

A Gamified Method for Construction Engineering Education: Learning through Guided Active Exploration

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Abstract: Experiential learning through active exploration can play a vital role in fostering critical thinking and problem-solving skills in engineering education. However, the complex nature of the construction industry in the 21st century cannot afford an education through trial and error in a real environment. This case study aims to promote experiential learning in construction engineering education by designing, implementing, and empirically evaluating a novel gamified pedagogy that directs students to discover systematic solutions for fundamental construction engineering problems. The game-based pedagogy was implemented in the context of construction project scheduling. The proposed pedagogical method and its gamified elements are designed based on the constructivism learning theory and are grounded in state-of-the-art literature through research-based instructional strategies and conceptual frameworks. A scenario-based interactive game, called Zebel, was developed using the Unity game engine. Using a series of preassessment and postassessment instruments, the method was implemented and evaluated in a graduate-level course for construction planning and scheduling to collect empirical data. The outcomes of this case study indicated that the pedagogy successfully guided students with no background and prior knowledge in construction scheduling to discover the fundamental concepts and systematic solutions for the given problems. Although the focus of this study is on construction scheduling, the proposed pedagogy based on active exploration in an interactive game environment can be adopted in other contexts in construction education. DOI: [10.1061/JCECD.EIENG-2019](https://doi.org/10.1061/JCECD.EIENG-2019). © 2023 American Society of Civil Engineers.

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Introduction

The construction sector is one of the largest industries in the world economy. In the US, the construction industry employs more than 7.8 million professionals (US Bureau of Labor Statistics 2023) and creates nearly \$1.3 trillion worth of structures each year (Statistica 2022). Despite the criticality of this industry, construction projects are overwhelmed with delays and suffer from inefficiency and cost overrun (Zidane and Andersen 2018). In addition, unprecedented challenges such as climate change, technological revolutions, and population growth make successful planning and management of construction projects even more complicated. Future generations of construction engineers equipped with a deep understanding of fundamental concepts and a repertoire of problem-solving skills have a critical role in revolutionizing this industry.

Construction engineering education, at the nexus of engineering design and project management, is responsible for preparing future construction engineers for facing and solving unprecedented problems. However, the existing construction engineering programs, to a considerable extent, rely on educational models that predominantly engage students with well-structured and closed-ended problems.

Previous studies have convincingly shown that traditional content-centered, and didactic teaching methods are ineffective for developing a deep understanding and knowledge transfer. Neither of these methods adequately addresses the development of critical problem-solving skills. Active and collaborative instruction, coupled with effective means to encourage student engagement, invariably leads to better student learning outcomes (Kuh et al. 2011; Weimer 2013). Despite these findings, the existing construction engineering curricula rarely offer a scaffolding approach to engage students with exploration and discovering systematic solutions for fundamental engineering problems and novel challenges.

A vital key to fostering learning through exploration and discovery is experiential learning (Kolb 2014). Experiential learning is a process in which students are purposefully engaged in a direct experience to learn through reflection on doing (Lynch and Russell 2009). A pedagogical strategy designed based on experiential learning provides students with opportunities to take initiatives, make decisions, observe the outcomes and consequences of their decisions, recognize their mistakes and successes, and discover new knowledge (Guerra and Shealy 2018). In experiential learning, reflection on learning during and after experiences is integrated into the learning process. This reflection leads to critical thinking and knowledge synthesis (Boud et al. 1993).

Interestingly, experiential learning has a long history in construction engineering. The history of construction dates back to the Neolithic era (i.e., the New Stone Age), roughly from 9,000 to 5,000 BCE (Violatti 2018). Many prehistoric structures, including megalithic temples in Malta (from around 3,600 BCE) and the Egyptian pyramids (from around 2,500 BCE), are still standing. However, Newton's laws of motion, which laid the foundation for classical mechanics and, consequently, structural analysis, were first published in 1687. For thousands of years, structures were built without formal theories that mathematically explain why they stand. The evolution of construction engineering from ancient times to the seventeenth century was mainly based on discoveries

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through trial and error that helped craftsmen empirically distinguish good design and construction methods from less effective approaches (Abrams 1994).

From the seventeenth century, when Newton presented his laws of motion, engineering concepts gradually developed stronger connections with mathematical expressions. The mathematical representation of engineering concepts is the foundation of modern engineering and engineering education. However, through time, educational programs in many engineering fields, including construction, have evolved into rigid systems that mainly train students to follow specific procedural algorithms for inserting data into well-defined equations and calculating expected outcomes for closed-ended problems. Such educational programs offer little opportunity for students to engage in active learning that can help them gain first-hand experience and guide them toward discovering solutions.

The long history of empirical learning in the field of construction engineering shows the significant potential of cognitive development through direct experience and reflection on what works in particular situations (Boothby 2018). Of course, the complex nature of the construction industry in the 21st century cannot afford an education through trial and error in the real environment. However, recent advances in computer science can help educators develop virtual environments and game platforms that allow students to explore various scenarios and learn from their experiences. A potentially effective approach to creating virtual environments where students can engage in active exploration is gamification.

Gamification and Its Applications in Construction Education

Gamification or serious games apply game elements and principles in nongame contexts (Dicheva et al. 2015). If appropriately designed, serious games can provide an interactive environment where users can engage with technical contexts, explore different scenarios, acquire new knowledge, and connect that knowledge to their existing mental models (Deshpande and Huang 2011). The term gamification was coined by Nick Pelling in 2002 and hit the mainstream around 2010 (Pelling 2011). The elements of a gamified system can be categorized into three groups:

- dynamics, which defines the big picture aspect of the game and includes elements such as constraints, narratives, progression, and relationships,
- mechanics, which defines the processes that drive actions forward and includes elements such as challenges, chance, competition, cooperation, feedback, resource acquisition, rewards, transactions, turns, and win states, and
- components, which shows specific instantiations of mechanics and dynamics and includes elements such as points, quests, achievements, badges, avatars, and virtual goods (Werbach and Hunter 2012).

