5. Given these strategies and outcomes, evaluate and explain the risks and tradeoffs in managing project duration, productivity, cost, quality and safety.

To achieve these objectives, the game was conceived as a two-mode process (Fig. 1) in which students first develop a plan for a small pavilion project (Fig. 2) according to specific project objectives (e.g. adhering to budget and/or project duration) and then, simulate daily construction activities based on their plan. While the simulated construction period varies according to students' plan, we based the game on a seven-day duration as a frame of reference for a real project. In the simulation phase, students acting as superintendents "hire" and dynamically allocate resources daily on site for each starting activity based on their plan, adjusting for unexpected effects of adverse weather and fluctuating labor productivity due to varying levels of workers' experience, overtime requirements, or site congestion. At the end of each simulated day, the game generates a progress report for students to review and make any necessary resource adjustments for the following day. Figure 1 illustrates the intended learning process in which students plan and manage the construction project, and also how they can test various construction sequences to implement the most effective plan.

Grounded in the Kolb's learning cycle [49], this experiential learning process allows students to test, observe, act and reflect upon the project outcomes, thus gaining a holistic understanding of the relationships between activity sequence, resources allocations, and various other dynamic factors. Through experimentation, students are able to develop problem-solving skills such as identifying

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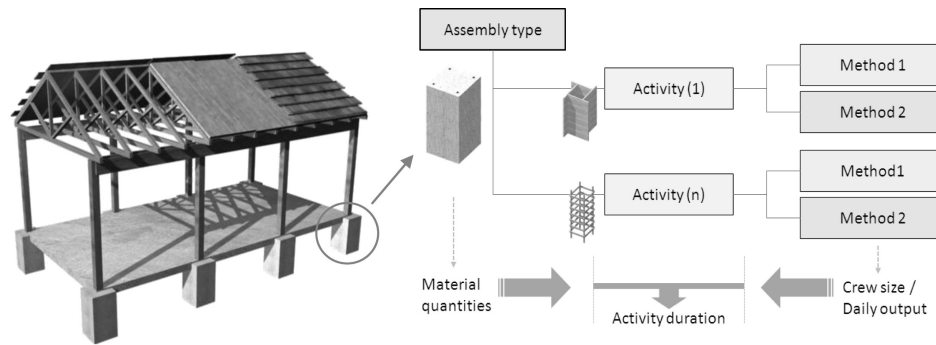[1] Available for free download at www.engr.psu.edu/vcs

Fig. 2. The VCS3 model of the pavilion project (left) and a diagram of the activities and different methods associated with each assembly type (right).

challenges, and testing alternatives to arrive at most optimal solutions. Specifically, we designed the VCS3 simulation game to:

- Promote application of construction knowledge to resolve conflicts;
- Establish a broad understanding of construction planning and management through a holistic approach to representing its interrelated components;
- Facilitate learning by allowing students to experience the outcomes of their decisions within a short time frame;
- Provide a realistic, risk-free, and fun experiential learning environment where one encounters success and failure without actual consequences; and
- Encourage reflection and discussion of the learning experience.

3.1.2 VCS3 simulation game design

To fulfill the above learning objectives and promote this process of dynamic iteration of alternatives, the VCS3 game development primarily addresses a standard critical path method (CPM) approach to teaching construction planning and introduces the system dynamics model and automated calculation of both as-planned and as-built schedules [50, 51].

The CPM method, which is typically employed in traditional construction curricula, requires a high level of technical competency, and has been deemed insufficient in teaching students about fluctuating labor productivity and changes that typically occur on a construction site [52, 53]. Under the traditional approach, students gather construction productivity data from common data sources such as RS Means, and calculate activity durations before developing a sequence, which is a time consuming process that typically limits the exploration of alternative solutions. In contrast, the VCS3 automatically calculates construction activity durations from the daily production outputs of the selected resources and associated material quantities (Fig. 2, right). The underlying system dynamics model calculates actual (as-built) durations from the resources students allocate during the simulation and labor productivity based on workers' experience, weather, overtime, or congestion.

