



Design of a Construction Simulation Educational Game Through a Cognitive Lens

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Abstract

Recent advances in digital technology have expanded the adoption of computer modeling software in the Architecture, Engineering, and Construction (AEC) Industry. This adoption has also initiated changes to curricula and teaching dynamics. In particular, in the field of construction engineering and management, visualization software is being implemented to support students' learning and cognition. One example is simulation games, such as the Virtual Construction Simulator (VCS), developed and implemented to engage students in an active learning environment by simulating the planning and management of a construction project. The previous version of the VCS has shown great potential in enhancing students' motivation and basic learning of dynamic construction concepts, traditionally acquired through practical experience. A new version has been developed utilizing the ADDIE (analyze, design, develop, implement, evaluate) framework for the design of instructional material. Through the development of the VCS4, we aim to illustrate how a rigorous analysis of cognitive models and theories, instructional design guidelines for multimedia learning, fundamentals of human computer interaction theories, and 4D simulation guidelines, can support the design and development of an educational simulation game. The game is designed using several modules to target differing levels of experience from outreach efforts of high school students and underclassmen, to senior construction engineering students in technical courses. Three different learning modules, with scaled learning objectives, were developed to target undergraduate to graduate students learning about construction engineering and management. The design of the game was dictated from new game mechanics and features, which aim at supporting the engagement as well as the acquisition of higher order cognitive skills. Additionally, the development will illustrate the dynamic nature of the VCS4 by using Building Information Models for the development of additional learning modules. The presented work illustrates how the influence of instructional theories and design can support the generation of a new learning platform for construction engineering and management.

1. Introduction

One of the main objectives of engineering education is to shape students that possess a wide variety of knowledge, skills, and attitudes obtained as a result of education, experience, and achievement.^[1] This holds true for construction engineering students, who are challenged with real world problems during their education and after graduation. This educational objective requires educators to prepare their learners to solve real world problems, with which the Architecture, Engineering and Construction (AEC) Industry will challenge them. However, most traditional educational methods challenge the students with incomplete or well-structured problems, which do not represent the complex nature of the construction process. With the increased adoption of Building Information Modeling (BIM), educators have started to teach their students to utilize computer technology to solve complex problems. While BIM technology allows students to generate designs and experiment with different construction solutions, it is mainly designed for professionals and not for educational purposes. To address the main challenge of exposing students to the ill-structured nature of construction, previous research has leveraged the potential of simulations and serious games. Educational serious games have shown great promise in their ability to provide students with an experiential learning environment. An example is the Virtual Construction Simulator (VCS), designed by the Computer Integrated

Construction (CIC) research group at the Pennsylvania State University. The VCS, currently in its third iteration, is a simulation game that has shown great potential in motivating and engaging students.^[2] As a continuation of research efforts, the development of a new VCS(4) aims to address the challenge of assessing higher order thinking skills in the problem-solving domain, by revisiting the game design. The following presented work will illustrate how a rigorous analysis of cognitive models and theories, instructional design guidelines for multimedia learning, fundamentals of human computer interaction theories, and 4D simulation guidelines, can support the design and development of an educational simulation game.

2. Construction: a complex problem

The construction process is riddled with unknowns that cannot be predicted in the planning process. These unknowns make the construction process an ill-defined problem. According to Schraw et al. an ill-defined problem might have no solution, or there might be multiple solutions with no proper procedure to obtain them.^[3] The traditional lecture based classroom provides the students with learning activities based on well-defined and fragmented construction problems, which do not prepare them with proper decision making skills, required for entering the construction industry.^{[4][5]} While BIM and CAD software have started to become integral in most architectural and civil engineering departments, they do not provide the students with educational challenges that prepare them for the industry, and often require a level of existing construction knowledge.^[6] Therefore, traditional teaching approaches remain limited for providing students with the necessary experiential knowledge to prepare them for the AEC industry.^[7] The advances in visualization and BIM research have illustrated the value of simulations in the planning and managing process of construction. For example, VITASCOPE and STROBOSCOPE, which are 3D visualization systems that animate construction processes by using Discrete-Event Simulation Tools, have demonstrated the benefits of simulations in the evaluation process of earthmoving operations.^{[8][9][10]} Other examples of successful simulation research efforts are CONSTRUCTO, SBID, and AROUSAL, have also started to be implemented in academic environments. Meanwhile educational simulations, such as MERIT, and simulation games, such as COINS, have also started to be implemented in academic environments.^{[11][12][13][14][15]} Virtual Coach, developed by Rojas and Mukherjee, is a web-based situational simulation environment that presented the participants with fast decision making events, generated by the system dynamics.^[16] Another example is the Project Management Simulation Engine for project management education, which allowed the user to generate customized simulations.^[17] Additionally, Chen et al. developed SONG, a network growth simulator program, which allowed for students to learn about transportation engineering and traffic planning.^[18]