Designing gamified solutions for construction education and training has received growing attention in recent years. Ilbeigi et al. (2023) conducted a systematic scoping review of the existing literature in that area to analyze the extent of the knowledge and potential directions for future research and scholarly works. They identified and reviewed more than 100 studies that discussed gamification in the construction sector. Among them, 49 studies proposed new game-based solutions for construction education and training. These studies targeted various aspects of construction education and training, including safety (e.g., Pietrafesa et al. 2020), structural analysis (e.g., Patil and Kumbhar 2021), construction methods (e.g., ElGawely and Nadim 2020), lean construction

(e.g., Tagliabue et al. 2021), architectural design (e.g., Khah et al. 2019), building information modeling (BIM) (e.g., Pütz et al. 2020), sustainable development (e.g., Rogora 2021), equipment planning (e.g., George et al. 2016), economic decision analysis (e.g., Josiek et al. 2020), and project management (e.g., Holzmann et al. 2018).

The search process during the aforementioned synthesis study revealed a clear upward trend in the number of studies proposing gamified solutions for education and training in construction engineering. However, the results of the scoping review indicated that the extent and level of maturity in the existing studies are still very limited. Most of these studies directly introduced new concepts in a game environment. For example, in the area of construction methods, Goedert et al. (2013) developed a simulation-based game that introduces various activities in bridge projects. Some other studies, such as that by Eiris Pereira and Gheisari (2019), went one step further and developed virtual environments to train students in more realistic situations. Although these works effectively contribute to gamification applications in construction education, they did not offer an opportunity to educate students through experiential learning and guided active exploration. Therefore, little is known about the effectiveness of such pedagogical approaches on students' ability to discover systematic solutions for engineering problems. This knowledge gap motivated one of the identified potential directions for future investigations in the scoping review study by Ilbeigi et al. (2023).

The primary objective of this case study is to design, develop, implement, and empirically assess the performance of a novel gamified pedagogical method that helps students learn through guided active exploration. More specifically, we examined whether guided active exploration in a digital game environment improves students' ability to discover systematic strategies to solve fundamental engineering problems. We implemented the proposed pedagogy in the context of construction scheduling. However, as discussed in the following sections, the envisioned method and the outcomes of this case study can be transferred and adopted in other domains of construction education.

The remainder of this paper is organized as follows. First, we articulate the research questions that this study aims to address. Second, we introduce the methodology, including the theoretical learning framework that shapes the proposed gamified strategy, the design of the game, and assessment tools. Next, we describe the implementation process and its outcomes. We then outline the lessons learned and discuss how the outcomes of this case study can be transferred to other aspects of construction education. Finally, we summarize the results, discuss the contributions of this study to the body of knowledge, and depict future research directions.

Research Objective and Questions

This case study aims to assess the effectiveness of guided active exploration in a digital game environment on students' ability to discover systematic solutions for fundamental engineering problems in the context of construction scheduling. More specifically, this study addresses the following two questions:

- Question 1: Does a guided active exploration in a digital game environment improve students' ability to discover systematic strategies to solve fundamental problems in construction engineering?
- Question 2: How do students perceive an interactive digital gamification platform that lets them explore scenario-based construction engineering problems as a formal learning tool?

Methodology

To address the objective of this study, we designed and developed an online game called Zebel. The game provides an interactive digital environment where users try to solve fundamental problems in construction planning and scheduling presented in realistic scenarios through guided active explorations. Fig. 1 shows a snapshot of the game. The scenario-based problems facilitate sense-making and engage students in understanding, analyzing, and solving open-ended problems in that field. During the active explorations to solve these fundamental problems, users are exposed to fundamental engineering problems and try to discover systematic solutions to solve them. The game and the proposed gamified pedagogy are designed based on the constructivism learning theory. In this section, after a brief review of this learning theory, we explain how it forms the structure and elements of the pedagogical method. Next, we describe the game development process. Finally, we introduce the assessment instruments that we designed and used to evaluate the effectiveness of the proposed gamified solution.

Constructivism Learning Theory

Constructivism learning theory is the most prevalent variant of cognitivism (Tobias 2010). It was introduced by Piaget (1952) and extended by a long list of researchers, including Bruner (1966), Ausubel and Robinson (1969), and Maturana (2006). This learning theory assumes that knowledge is constructed by learners as they attempt to make sense of their observations (Driscoll 1994). In constructivism, learning is a journey of discovering meaningful information from interactions between what learners already know and what they come into contact with (Newstetter and Svinicki 2014; Jumaat et al. 2017). The focus of constructivism is on knowledge construction rather than knowledge transmission (Dalgarno 1996).

The principle of constructivism is an individualized representation of knowledge based on active exploration and learning by interaction (Kerka 1997). In constructivism, each learner may have a slightly different mental learning model that combines all the learner's past experiences and their interpretations of the new observations (Smith et al. 2005). The constructivist learning framework is aligned with the objectives of this research as it offers a rationale for curriculum integration that connects learning with the practices associated with the workplace (Duffy and Cunningham 1996).

The envisioned gamified pedagogical method in this study is designed based on a constructivism framework proposed by Obikwelu and Read (2012), specifically for learning through gamification. This framework is designed based on best pedagogical practices and revolves around the following six essentials:

1. **Modeling:** This involves leveraging learners' prior knowledge and providing them with background knowledge related to the learning objectives of the game (Newstetter and Svinicki 2014). The goal of modeling is to enable students to build a conceptual model of the process required to attain the game's learning objectives (Dennen 2004). In the envisioned game, students who will use the game have some level of understanding about construction projects. The game also uses animated demonstration videos to provide background information about the construction scenarios. For example, in each chapter of the game, a short animation introduces the problem, objectives, tasks, and resources, including different types of heavy equipment involved in that scenario-based problem.
2. **Reflection:** This involves the process by which the learners logically organize their thoughts and connect their preliminary ideas to separate the more important presumptions from less important ones (Hargis 2001). The modeling and the reflection phases help learners form their personal synthesis of knowledge that initiates the strategy formation process (Kiili and Ketamo 2007). In the envisioned game, the student's prior knowledge and the design of the game and its features will give students ideas about the objectives of the game, how to start it, and how to proceed.
3. **Strategy formation:** This involves learners' efforts to form appropriate playing strategies to solve the problems the game provides (Kiili 2007). In the envisioned game, after understanding the game and its features, students will start thinking about how to use available resources to solve the problem. For example, what type and how many pieces of each type of equipment are needed to successfully solve the problem, considering limitations such as available budget and time?
4. **Scaffolded exploration:** This entails learners' exploration of the scaffolded game world, where they perceive the impacts and consequences of their actions through various game elements (Torrente et al. 2011). The aim is to guide the learners to a mode of problem-solving on their own (Sharma and Hannafin 2005) through the support that the game provides as they carry out different activities. In the envisioned game, students are able