Table 2 summarizes the VCS3 game and pedagogical elements designed to contribute to enhanced learning, motivation and information retention. The simulation component with the game's system dynamics model provides a realistic and feedback-based learning experience. Importantly, the ability to repeat the construction simulation allows stu-

Table 2. VCS3 simulation-game and pedagogical elements

Simulation	Game	Pedagogy
Interaction: Minimized manual input Rapid development of options Immediate feedback Repeatability	**Goals** /scenario-driven exploration **Rules** Logical/physical constraints	Learning objectives Learning scenarios Experimenting

Functional realism
System dynamics model
Factor variability
	Uncertainty / variability
	    Dynamic factors /(random events)
	Scoring/ performance tracking
	    Progress reports
		Levels of difficulty
		
		Scaffolding / guidance

Visualization
4D plan review
Actual progress simulation
	Competition
	    Against the goal/players
	Rewards
	    Virtual incentives/rewards
		Reflection / debriefing

Model of reality	*Engagement*	*Learning*

dents to iterate and explore possibilities by adopting and modifying different strategies in a short time.

Game elements aim to engage students in a fun learning experience as well. Its defined rules establish the criteria for success while managing uncertainty and rewards, and provide a means for students to test strategies and view the construction challenges from different perspectives. As a result, risk-free failure becomes a critical precondition for learning, prompting students to repeat the process until they resolve conflicts.

Lastly, the game's pedagogical approach incorporates simulation and game elements to facilitate the learning process through guidance, help and reflection. To be effective, simulation games should be designed and implemented to account for different levels of prior knowledge and different learner types. Debriefing or reflection as a critical part of the experiential learning help students clarify and resolve any conflicts during the simulation experience, establish relevance to the real world, and generalize lessons learned in order to apply it later in different situations [47, 54].

3.1.3 Game play

For the VCS3's learning scenario, a relatively small pavilion project (Fig. 2, left) was scaled to exemplify the decisions made in planning and managing construction, while not overwhelming students with the information. We asked participating students how fast they could complete this pavilion project within a $15,000 labor and equipment budget. We stipulated that students would compensate workers for the entire day regardless of actual hours worked on site, and that the contract did not allow for overtime or weekend work.

To achieve this objective, students were asked to first draft a construction plan and then test it in the VCS3. During the planning phase, students considered various decisions, such as grouping objects into construction zones, choosing construction methods for each of the listed activities associated with a particular assembly type, (Fig. 2 right) selecting the size of labor crews, and sequencing activities without violating physical or sequence constraints (e.g. placing column before footing, or placing concrete before reinforcing).

After the construction plan is in place, students review their overall planned schedule duration, either in the VCS3 or Microsoft Project application, and proceed to simulate the "actual" construction. Each simulated day, students consult their as-planned schedule to plan the hiring of staff, with the option of retaining more labor than required if they elected to accelerate their schedule. Once the construction starts, students continuously allocate available resources for the activities ready to start, or otherwise wait until they become available. The VCS3 updates the construction progress at ten-minute intervals to show what resources are active (i.e. assigned) versus idle (i.e. unassigned). At the end of each 8-hour day, the application generates a report summarizing construction progress, productivity rate and hours worked for each resource, cost, and the weather report. After reviewing the report, students begin the next day by repeating the process until the pavilion is completed.

3.1.4 VCS3 simulation game evaluation

Before we tested the VCS3 in the classroom, we evaluated the game for its representational validity, or how closely it fulfilled its teaching intentions (Table 3). To ensure consistent and reliable performance, each simulation step output was manually

Table 3. VCS3 evaluation categories

		The Evaluation Questions	Data / Method	Source
Testing - Validation	Application performance	Is the simulation game reliable?	Crashes, bugs, error messages	Beta-testing
		Is the simulation consistent in its performance?	Same output in each run	Beta-testing
	Content	Is the content accurate?	Review with faculty and industry members	Faculty / experts
		Is the content relevant to the real world scenarios?	Review with faculty and industry members	Faculty / experts
Class implementation	Usability	Is the simulation game easy to learn to use?	Post-test questionnaire	Students
		Does the simulation account for learner's experience?	Post-test questionnaire Debrief	Students
	Learning	How well do the students meet the learning objectives after the simulation?	Pre- and post-test quest. Debrief	Students
		Is the simulation time adequate to maximize the learning gains?	Pre- and post-test quest. Debrief	Students
	Realism and motivation	Is the simulation game realistic and compelling?	Post-test questionnaire	Students