2.1. The virtual construction simulator

The Virtual Construction Simulator (VCS) is another example of an educational simulation game. The aim of the VCS is to teach students the changeable nature of the construction process and the unpredictable factors that influence it. The VCS allows the learner to develop and manage construction schedules, while experiencing the variance between the as-planned and the as-built schedule.^[2] The game has gone through several iterations and the latest development efforts have produced the VCS3.^{[2][19]} The VCS3 was developed with the Microsoft

XNA Game Studio Express game engine. The game implemented new game mechanics and simulation factors that affect the construction process, such as learning curve of the workers, weather, overtime, etc. The assessment of the VCS3 was based on the Kirkpatrick and Kirkpatrick's framework for evaluating training programs by looking at learners' reaction, learning, behavior, and results.^[20] The assessment focused on students' ability to list, identify, and rank factors that affect the schedule. The learners' motivation was measured through the use of an adapted pre- and post-test called the OnLine Motivation Questionnaires.^[21] The assessment results have proven the VCS3's capability to motivate the students and increase their general knowledge of the construction planning process.^[2] However, while the VCS positively affected students' overall learning and motivation, the results still do not fully reveal the VCS3 simulator's ability to promote higher order thinking skills.

3. Instructional design of the virtual construction simulator 4

The past experiences of the VCS3 have demonstrated that the game has great educational potential. This potential is being addressed with a new phase of research and development of a new version of the game, the VCS4. With the next generation of the VCS, the development will focus on designing a new interface, additional features and content, and conducting further assessment of the game's potential for teaching higher order thinking skills. The ADDIE model framework for instructional designers was utilized to direct the development of the new VCS project (see Figure 1). The ADDIE model framework was developed for military training by the Center for Educational Technology at Florida State University, but it has become an accepted model in instructional design.^[22] The model divides the process of instructional design into *analysis, design, development, implementation, and evaluation*.^[23] The analysis, design, and development steps are explained and described in the following subsections. The process will illustrate how the analysis of previous research in learning theories, instructional design, and interaction guidelines was central for the design and development of the VCS4. The implementation and evaluation steps of the VCS4 will be covered in future publications.

3.1. Analysis

In the analyze phase of the ADDIE model, the instructional designer has to study and examine the instructional challenge. In this examination, the target audience, their environment, learning theories and objectives, and delivery methods are identified.^[23] With the new version of the VCS, the research team aims to widen the target audience and environment. The learning objectives for the game, or as Branson et al. refer as performance standards, have been already outlined in previous publications.^{[23][24]} Lastly, a model for solving construction problems is proposed to support the development of the game.