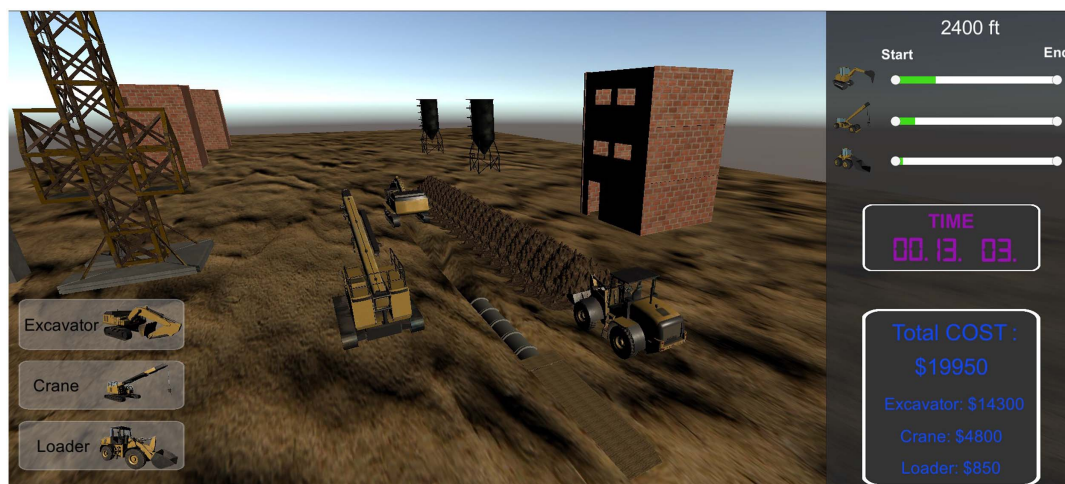


Fig. 1. Snapshot of the gameplay.

to perceive the consequences of their actions constantly through game elements such as points and resource utilization. Depending on the complexity of a problem and student's performance, the game may provide them with some hints as well. Eventually, based on students' progress, feedback from the game, and new information that is added to student's cognitive organization, students can adjust their actions and update their strategies.

5. **Debriefing:** This involves a description of events that occurred in the game, an analysis of why they occurred, and the discussion of mistakes and corrective actions by learners (Garris et al. 2002). Debriefing is a fundamental link between game experiences and learning that helps learners deconstruct the activity and then connect it to their mental models (Nicholson 2012). This learning-oriented approach encourages students' choices, and pursuits are built around progress and mastery through effort rather than students' concerns about their ability level (Dweck 1986). In the envisioned game, depending on the game scenario and students' performance, Zebel sometimes prompts users to explain their observations, challenges, outcomes of their decisions, and strategies to solve the problem. Students will be asked to type their responses in a pop-up box.
6. **Articulation:** This involves students' sharing of their game experience and acquired knowledge to progress toward collective goals of understanding. Articulation encourages the social negotiation of meaning that is a primary means of solving problems, building personal knowledge, establishing an identity, and most other functions performed in teams (Jonassen and Strobel 2006). Articulation is motivated by the argument that peer interaction plays a critical role in facilitating cognitive growth (Piaget 1952). In the envisioned game, the game platform provides an online forum where students interface with their peers and share their ideas and findings. The forum also allows students to ask questions and discuss each other's comments and ideas.

The Zebel Game: Design and Development Process

In this section, first, we present the content and scenarios of the game. Next, we briefly explain the development process.

Design of the Game: Content and Scenarios

The first chapter of the game, which is the focus of this study, concentrates on the critical path method (CPM) for learners with no prior knowledge and experience in scheduling. CPM is the most common method of scheduling in construction projects. It determines the order of activities and their start and finish times based on their logical dependencies and timing flexibility due to parallel paths through the network of activities. The timing flexibility in an activity, also known as float or slack, is an essential concept in understanding how the CPM works and prioritizes activities in response to limited resources. The first chapter of the game aims to direct students to discover this concept and its application in scheduling a construction project with limited resources through active exploration.

This part of the game presents the students with a scenario in which they must schedule a set of heavy construction activities in two adjacent sites, i.e., east and west sites. Fig. 2 shows the demo of the game. Fig. 3 shows a snapshot of the gameplay for the CPM. The east side has more activities with longer durations compared with the west side. The activities on both sides share a limited number of heavy equipment (e.g., dozer and grader). In certain cases, the user needs to decide which activity should have priority to get the equipment and which should be postponed to complete the entire project (i.e., both east and west sides) in the shortest time possible.

For example, the construction activities on both sides begin with clearing by a dozer. However, there is only one dozer available, and students need to realize and postpone one of the activities in order to accomplish the entire project with the limited resources that are available. This scenario aims to guide the students to discover four fundamental facts: (1) not all activities have the same level of criticality in terms of needing to be completed as soon as possible, (2) critical activities form the longest path in the network of activities, (3) noncritical activities can be delayed to certain extent without affecting the completion time of the project, and (4) delaying the start time of noncritical activities can be a solution to address the issue of limited resources in a project.

While playing, after learning about the tasks, equipment, and constraints of the game through a demo, the students will plan a



Fig. 2. Demo of the game.