Table 4. Course implementation data with the breakdown number of responses per evaluation category

Course/ implement. year	Course enrollment	# of questionnaire repondents		Pre-test data			Post-test data				
		Pre-test	Post-test	Learning	Motivation	Experience	Learning	Motivation	Experience	Focus group	Handouts
AE372 (2010)	97	85	81	76	85	-	69	80	81	-	87
AE572 (2010)	9	9	9	9	9	-	9	9	9	(8)	9
AE372 (2012)	99	88	79	85	88	-	71	78	79	-	89

calculated and compared with repeated simulation runs. Three construction faculty and two industry representatives then reviewed the application in terms of relevance and representation of actual project scenarios with respect to the learning objectives. The VCS3 usability was also tested with a group of 10 graduate student volunteers not involved in its implementation, who completed the VCS3 assignment. Their feedback was used to improve the user interface, application performance, and correct application errors. Application parameters, such as the simulation length, were also tested prior to full scale classroom implementation.

To evaluate the learning effectiveness and the usability of the VCS3, we employed Kirkpatrick's framework of four levels of learning [55] as an assessment framework because it examines both cognitive and affective (i.e. motivational) components of learning, and also considers student attitudes toward the game and their experience as indicators of the application acceptance.

The cognitive component of the assessment, informed by the Bloom's taxonomy [1], evaluates students' domain knowledge of basic concepts of construction scheduling, including activity durations, resources, productivity, and construction methods; and students' abilities to synthesize, summarize concepts, and predict possible outcomes given different scenarios as an effect of the VCS3.

Motivation has also been recognized as important to the learning process [31, 56–58], and is broadly defined as the willingness to engage in a specific task and invest time and effort in an experience. Motivation was measured using the adapted On-Line Motivation Questionnaire [59] as a pre- and post-test self-report instrument of students' emotional response to the task, perceived importance, effort and performance.

Lastly, acknowledging the existence of different learner types, attitudes and reactions to the simulation game provide us with an initial understanding of students' acceptance of the VCS3. Questions about specific application features and the simulation experience overall, help us to determine if there was a favorable reaction as a necessary condition for increased motivation and potentially increased learning.

3.2 Classroom implementation

The VCS3 game simulation was tested between 2010 and 2012 at the Pennsylvania State University in an introductory building construction course (AE372) of approximately one hundred undergraduate students and a graduate level project management course (AE572) of nine students (Table 4). During a two-hour practical session, students were asked to complete the assignment (Appendix A) and online pre- and post-tests questionnaires measuring the level of learning, motivation, and students' attitudes toward simulation experience [51, 60]. Although completing the assignment was a class requirement, participation in the study and survey completion was voluntary. Performance on the assignment (i.e. reported duration and cost) was not part of the VCS3 assessment, however, students' handouts were collected to further understand the results and troubleshoot potential VCS3 errors. After the first class implementation, we changed the assignment handout and the scenario somewhat (Appendix B). These changes are detailed in the following section.

3.3 Evaluation results

The results of class implementations of the VCS3 exercise indicated benefits in providing a visual, interactive, realistic and engaging learning experience with a significant effect on students' motivation [50, 60]. In addition, students demonstrated an increased understanding of construction planning and how changes in construction and resource management can affect their plans. While we more fully describe specific assessment questions and analyses in [60], study results are presented here with respect to the following evaluation questions and the adjustments we made to the subsequent implementations.

How has the students' learning changed based on the simulation gaming activity?