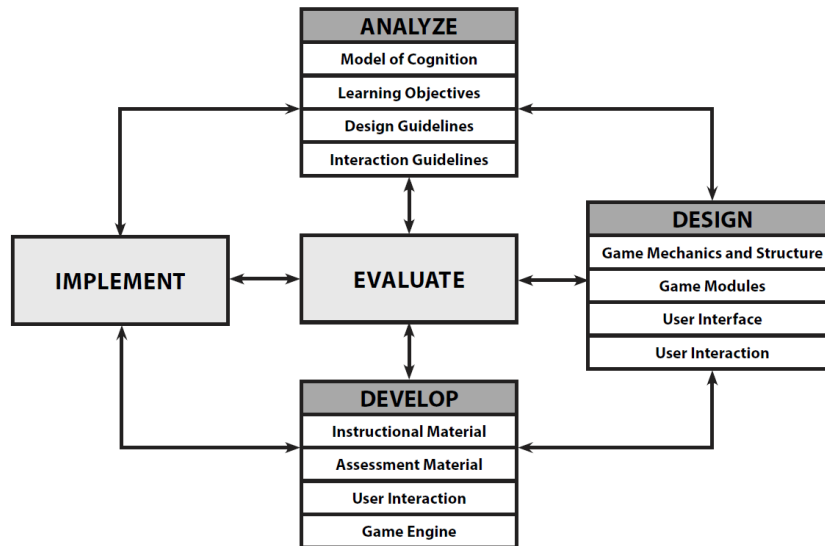


Figure 1. Development Process of the VCS4 based of the ADDIE Model

3.1.1. Audience and environment

The flexibility of simulation games allows the designer to develop games that can target a wide range of students and learners in a variety of instructional environments. The chosen environment for the delivery of the VCS activity is the classroom environment. The audience of the activity can vary. The VCS3, targeted students in their last year of high school or undergraduate college students in an introductory course focused on construction engineering. With the VCS4, the researchers have widened the scope and decided to target undergraduate construction engineering students in their advanced years of study, together with first year graduate students, (see Table 1).

Table 1. VCS Audience

| VCS Module | Target Audience |
|--------------------|--|
| Wood Pavilion | Senior High School – Sophomore College Student |
| Steel Structure | Junior College Student – First Year Graduate Student |
| Concrete Structure | Junior College Student – First Year Graduate Student |

To target this audience, additional learning modules have been added to the VCS. The first module, present in VCS3, engages the students in the construction of a wooden pavilion. This module can target high school and early undergraduate students. The second and third modules are of the same facility, a dormitory located at the authors' university. The facility was modeled and constructed with a steel structure. For the purposes of developing the VCS module, a separate design model was developed for this building with a concrete structure. The steel and concrete modules are targeted toward students that possess greater knowledge of construction engineering. These modules could potentially be extended for training of industry practitioners; however, the current scope of the VCS simulation has not yet reached this audience.

3.1.2. A cognitive model of problem solving

According to Schunk, problem solving is one of the most important types of cognitive processes that occur during learning.^[25] Problem solving is a learning process that can be defined as the cognitive process to achieve a goal that does not have a direct solution.^{[25][26]} Different models have been developed to describe the problem solving process, such as Bransford's *IDEAL* model and Pölya' model.^[27] According to Pölya, there are four main phases in the problem-solving process: *understanding the problem*, *devising a plan*, *carrying out the plan*, and *looking back*.^[28] In previous work, Jonassen formulated a model for solving ill-structured problems, which expanded on the cognitive process of problem solving.^[29] These models provide the basic problem-solving cognitive sub-processes that Mayer and Wittrock summarize as *representing*, *planning*, and *executing*.^[26] In previous literature, Van Meter et al. developed the Integrated Problem-Solving (IPS) model which aimed at comprehensively encompassing problem-solving processes, prior knowledge, and symbol system transformation.^[30] The IPS model is composed of three phases: *problem representation*, *problem framing*, and *problem synthesis*.^[30] The model has shown its ability to effectively illustrate the student's analysis processes in solving free body diagrams in statics.^{[30][31]} In addition to cognitive processes, it is essential to consider the role that metacognition and self-regulated learning has on the students learning processes. Metacognition can be defined as the awareness of one's own abilities, cognitive resources and processes, and knowledge.^[32] Metacognition's processes mainly target the monitoring, controlling and evaluating the cognitive operations and products while problem solving. In their four-stage model of self-regulated learning, Winnie and Perry describe self-regulated learning as an event or a transient state situated within a larger series of states over time, where metacognitive monitoring, with internal feedback, is central.^[32] Therefore, they place metacognitive monitoring at the center of the model, as it is fundamental to self-regulate one's learning especially when considering learning and problem-solving with different mediums.