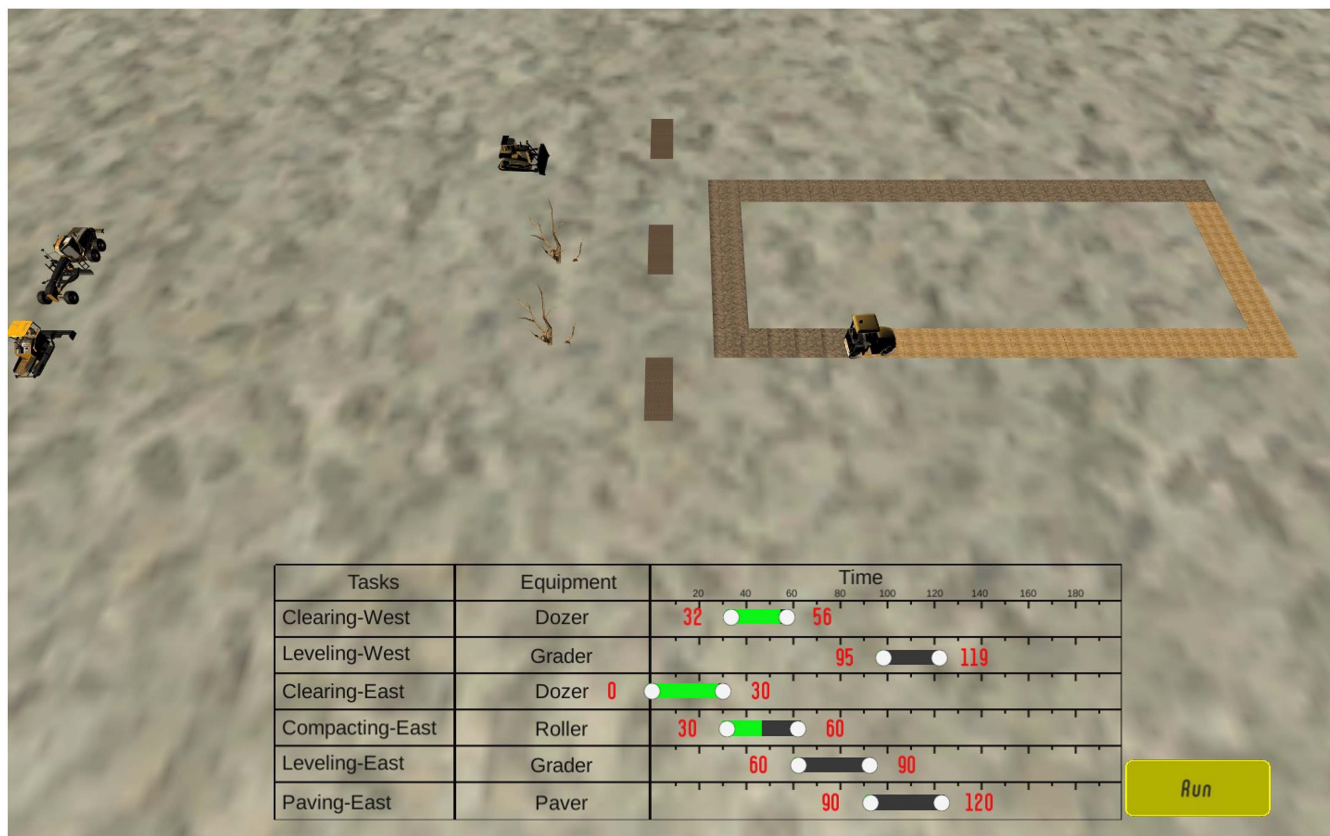


Fig. 3. Snapshot of the game for the CPM.

Now that you successfully scheduled the project. Could you explain your strategy?

Enter text...

Submit

Fig. 4. Example of the debriefing mechanism.

preliminary strategy and guess a start time for each activity, observe the outcomes of their decisions, receive feedback from the game, adjust their strategy, and keep trying until they achieve the goal. They are also required to explain their observations and strategies through the game's debriefing mechanism. Particularly, when a user achieves the goal, the debriefing mechanism will ask the user to explain a systematic approach to solve this type of problem (Fig. 4).

After recording the response, the game shows a diagram highlighting the floats in each non-critical activity in the game without any explicit explanation (Fig. 5). It then repeats the question to check whether the users would like to change their proposed strategy after seeing the diagram.

After successfully completing the first scenario and recording students' inputs, the game presents two more scenarios to further immerse students in understanding the distinction between critical

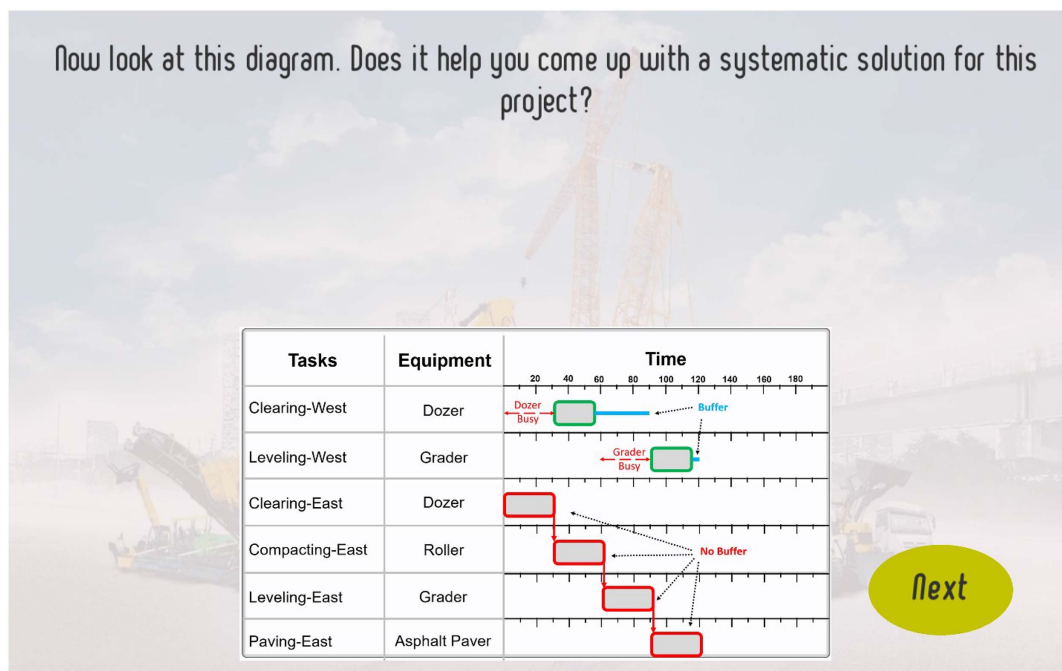


Fig. 5. Game mechanism to guide students toward discovering a systematic method.

and noncritical activities. First, the game explains that due to some technical complications, we need to postpone one of the activities on the west side for 10 units of time. Students are asked to implement that change, run the simulation, and explain their observations in the next debriefing pop-up box. The students are explicitly asked if the 10 units of time delay in that activity led to a change in the overall completion time of the project. Considering that the activity is not critical and has a float greater than 10 units of time, it is expected that the students report no change in the completion time of the project.

In the following scenario, the game explains that now due to an unforeseen situation, we need to delay the start time of the first activity on the east side for two units of time. Again, the students are asked to implement that change and any other needed change to respect the constraints of the game scenario (e.g., logical order of the activities and not overlapping activities on the same side). Considering that the activities on the east side are critical, it is expected that the students postpone all activities on that side for two units of time and observe that the delay in that activity triggers delays in the following activities and eventually affects the completion time of the project. The debriefing mechanism asks students to explain their observations and records their inputs.