Pre- and post-test responses, in which students discussed both their perceived difficulty of having control over certain productivity factors and estimating the effects of measures to increase the production output, indicated the VCS3's potential to influence and shift student attention to the simulation content. While responses indicated students were more or less similar in hitting the target both before and after (e.g. efficient sequence affects the overall duration), their explanations of these effects tended to be more elaborate and descriptive post- simulation. Specifically, students remarked on managerial challenges, such as coordinating activity start times and allocating resources to avoid delays and idle resources. For example, realizing that curing concrete delays the commencement of other site activities, students used strategies to begin the concrete pouring activity near the end of a workday to allow for overnight curing. In addition, during our debriefing discussions, students reflected on the time/cost tradeoffs of employing multiple crews to accelerate activities and finding ways to balance resources more efficiently. One student added that it took one entire simulation run before beginning to understand how to efficiently use resources. Thus, students learned that planning a construction schedule was relatively easier than actually managing a project, particularly given delays due to weather and decreased initial productivity. Another student remarked that doubling crews for a second VCS3 run did not necessarily accelerate the schedule as anticipated, but did increase costs. Only after a third run did this student realize that successful completion was contingent on a more efficient construction activity sequence.

As stated before, because this study focused on evaluating a learning process, student performance on the VCS assignment was not part of our learning assessment. However, the analysis of students' handouts revealed a broad range in time and cost required to construct the pavilion in the given scenario. When students were asked to test how quickly they could construct the pavilion without exceeding the given budget, they were not given a reference point of an average or expected project duration, which resulted in project durations ranging from four to twelve days. Given that their main goal was to stay under the budget, most students decided to spend the least amount possible, but the lack of duration reference may have resulted in the majority of students not knowing how their solution ranked and whether their performance could be further improved. The in-game metrics, such as the scale of lower to higher duration or cost performance, for example, would be an important part of the feedback mechanism that drives the improvement on the students' part. While embedding performance metrics into the simulation game structure may challenge the flexibility of custom learning scenarios, metrics can be incorporated in the project scenario through more defined constraints and rules.

Following the first implementation, the assignment scenario was changed to include a more detailed project scenario with a goal of completing the project in six days or fewer (Appendix B), offering virtual incentives or penalties if completed ahead or behind the schedule. In addition to the assignment, we provided students with a log to document their decisions for each simulation run. Based on the students' comments from the first implementation, we increased the VCS3 average daily simulation speed from four minutes to less than a minute. Consequently, the students' reported durations ranged from 4 to 6 days. In addition to pre- and post-test surveys, the focus group with the students following the exercise provided more in-depth feedback and comments on the experiences, challenges and suggestions for improvement.

Was the time commitment appropriate for the skills and information gained?

In the first implementation, the simulation speed was markedly slower, which students found frustrating. A single day simulation duration ranged from 3–7 minutes, possibly limiting the number of complete runs in the given two-hour practicum time. At the same time, we observed that while waiting for slow simulations to finish, many students' attention would shift toward doing something else, e.g. browsing the internet. Conversely, students in the subsequent implementation reported the ability to run several simulations in a shorter period as very helpful in optimizing their strategies. In this case, simulation speed was one of the factors suggesting that testing of different approaches in a relatively shorter period fostered sustained attention. Appropriate speed can stimulate repetition, which has been linked to learning outcomes through the process of "revisiting" new material until the learner becomes familiar with it [61]. Controllable simulation speed may be an appropriate method to addressing differences in learning style and experience level by allowing students to either focus on detailed information during the simulation process or move faster to the outcome.

How should the simulation activity change to maximize learning?

Students seemed to have had the most difficulty with the inability to undo actions and decisions after the simulation began. While "undoing" decisions is

not a realistic option in planning and management processes on a construction site, the VCS3 decision process restricts any changes that can be made to the planned schedule and remaining activities once the simulation starts. Thus, the VCS3 allows changes in crew sizes during the simulation, but it does not allow for changes to the activity sequence or the construction methods once they have been selected. The ability to change the non-started activities would provide more flexibility. Several students recommended adding this functionality in the next development phase. Related to this, students reported that a more intuitive graphical representation of as-planned and as-built schedules would help them better understand how construction progress differed from their original plan. To summarize, the following changes were suggested to improve the VCS3:

- Allow for altering construction sequences and methods for remaining activities between the daily simulations;
- Allow users to add more crews to in-progress activities (currently, once activities begin, the number and type of resources assigned are fixed);
- Provide tips and explanations during the decision making process;
- Allow users to review the planned daily budget spending before starting the simulation;
- View the weather forecast before the day simulation starts to make decisions about which activities to start; and
- Compare as-planned and as-built schedule throughout to track progress.

Were the students engaged and did they enjoy the simulation activity?