Based on the reviewed literature, a model for solving construction engineering problems had to be developed. This model mainly focuses on cognitive and metacognitive problem-solving processes, prior knowledge, and the utilization of visual representations (see Figure 2). This model is based on the Van Meter et al. IPS model with a lens on ill-structured problems provided by Jonassen's model, together with Winne and Perry model of self-regulated learning and metacognition.^[29] Retaining the structure of the IPS model, the proposed model is divided in three main phases: *problem representation*, *problem execution*, and *solution evaluation*. Leveraging Winne and Perry's work, metacognitive processes are iterative events that support each of three main phases of problem-solving. Based on this model the learner can move between the phases of problem-solving in a non-linear way, as the metacognitive self-regulative processes are iterative events that influence the learner's problem solving process. Winne and Perry cognitive conditions are also retained in this model, mainly the learner's own domain knowledge and knowledge of the task.

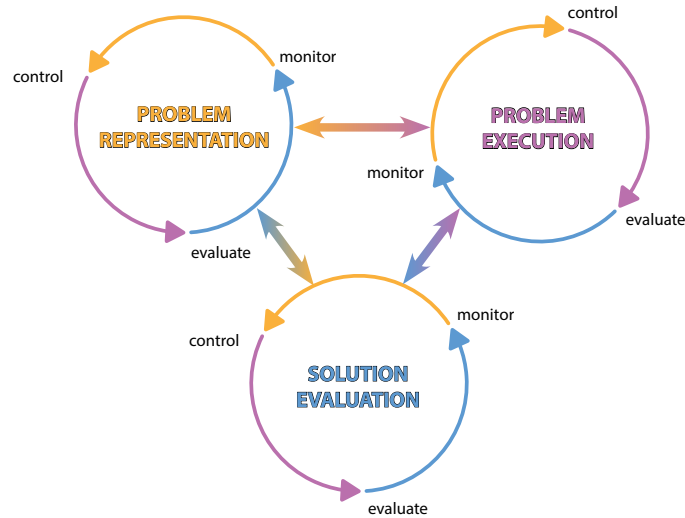


Figure 2. Problem-Solving Model for Construction Engineering Education

3.1.2.1. Problem representation

The problem-solving process begins with the development of the problem's representation. During the *problem representation* phase the following cognitive processes are performed: the understanding and identification of the problem constraints and tasks, the exploration of the problem space, and the development of a possible solution, and assessing the viability of alternative solutions.^[29] The metacognitive self-regulative processes that support this phase aim at the *monitoring*, *controlling*, and *evaluating* the cognitive process in this phase.^[32] The *visual representations* that are supporting these processes, by furthering the understanding and identification of the problem constraints, are the project's summary, the information presented with the 3D model, and the phasing and sequencing environments. Several visual representations are supporting the learner's metacognitive self-regulative processes by allowing the generation of possible solutions, such as the selection and sequencing of 3D assemblies, and their assessment, with the preview of the sequence. Lastly, *prior knowledge* is required to support the identification of optimal construction methods and activities related to the project's facility.

3.1.2.2. Problem execution

In the *problem monitoring* phase, the student begins to implement and monitor the execution of a proposed solution.^[29] The construction simulation requires the identification and selection of daily resources, the review and analysis of daily construction performance, such as the total budget and time, the learning curve, the weather of the day, and identification of the factors affecting the construction. The metacognitive self-regulative processes that support this phase aim at *monitoring*, *controlling*, and *evaluating* the cognitive process in this phase.^[32] The *visual representation* that will support the cognitive process is a daily scheduled activities summary, from which the student chooses the resources for the day. The analysis of the construction process is supported by performance metrics, which display information such as learning curve, time, weather, and number of idle workers. In order to analyze the construction process, a daily report will provide feedback with the performance metrics. When assigning the

daily activities, the student will have to possess *prior knowledge* in construction methods and factors affecting the construction process.