Finally, the game provides a formal definition of critical activity. More specifically, the game notes: "In construction scheduling, if a delay in an activity results in a delay in the finish time of the entire project, that activity is considered critical. However, noncritical activities can delay to a certain extent without affecting the original finish time of the entire project." The game then lists all the activities of the scenario in a table and asks the students to mark those that are critical based on their observations.

Immediately after finishing the game, students have access to the online articulation platform to share their experiences and discuss their strategies.

Development of the Game

The Zebel game was created using the Unity game development platform. Unity is a cloud-based game development engine that

provides a wide range of services, including a software development kit (SDK), an application programming interface (API), a series of game object libraries, plugins, and predefined functionalities. For the game's debriefing and articulation mechanisms, a cloud-based application was developed to collect user and usage information using a RESTful web service utilizing Firebase, a Google cloud solution platform. Upon completion of each game, either successfully or by running out of time, the user's activity log and other relevant information will be decoded into a JavaScript Object Notation (JSON) document and submitted to the backend over the internet. This data, along with user information, is stored in a Not only Structured Query Language (NoSQL) database for subsequent processing.

Assessment Instruments

The effectiveness of the gamified pedagogical approach is assessed through five instruments: (1) a prior knowledge survey, (2) a benchmark exam, (3) a game assignment, (4) a postgame exam, and (5) postgame semistructured interviews. The prior knowledge survey, administered in the first session of the class, aims to evaluate students' level of familiarity with the CPM method and identify students with considerable prior knowledge. The collected data from students with considerable prior knowledge about CPM were excluded from the assessment analyses. The benchmark exam, conducted in the first session of the class, aims to understand the extent to which students are able to comprehend and solve construction planning and scheduling problems without specific lessons. The questions are designed in a way that is understandable for students with no background in construction planning and scheduling. Particularly, technical terms and definitions have been avoided.

The questions in the benchmark exam are aligned with the learning objectives of the game and scenarios that students will face while playing the game. More specifically, the benchmark exam, first, evaluates the extent to which students are able to define the concept of float and its synonyms (e.g., flexibility, buffer, and time sensitivity) in construction scheduling. Second, it describes a

simple construction scenario and asks students to identify activities that are more critical to be done as soon as possible (i.e., critical activities). Third, it provides another construction project scenario and asks students to determine the shortest possible time to finish the project. The scenarios in the benchmark exam are not identical with those in the game, but they share a certain similarity in terms of their complexity level.

The game assignment requires students to use and successfully complete the Zebel game. The game platform records all students' inputs and decisions in log files. Analyzing the log files shows how students set their strategies and update them throughout the game. The postgame exam, aligned with the benchmark exam, evaluates students' progress in the understanding of the fundamental concepts and ability to solve fundamental scheduling problems after their experience with the game. Finally, the semistructured interviews, conducted after analyzing the data collected through the previously mentioned instruments, help us evaluate the effectiveness of the proposed method and students' perceptions of the proposed methodology more rigorously. Fig. 6 summarizes how the assessment instruments collect data to address the two research questions.

Implementation and Empirical Data Collection

The gamified pedagogical method was implemented in a graduate-level course titled *CM-529: Construction Planning and Scheduling* in the Department of Civil, Environmental, and Ocean Engineering (CEOE) at Stevens Institute of Technology in Fall 2022 and Spring 2023. The contents and course materials were identical in both semesters, allowing the researchers to combine the collected data in both semesters during the analysis process. The Zebel game served as a formal teaching tool. Seventy-four students registered for the course during those semesters. Because this project seeks to understand personal information about human subjects, including students' individual perceptions, Institutional Review Board (IRB) requirements and approval were secured before conducting the study. Consent forms were administered on the first day of class,

and the students were informed that some of the classroom activities and assignments would be monitored as part of a research project. Students could choose to opt-out without any effect on their grades; in such cases, their assignments would be excluded from the research analysis. All 74 students agreed to participate in this study.

The results of the prior knowledge survey indicated that 11 students had some level of familiarity with the fundamentals of CPM. Those students still participated in the activities and played the game. Considering that they already had familiarity with CPM, they were able to accomplish the game's goals in only one or two rounds and explain their strategies clearly. However, to effectively evaluate the performance of the proposed gamified pedagogy, their data were excluded from the analysis process in this study. The students worked on the game assignment in the second week of the class before any introduction to CPM and its fundamental concepts, including float and its utilization to tackle resource allocation problems in parallel chains of activities.

Analysis and Results

Fifty-nine out of the 63 students who did not have prior knowledge of CPM worked on the assignment and completed it before the deadline. The average number of attempts to accomplish the game was 6.03, with a minimum of one, a maximum of 17, and a standard deviation of 4.02. Fig. 7 shows the distribution of the number of attempts.

Analyzing the recorded log files showed that a typical mistake, mostly in the first rounds of playing the game, was related to a lack of attention to the logical order of the activities. Although the game demo explained the scenario of the project and the order of the activities, 68% of the students (i.e., 40 out of 59), at least once, did not set activities in the correct logical order (e.g., clearing the site by a dozer should be executed before leveling the site by a grader). In total, 39% of the generated error messages alarmed the students to pay attention to this issue.