Fun and pleasure are typically not considered as critical attributes of learning environments, but are key driving motivators in constructivist environments in which the learner leads the inquiry [62]. Study results show a significant increase in the level of motivation after the VCS3 simulation [60], with the majority of students reporting they enjoyed the activity because it was visual, interactive, fun, relevant and realistic. For many students, the ability to modify actions and decisions fairly quickly and the sense of controlling the process was contributing to their sense of engagement. Several students reported that the challenges they encountered in managing the construction process were also fun, particularly managing resources to avoid idling. While the challenge stimulates sustained interest in the learning experience, several students also expressed their desire for more helpful information during the simulation process. In this sense, learner differences and their levels of experience should be addressed in the VCS3 through added scaffolding and additional information, such as explanations or hints given during the decision process.

4. Discussion of limitations and practical implications

This section discusses our observations relevant to the design, implementation and assessment of educational simulation games based on our results. Designing effective instructional environments hinges on understanding the theories and assumptions of how students learn. The VCS3's underlying system dynamics model captures the core function of simulation games to represent complex systems involving uncertainty and changeable processes. However, the application's relatively small project and decision-making scope may still constitute a complex and dynamic learning environment to a level in which students with little understanding of construction concepts may struggle in interpreting the results of their decisions. While most students in our study were successful in identifying specific planning and management challenges throughout the simulation, the need exists to develop a more guided learning process using in-game help, explanations and tips. As a result, the next step of the VCS3's development is to structure this support as difficulty levels that could better account for differences in learning preferences and levels of prior knowledge.

The design and development of instructional simulation games is also challenging due to the tension between providing clear instructional strategies and incorporating integral simulation game attributes, such as variability and randomness. And while randomness is a simulation game characteristic that often contributes to a sense of fun, managing this attribute requires careful consideration when these games are developed for instructional purposes. In addition, to game players, randomness could be seen as a loss of control over the learning process, and cause confusion if performance is perceived as determined largely by random events rather than strategy. Nevertheless, random events may be valuable simulation game levels when learners possess sufficient domain knowledge and confidence to tackle situations that are more complex.

A challenge in educational simulation game research is choosing the appropriate metrics to capture learning gains that can occur as an effect of playing these games. As a result, concerns exist on the validity of learning outcomes [63], though when used alongside standard instruction approaches, simulation games can be effective in long-term retention and transferability to actual situations [64]. Due to participant availability and class sche-

duling constraints, the VCS3's learning effects were measured using a pre- and post-test design. Although this approach is common in educational research, its lack of randomization and relatively short period between surveys can limit the degree of certainty to which results can be interpreted and generalized. This study measured learning gains by focusing on process rather than student performance or the quality of final outcomes. Although student reports showed a broad range of results that could be interpreted as better or worse, most students succeeded in identifying the common challenges involved in the planning and management decision process. This finding aligns with research suggesting that performance and learning are often not correlated [65]. At the same time, extensive learning gains were difficult to detect because of the limited number of system dynamic factors implemented at this stage. For this reason, the learning measurement items could not include information that was not covered in the VCS3 simulation game.

The process also remains difficult to fully capture due to learners' differences and their ability to adequately express what they learned. Challenges associated with this limitation are difficult to address for several reasons. The learning process involved in using a simulation tool is process based where students cycle through the stages of hypothesizing, generating a solution, testing, reflecting on the outcomes and adjusting the solution accordingly. Capturing these processes can be very difficult for students either because they may not be aware of what they are actually learning or they may not be able to articulate it. The inherent drawback of self-reporting is that is makes the learners aware of their unconscious thought process or experience, and thus changes them by making them explicit [66].

Yet, self-evaluation in which students reflect on their performance or decisions in terms of goals, judgments, outcomes, or future actions (e.g. student decision log) play important part in building metacognitive skills leading to increased overall learning of problem-solving and performance [67]. Interpret-

ing our findings hinged on data collected solely within a two-hour session could not provide a complete summary of the learning processes involved and their long-term effects.