3.1.2.3. Solution evaluation

The last phase is the *solution evaluation* where the problem solver has to evaluate the final solution by viewing the final report, possibly plan the next construction sequence, and identify the factors affecting the construction process. The cognitive processes that can take place are: planning of the next construction solution; evaluation of the final solution; compare planned versus actual construction; and identification of the factors that have affected the construction process. The visual representation that supports these processes is the final report illustrating how the construction's productivity has varied based on the students' choices and the field factors. Lastly, prior knowledge that can affect these cognitive processes is related to the factors that affect the construction.

3.2. Design

The second phase of the ADDIE model is the design of the instructional activity. In this phase, the results from the analysis are used as guidelines for the design of the instructional package. The audience, environment, and learning objectives provided the framework for the designers to structure the game. According to Schell, a game has to have four basic elements: *mechanics, story, technology, and aesthetics*.^[33] Even though the VCS is not a story-based simulation game, a problem and project context is provided. The main focus of the design was mechanics, aesthetics, and technology. The following subsections will give an overview of the game mechanics, which were designed to address the new research questions, together with a description of the new interface aesthetics and features. The technology aspects of the game design are discussed in the development section.

3.2.1. The game mechanics

Game mechanics are the rules that direct the game play.^[33] The mechanics provide a structure for the game where the students can view their challenge, interact with the problem, and achieve a goal. Since the new research questions aimed at assessing the VCS's potential to enhance students' problem solving ability, the VCS4's game mechanics had to be redeveloped, and additional features, not present in the VCS3, had to be implemented. The research focus on problem solving required adding an iterative nature to the game in the way learners evaluate their proposed plans. The iterative nature of playing will allow the students to test their mental model and develop better problem-solving skills. Additionally, these new mechanics focused on laying out the game's structure, goals, scenes, interactions, and data flow. With this iterative nature at its core, the research team developed new game mechanics (see Figure 3).

The presented game mechanics illustrates how the students will go through an iterative process of planning, testing the plan, and evaluating the results to then repeat the process to improve their plan. The mechanics were then translated into a game structure, which is at the base of each learning module. The structure is divided into several scenes (see Table 2) dictated by these mechanics. Each of the scenes provides the student with a graphical user interface (GUI) to perform the desired actions. The structure and steps for each of the scenes were then

further broken into process maps where interactions, game features, graphical elements and their function, and the flow of data were mapped. After the entire game structure was mapped, the team focused on the design of new features not present in the previous VCS.

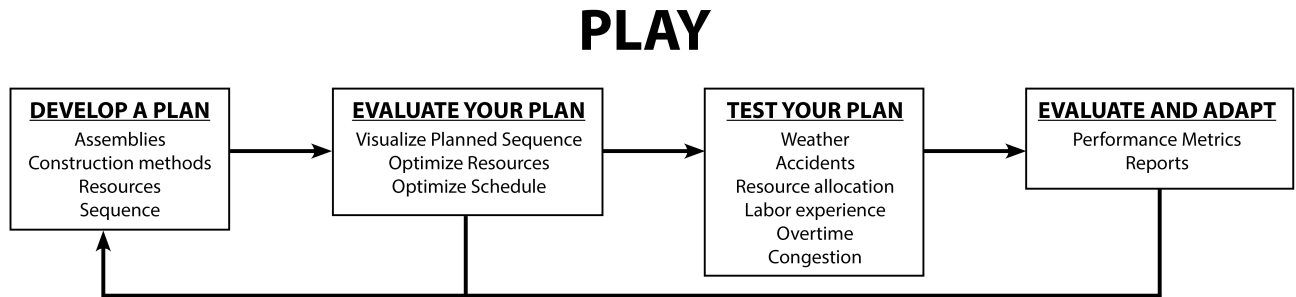


Figure 3. VCS4 Game Mechanics

Table 2. Structure of the VCS4

| Game Mechanics | Game Scenes | Purpose of the Scene |
|--------------------|-----------------------------|--|
| Develop a Plan | Start Menu | Introduce the project information, e.g. start date, budget, location, etc. |
| | Exploration and Walkthrough | Perform for on-site walkthrough and interaction with building elements. |
| | Phasing | Select building elements for assembly construction. |
| | Methods Selection | Select optimal construction methods. |
| | Sequencing | Develop optimal construction sequence. |
| Evaluate the Plan | Sequencing | Analyze optimal construction sequence. |
| | Resources Allocation | Select optimal construction crews. |
| Test the Plan | Simulation | Manage and select daily resources during construction. |
| Evaluate and Adapt | Daily Report | Analyze and evaluate current status of construction. |
| | Final Report | Analyze and evaluate the entire construction process. |