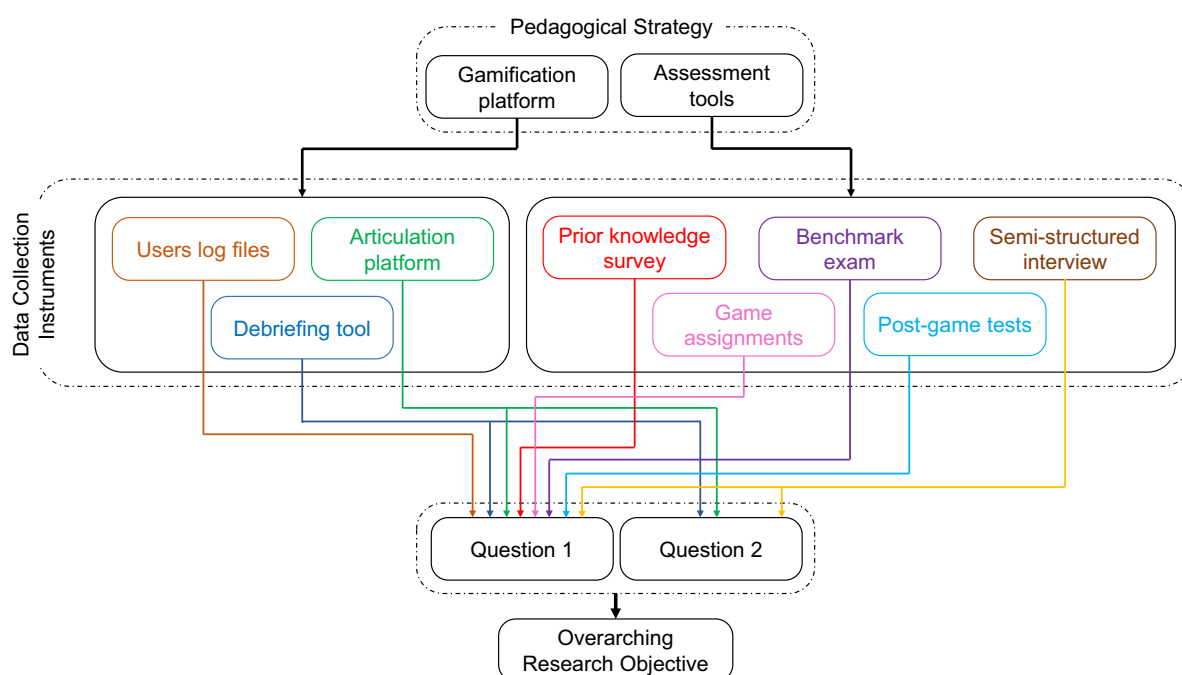


Fig. 6. Data collection process via assessment instruments.

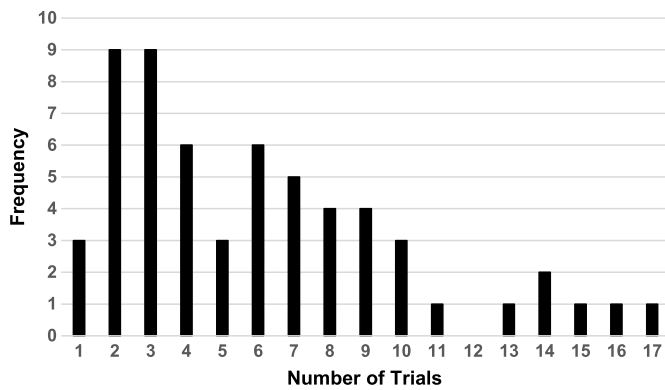


Fig. 7. Distribution of the number of trials to successfully finish the game.

In addition, 11% of the error messages reminded 24 students that they could not overlap activities on one side. As mentioned previously, for the sake of simplicity and guiding students toward discovering the CPM method, the instructions presented in the game demo ask students not to overlap activities on one side of the project. However, they can overlap activities from one side of the project to those on the other side. Similar to the error related to the logical order of the activities, this error message mostly occurred in the early rounds of students' attempts.

Next, 26% of the error messages were related to the limited resources issue. As mentioned previously, for each type of equipment, only one piece is available. Therefore, students must find a solution when more than one activity needs the same equipment. The solution that students are expected to discover is to postpone some activities that will not affect the finish time of the project (i.e., noncritical activities) to avoid overlapping between activities on both sides of the project that depend on the same equipment. Finding this solution is the basis for the primary learning objectives of this teaching approach. In total, 65% of the students (i.e., 38 out of 59) received this error message at least once. Eventually, all students were able to find the solution and solve this problem by postponing the noncritical activities on the west side of the project. Finally, 69% of the students (i.e., 41 out of 59) received error messages indicating that although their schedule did not violate any one of the game conditions (e.g., limited resources or overlapping activities on one side), they could finish the project in a shorter duration. In most cases, students got this message when they ordered all activities on both sides after each other and did not overlap any activities. Fig. 8 shows the percentage frequency of each error type.

As mentioned previously, all 59 students who did not have any prior knowledge of CPM were eventually able to solve the problem and achieve the correct schedule. However, successfully solving the problem does not necessarily indicate students' ability to discover a systematic solution and deep understanding of the essential concepts related to CPM. Analyzing the students' inputs in the debriefing mechanisms facilitates evaluating their understanding and ability to discover systematic solutions. The students' responses to the first debriefing question asking their strategy upon finishing the first scenario showed that 62.7% of the students provided clear statements indicating that they understood that flexibility in the start time of activities (i.e., floats) is created because of the parallel chains of activities on the two sides. They also realized that overlapping the activities on both sides helped them reduce the total duration of the project and also noticed that the activities on the west side could be postponed to some extent in order to solve the limited resources problem.

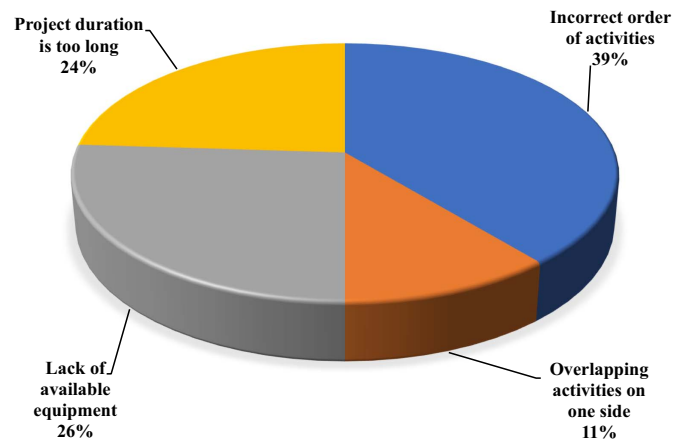


Fig. 8. Frequency of each error type.

As mentioned previously, after recording the students' responses, the game showed a diagram highlighting the floats in each noncritical activity in the game without any explicit explanation (Fig. 6) and asked them again to present a systematic approach to solving the scheduling problem in the first scenario. The log files of the debriefing mechanism revealed that the percentage of students who showed evidence indicating that they understood the role of overlapping and then postponing activities on the shorter path to solve the resource allocation problem increased to 93.2% after seeing the diagram. Next, students were asked whether all activities in a project hold an equivalent level of importance and sensitivity concerning their timely completion. The recorded data indicated 72.8% of the students responded that they do not think all activities have the same level of importance in terms of time sensitivity. The game then shows the two scenarios in which students observe that delaying a noncritical activity (i.e., clearing by dozer on the west side) does not affect the finish time of the project; however, postponing a critical activity (i.e., clearing by dozer on the east side) affects the finish time of the project. The following question after these two scenarios showed that the percentage of the students who stated that not all activities have the same level of time sensitivity increased to 91.5%. When students observed these scenarios, they were still unfamiliar with the formal definition of float.