Both the learning assessment used in this study and its implementation would have benefitted from direct involvement with respective class content and instructor input on the learning objectives. For future VCS3 classroom implementation, a preferable approach would be to have the course instructor align assessment questions with learning objectives. For that reason, one of our study objectives was to provide instructors with the VCS3's implementation and assessment materials, which can be customized to fit the class' objectives. Alternatively, a more coordinated and synchronized implementation with the class instructor could allow us to further refine the learning assessment and post-simulation discussion. With this approach, a more time-distributed study could help us track long-term learning gains. The two-hour practicum time used for this study included an introduction, user training, the simulation exercise itself and administering both surveys. Ideally, students should be given more time to learn and practice how to use the VCS3 prior to the exercise. While current VCS3 speed would easily allow for an additional implementation within the same period, our initial implementation did result in some frustration caused by simultaneously learning the application and its content. As a result, our learning assessment was confounded with reflections on learning how to use the software rather than a focus on the information learned.

For the broader adoption of simulation games, an important question is how to best incorporate these learning tools into course curricula. One of our objectives for the VCS3 was to allow for its easy implementation into typically dense course schedules through documenting its development and dissemination material. Fig. 3 proposes a multi-pronged approach to incorporating the VCS3 and evaluating its effectiveness. The user debriefing process remains an important post-simulation
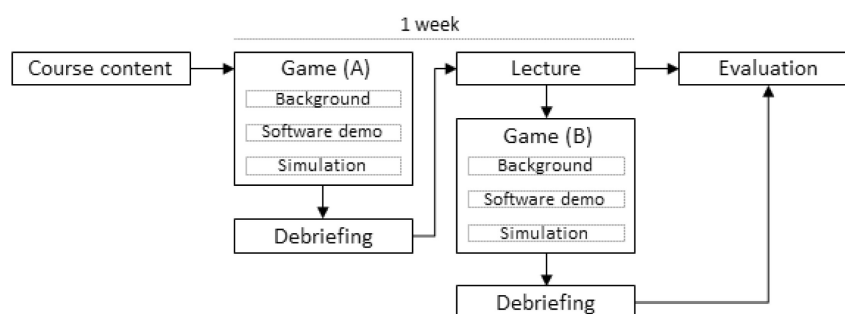

Fig. 3. Proposed integration of the VCS simulation game in the course.

reflection exercise, and can consist of a discussion with the instructor, repeating the simulation outside of class, or a meta-reflection on goals, strategies, actions, and outcomes. In addition, the meta-reflective questions which can be posed both during and after the simulation exercise can help students learn how to learn, i.e. better understand what strategies they employed and why, and what they would change in future runs. Ideally, the game should be integrated with class content as part of a broader learning activity, allowing time for learning the software and post-simulation reflection.

5. Conclusion

The VCS3 simulation game was developed to provide students with holistic planning and management game, and offer custom learning scenarios with robust instructional support for its broader adoption in the construction curricula. To date, all VCS3 classroom implementations have suggested its simulation experience as realistic, visual, hands-on and fun, and an appreciation of being able to test options and see results very quickly. Based on the results, both the VCS3 simulation game and the assessment are being continually improved. Game speed has been increased to maintain the students' attention, though variable speed could address the learner differences. Because the budget with the daily reported costs is the only incorporated performance metric within the current VCS3 version, it is important that the accompanying learning scenario defines relevant metrics or goals for students to compare against. In the subsequent implementations, expected completion deadline added to the available budget reduced the variance of students' reported construction durations, and at the same time added to the challenge of planning and effectively managing construction to achieve both. The log sheet for students to record their decisions for each simulated day has been included in the subsequent assessment material to encourage reflective evaluation of the employed strategies and their outcomes. Although the validity of self-reporting in terms of what students think they learn is somewhat debated, self-reflection on the performance and evaluation of procedural steps is recognized as part of the metacognitive learning, which is a critical component of problem solving.