3.2.2. Vcs4 modules

The VCS4 will not only include the previously developed wooden pavilion, but also new learning modules. The two added modules are of the same facility, Chace Hall, located at the Pennsylvania State University campus. A graduate structural engineer from the Architectural Engineering department developed a concrete structural model of the building with the same building footprint and floor to ceiling heights. Utilizing the concrete structural model, the research team performed a construction analysis of the facility and produced a report for the development of the module. An overview of the concrete project is given in the report (e.g. cost, area, start date, etc.), together with the learning objectives for the module. The report then gives a breakdown of the building elements that the students will have to group and sequence. For each

element, the report also provides construction activities, construction methods, crew size, rate of construction, and cost. These values were calculated together with a concrete specialist with over 25 years of experience with planning and managing construction projects. The report will allow for the research team to package all of the necessary data to be included in the development phase.

3.2.3. User interface and interaction

With advances in technology, educational research has placed particular focus on multimedia learning to provide learning experiences to students.^[34] Mayer's cognitive theory of multimedia learning defines learning as the process of building mental representations and constructing knowledge from words and pictures.^[35] Multimedia learning can now provide students with an environment where they experience and interact with the medium. Mayer's work builds on several cognitive theories of learning and processing, to propose the Cognitive Theory of Multimedia Learning (CTML). Based on this model of cognition and research, Mayer developed a set of design principles for multimedia learning, which aim at reducing extraneous processing, managing essential processing, and fostering generation processes.^[36] The work of Mayer provides the foundation of cognitive learning theories and design principles necessary for the development of educational research with multimedia.

Using Mayer's design principles and the guidelines, together with previous research efforts in the field of 4D visualization, information visualization, and human-computer interaction, the research team was able to develop a set of guidelines and standards for 4D application development.^[37] Based on these standards the game allows the learner to overview and simulate the construction model, zoom into the model, filter the information, and query details of the model.^[38] Additionally, shadows and luminance difference were used to distinguish highlighted elements, color saturation was utilized to distinguish object selection, and various levels of transparency were used to dictate the status of a construction activity.^{[46][40]}

The aesthetics of the game provide the look and feel to the game.^[33] Game aesthetics include the GUI that delivers the user a set of graphical tools for the interaction with game. The user interface (UI) had to be completely redeveloped for the VCS4, in order to include all the desired new features. Through a storyboarding process, the research team developed mockups of the interface for each scene of the VCS4. The generation of these storyboards allowed the team to integrate the previously described game structure and features into a user-friendly and intuitive interface. The storyboarding process focused on the shift from a table based GUI, to a minimalistic 2D interface with a strong focus on the 3D model. Each of the scenes was storyboarded to include both 2D and 3D elements, together with the desired interaction to be included. This process allowed for an easy transition into development in the game engine environment, which is discussed in the following section.

The VCS4 design focused on allowing the learner to interact directly with the 3D model. Starting with the addition of an exploration and walkthrough scene, the team developed an interactive 3D model where the students can directly click on any building element and view construction information regarding the element. Furthermore, the scene allows for the student to use an avatar to walk in the construction site and have a closer look at the facility. In the

grouping scene, the team redeveloped the method for the generation of construction assemblies, which allows the students to directly click on the desired 3D elements and generate a construction assembly. The sequencing scene was completely re-designed. While the previous VCS allowed for the students to generate their construction sequence by sequencing the planned activities in a table or Microsoft Project Gantt chart, the VCS4 asks the students to directly select the 3D construction assemblies and select a construction relationship, either overlapping or sequential. The schedule of construction is then generated for the student and it can be previewed through a simple 4D simulation (see Figure 3). The simulation scene was also re-designed to provide visual monitoring and feedback on the construction process. The workers' performance, such as learning curve, activity, experience, and fatigue are reported to the students. Lastly, the daily reports were also redesigned to include visual feedback on the overall performance of the construction process.