Finally, in the last question of the game, where the definition of a critical activity is provided and students were asked to mark critical activities in the scenario, 57.6% of the students marked all critical activities correctly. This percentage is considerably lower than the percentage of the students who demonstrated a clear understanding of how to use overlapping to postpone less time-sensitive activities in order to address the resource allocation problem, and lower than the percentage of the students who stated that they do not believe all activities hold the same level of importance in terms of being completed on time. The reasons that not all those students who successfully answered the previous questions but could not mark the critical activities correctly were investigated through the semistructured interviews. Fig. 9 summarizes students' performance in the debriefing mechanism of the game platform.

Immediately upon completing the game assignment, students had access to the articulation platform to share their experiences and discuss their strategies. In total, 57 comments were submitted by 41 students. They engaged in detailed conversations to share their experiences and discuss their strategies for solving the problem, as well as how they arrived at the correct solution. All comments were positive. "Doing an assignment by playing a game is the most unique and interactive way of learning the subject content

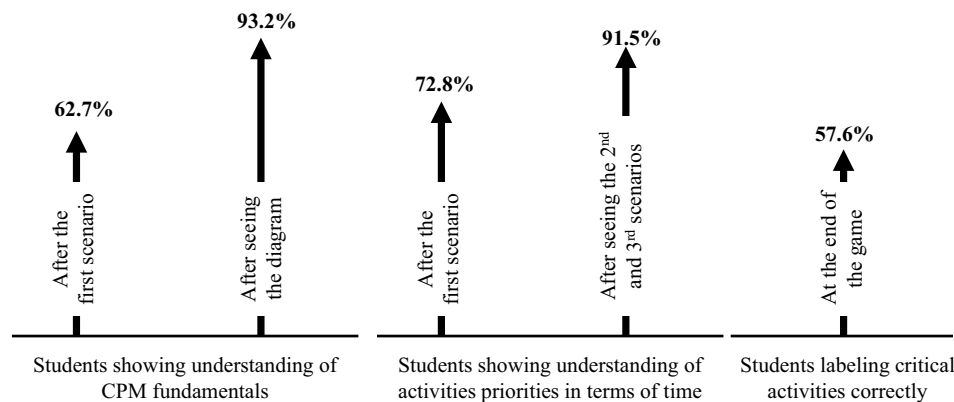


Fig. 9. Summary of students performance in the debriefing mechanism.

I have ever done,” one of the students noted on the platform. “This way of teaching does stay in the mind for a longer period of time than regular teaching” another student commented. “It was quite new to me and I found it interesting. It gave me very clear understanding about critical activity. I like the delay of activities has different impact on project duration,” another student noted. “Although this evaluation is presented in the form of a simple interactive game, it still presents and demonstrates the real-world problems one will encounter as a project manager/construction manager in the field,” one of the students with professional experience in construction scheduling noted.

Some comments by students included suggestions to improve the game platform. For example, one student noted, “I feel that the instructions could have been slightly clearer. For example, if the activities were numbered, it would have helped us better pay attention to the order of activities.”

In the following session after the game assignment, the postgame exam was administered. The questions in the postgame exam were aligned with the questions in the benchmark exam. To evaluate the effectiveness of the proposed gamified methodology quantitatively, we statistically compared the students’ performance in the benchmark exam and postgame exam. The statistical comparison was conducted using significance testing for proportions based on the binomial distribution (Montgomery and Runger 2010). The objective of this test was to check whether two proportions are statistically different from each other. In our case, we compared the percentage of the students who answered a question correctly in the benchmark exam with the percentage of the students who answered the corresponding question in the postgame exam correctly. The null hypothesis is that the two percentages are equal, and the alternative hypothesis is that they are statistically different

$$H_0: p_b = p_p \quad (1a)$$

$$H_A: p_b \neq p_p \quad (1b)$$

where p_b = proportion of students answering a question in the benchmark exam correctly; and p_p = proportion of students answering a question in the postgame exam correctly.

The test statistic is calculated as follows:

$$z = \frac{p_p - p_b}{\sqrt{\frac{p_b(1-p_b)}{n}}} \quad (2)$$

where n = number of students.

Table 1. Results of the significance testing for proportions

Question	p_b	p_p	z
Understanding float	0.016	0.898	52.44
Identifying critical activities	0.067	0.762	21.23
Calculating the shortest duration of a project	0.42	0.966	8.43

Table 1 presents the percentages of students answering each question correctly in the exams and the calculated test statistics. The results indicate that, at a 5% significance level, the null hypothesis for all three questions is rejected. Therefore, we can conclude that the increase in the student’s performance in answering fundamental construction scheduling problems after playing the game is statistically significant.

Finally, throughout the semistructured interview, we collected more information regarding students’ learning experiences. One of the critical questions was related to those students who were able to solve the problems in the game correctly, showed understanding of the concept of float and the fact that not all activities have the same level of time sensitivity in a schedule, but did not select critical activities in the last two questions of the game. During the interview, most of those students mentioned that when they were answering the debriefing questions in the game, they were under the impression that the criticality of an activity was related to the lack of a resource. Therefore, they only marked the activities on the right side that were competing for a limited resource. In other words, they realized that the longer path of activities (i.e., the chain of activities on the right side) is more important in terms of being done on time, but when they were asked to explicitly mark critical activities, they thought only the activities on the longest path that had a limited resource issue (e.g., clearing by dozer on the east) are critical. Interestingly, all these students mentioned that they realized their misconceptions and the right answer when they went through the articulation forum and read the discussions by other students. Therefore, although they did not answer those questions correctly during the game, other parts of the gamified learning experience helped them completely understand the topic.

Lessons Learned and Transferability of Outcomes

Throughout this case study, a series of practical and valuable lessons have been gleaned, enhancing the potential for the successful application of the proposed pedagogical approach in other contexts and future studies. First, the outcomes of this case study empirically show that guided active exploration in a digital game environment

can effectively direct students to discover systematic solutions for fundamental engineering problems. Although we implemented the proposed gamified pedagogy in the context of construction scheduling, other areas in civil and construction engineering, such as structural design, heavy equipment planning, and construction methods, can adopt the proposed solution and use the outcomes of this study.