However, the extent of the simulation game effects on learning remains elusive due to inherent classroom setting limitations and the nature of this study. While the VCS3 implementation can accommodate constrained class schedule, its effects on long-term information retention, attainment and better problem solving could be further tested in a time-distributed study. Debriefing and instructors'

involvement were recognized as critical to ensure effective learning gains, and combined with reflective self-assessment can contribute to higher-level metacognitive learning. While the pavilion project is relatively small, it was still sufficiently complex for students to grasp the extent of their decision outcomes and this is where the VCS3 would benefit from additional feedback mechanisms including performance metrics (e.g. projected vs. actual costs), scaffolding and levels of difficulty. Adding additional factors (overtime, safety, and congestion) would allow for more complex learning scenarios and more specific roles that would resemble actual construction processes, and role-playing in a team setting could provide data on the learning potential of a team-based and individual-based simulation experiences. While the next version of the VCS is currently being developed to address these limitations, its current free version with supporting materials aims to garner broader instructors feedback, which is currently lacking, to expand and improve the VCS into a robust and customizable experiential learning environment.

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Appendix A

Virtual Construction Simulator ®   s p r i n g   2010

How fast can you build the pavilion without exceeding the budget?

- The budget limit is **$ 15 000;**
- The budget includes **labor** and **equipment;**
- Labor and equipment are paid for the **whole day** on site regardless of how much they actually work;
- For this project, the labor provided is a **union** labor;
- Union labor by this contract does **not** work during the weekend and does **not** work overtime.

Your task:

Plan and simulate the construction schedule for the Pavilion project using the **V**irtual **C**onstruction **S**imulator application developed at the AE Department.

Report below how did you do, and compare how well you peer managers did ☺

Save and Copy the MS Project from the VCS onto Y:\VCS_AE372\MSProject_\"username".mpp

Name: _____

How long did the construction take? _____ **days**

How much did the construction cost? _____ $

The information provided above is for research purpose only. It will NOT be used for grading purposes or impact your grade for this class.

Department of Architectural Engineering _____ The Pennsylvania State University

Appendix B

The Pavilion Project

Constructing the Pavilion - Introduction

Summary

You are a construction manager at *PSUConstruction*, a mid size construction company based in State College, PA. You have been tasked with providing a construction plan to build the Pavilion project. The owner of this project however, insists that the pavilion is built in no more than 6 days as the reception for the business partners has been already scheduled. While exceeding 6 day time frame induces penalties and additional costs, the owner offers bonus savings if the project is completed ahead of the schedule and under the provided budget. You receive the pavilion documents and notice the structure comprises of:

- 8 cast in place concrete footings,
- cast in place concrete slab,
- 8 wood columns
- 6 pairs of beams
- 13 trusses
- sheathing and shingles

Based on your previous experience and initial look at the project, you are confident that you can build the Pavilion relatively fast and at low cost ensuring the quality and safety.

Managing Your Project

To give your estimate on time and cost, you will plan and simulate the construction of the project. You can repeat the process as many times you want until you are satisfied with the solution. Before you start the project, and each day as it unfolds, you will have an opportunity to adjust certain project parameters. Spend about 5-10 minutes when deciding on:

1. Construction Methods

For each building element type you can choose between different construction methods. One may be faster but more expensive than the other. Think about advantages and disadvantages of both.

2. Project Schedule

You may change your schedule (your target completion time) by changing the activity sequence and/or activity duration. Hiring multiple crews speeds up any construction activity.

2. Resources

More labor can do more work, but of course each additional labor also adds to project costs. The longer any laborer works on the site, the more experienced and efficient they become. Although you can have as many people on the site as you want, be careful as the site becomes less safe.

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The Pavilion Project

The project information

- The budget limit is **$ 15 000;**
- The budget includes **labor** and **equipment**;
- Labor and equipment are paid for the **whole day** on site regardless of how much they actually work;
- For this project, the labor provided is a **union** labor; union labor by this contract does **not** work during the weekend and does **not** work overtime;
- For each day ahead of completion you save **$1000**;
- For any remaining amount of the budget unspent, you get to keep **50%** .

Your task :

Plan and **simulate** the construction schedule for the Pavilion project using the **Virtual Construction Simulator** application developed at the AE Department.

Document all the decisions you made each day in the table bellow.

Report below your final results ☺

Name: [   ]

How long did the construction take? [   ] **days**

How much did the construction cost? [   ] $

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The table below will help you keep track of the progress and any challenges you may encounter

Day	No of People	No of Equipment	Comments (strategies, activity progress, challenges..)
Cost			
Cost			
Cost			
Cost			
Cost			
Cost			
Cost			
Cost			
Cost			