Figure 4. VCS4 sequencing scene

3.3. Development

In the development phase, the design of the instructional activity is generated. The VCS3 was previously developed with the C# programming language, in the Visual Studio Microsoft Developer Tools and rendered with the Microsoft XNA Game Studio Express. However, the VCS4's new desired features required a flexible game engine with a robust 3D physics and user interaction capability. To satisfy these requirements the Unity™ game engine was chosen. Unity™ is a game development environment with a powerful rendering engine. The engine is integrated with a complete set of intuitive tools and rapid workflows to create interactive 3D and 2D content.^[41] The Unity™ game engine allowed the research team to incorporate photorealistic graphics, streamline the 3D content generation, and simplify the publication of the game. The game engine allowed the research team to easily import Revit models and dynamically generate the learning modules, based on their learning objectives. The workflow to import Revit models in the game engine has been extensively outlined in previous publications.^[42] To develop a flexible UI, the research team decided to use the Next-Gen UI (NGUI) toolkit for the development of the UI within Unity. NGUI is a UI system and event notification framework for Unity, written in C#.^[43] Based on the storyboards, the NGUI toolkit allowed the research team to develop an interactive interface, which streamlines the user's tasks and alleviates cognitive load. The game was coded in the C# programming language.

3.3.1. Instructional materials

Several instructional materials have been developed to support the activation of the learners' metacognitive processes. During the game play, the students are asked to monitor their construction process on a handout, which is distributed at the beginning of the game play activity. They are asked to record their as-planned and final cost and schedule. Additionally, they are asked to record their daily labor efficiency. The handout will serve as a metacognitive prompt for the students to monitor their progress. Additionally, assessment instruments were developed to evaluate the learners' knowledge and problem solving skills. Mayer points out the necessity of assessing learning outcomes by evaluating knowledge retention and transferability.^[36] To do so, pre and post-tests were developed to assess various levels of cognitive thinking skills for each learning module. The tests were developed based on the problem-solving skills outlined in the analysis section. Based on the framework and learning skills, the learners are to be evaluated for their ability to represent, monitor, and evaluate a construction plan. The tests will be in the form of open-ended questions. The questions will require the students to reflect on the planning and managing of the construction process for a hypothetical building structure. These cognitive and thinking skills paired with problem-solving skills provided the foundation for the development of an assessment rubric. This assessment rubric provides an evaluation framework to assess and score student's performance on the pre- and post-test. This rubric will be utilized to facilitate future analysis. Each question of the test has a paired learning objective and thinking skill, together with a four-level scale evaluating the student's performance.

4. Conclusion

In this paper the authors have described the process for the design and development of a simulation game with the aim of engaging the learners' cognitive and metacognitive processes in solving complex construction problems. The analysis of past research supported the development of a model of cognition. The design and development of the game focused on translating the proposed cognitive model into structured game mechanics, with strong consideration for instructional and human computer interaction design guidelines. This research has illustrated an example of how an educational simulation game can be designed and developed with strong consideration for the engagement of cognitive processes.

The next step is the implementation and evaluation of the simulation game. The interdisciplinary nature of the research in construction engineering simulation games requires both qualitative and quantitative assessment methodologies. The qualitative assessment of cognitive processes will require gaining insight into the students' thought processes as they are engaged in the activity. Think-aloud protocols will be used to tackle this phase, since they have been successfully used to assess cognitive processes during well and ill-structured problem-solving, and can provide insight to students' metacognitive processes. The quantitative evaluation of the simulation game as a successful teaching method will require additional assessment beyond the think-aloud experiments. The assessment will evaluate for changes in knowledge retention, transferability, and acquirement and performance of cognitive processes.

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