Second, students' gradual progress throughout the game as they are exposed to different scenarios and receive immediate feedback for their decisions and strategies, shows the criticality of scaffolding in the proposed gamified pedagogy. This emphasizes the importance of coupling active exploration with well-planned strategies to guide students through coherent scenarios and feedback systems. This integrative approach is critical to direct students toward discovering systematic solutions effectively and efficiently.

Third, the outcomes of this case study indicated that designing gamified pedagogies is more than developing a game. Other aspects of the theoretical framework for game-based learning, including the articulation mechanism, play a vital role in students' learning. One example to show the importance of the articulation system is related to the students who successfully solved the problems in the game and demonstrated a clear understanding of a proper strategy to address the resource allocation problems in the debriefing mechanism but did not mark the critical activities correctly in the last question. As discussed in the previous section, the results of the semistructured interview indicated that most of these students realized their mistakes and learned the correct answer when they saw other students' discussions on the articulation platform.

Fourth, the empirical data collected in this case study showed that the proposed game-based pedagogy enhanced students' motivation and engagement. Although postgame participation in the articulation platform was not mandatory, many students actively shared their strategies and discussed what they learned there. The results of the semistructured interview also confirmed that many students found the gamified pedagogy exciting and engaging.

Fifth, the students' performance in the game assignment indicated that the quality of the demonstration mechanism for the game features and scenarios in terms of clarity and attractiveness directly affects students' attention toward the detailed rules of the game. Although the demo of the Zebel game completely explains the scenarios and rules of the game, certain errors students made in their initial attempts, such as violating the logical order of the activities, suggest they might have not paid heed to all the detailed information in the demo. Therefore, introducing more captivating visualizations to capture their attention more effectively could enhance the overall experience and performance of the students.

Lastly, the outcomes of the semistructured interview highlighted the importance of effectively integrating novel gamified pedagogies with conventional teaching methods. Although the Zebel game and the proposed gamified pedagogical strategy in this study were designed to teach CPM independently, and the outcomes of the postgame exam indicated that most students were able to correctly solve standard construction scheduling problems after the game assignment, many students stated in the interview that they still found the postgame lecture valuable. They mentioned that although the game effectively introduced them to different aspects of a CPM method, the postgame lecture helped solidify their understanding of the concepts learned through the game.

Conclusion

In this study, we designed, implemented, and evaluated the effectiveness of a novel gamified pedagogical method on students'

ability to discover systematic solutions for fundamental construction scheduling problems. The gamified method revolves around creating an interactive environment where students can learn through guided active exploration. The pedagogy and its game components were structured based on the constructivism learning theory. Analyzing the empirical data collected through game log files, in addition to a series of preassessment and postassessment instruments, indicate that the gamified method was able to direct students without any considerable prior knowledge to discover essential concepts and systematic solutions for fundamental problems. All students were able to successfully finish the game and accomplish its goal. The recorded data in the debriefing mechanism of the game showed clear evidence indicating that all students realized that some activities are less time sensitive and can be postponed in response to resource allocation problems. In the end, more than half of the students who never had any exposure to CPM and its fundamental concepts were able to correctly list the critical activities.

The data collected through the articulation platform indicated that students perceived the proposed gamified pedagogy as an interesting, engaging, and effective teaching mechanism. The outcomes of the preassessment and postassessment (i.e., a postgame exam compared with a benchmark exam) indicated that the proposed method was able to help all students define and identify critical activities and effectively use floats to address resource allocation problems. Findings from the semistructured interviews further revealed the benefits of the gamified learning experience in students' beliefs of understanding of the topic.

The primary contribution of this study to the existing body of knowledge is to design and empirically evaluate a novel gamified pedagogical method to foster experiential learning through guided active exploration in a digital game environment. This study contributes to ongoing research and scholarly works to promote learning at scale approaches that seek to use accessible technologies to educate a great number of students without any spatiotemporal limitation and dependency on expensive resources.

The outcomes of this study lay the groundwork and motivation for a series of future investigations aimed at designing the next generation of gamified construction pedagogies. First, further investigations on designing and evaluating immersive game-based teaching and learning methods using advanced emerging technologies, such as holograms, virtual, augmented, and mixed reality, for more complicated engineering concepts can be a potential topic for future studies. Questions such as how students perceive and interact with virtual objects in a digital and immersive construction environment to solve engineering problems can be answered in such investigations.

Second, augmenting gamified solutions with artificial intelligence (AI) to promote personalized learning can be another direction for future research endeavors. Using AI, dynamic games that can actively adapt their guiding mechanism and scenarios to students' performance can be designed to offer customized learning processes to learners with different knowledge backgrounds and needs. Finally, designing, developing, and evaluating modular game-based training methods that are seamlessly integrated with the daily responsibilities and activities of construction professionals can transform state-of-the-art methods for reskilling and upskilling workers in the construction industry.

Data Availability Statement

All data, models, or codes that support the findings of this study are available from the corresponding author upon reasonable request.

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References

- Abrams, E. M. 1994. *How the Maya built their world: Energetics and ancient architecture*. Austin, TX: University of Texas Press.
- Ausubel, D. P., and F. G. Robinson. 1969. *School learning: An introduction to educational psychology*. New York: Rinehart Winston.
- Boothby, T. 2018. *Empirical structural design for architects, engineers and builders*. London: Institute of Civil Engineers Publishing.
- Boud, D., R. Cohen, and D. Walker. 1993. *Using experience for learning*. Milton Keynes, UK: McGraw-Hill Education.
- Bruner, J. S. 1966. Vol. 59 of *Toward a theory of instruction*. Cambridge, MA: Harvard University Press.
- Dalgarno, B. 1996. "Constructivist computer assisted learning: Theory and techniques." In *Proc., ASCILITE96 Conf.*, 127–148. Tugun, Australia: Australasian Society for Computers in Learning in Tertiary Education.
- Dennen, V. P. 2004. "Cognitive apprenticeship in educational practice: Research on scaffolding, modeling, mentoring, and coaching as instructional strategies." In *Handbook of research on educational communications and technology*, 804–819. New York: Routledge.
- Deshpande, A. A., and S. H. Huang. 2011. "Simulation games in engineering education: A state-of-the-art review." *Comput. Appl. Eng. Educ.* 19 (3): 399–410. <https://doi.org/10.1002/cae.20323>.
- Dicheva, D., C. Dichev, G. Agre, and G. Angelova. 2015. "Gamification in education: A systematic mapping study." *J. Educ. Technol. Syst.* 18 (3): 75–88.
- Driscoll, M. P. 1994. *Psychology of learning for instruction*. Needham Heights, MA: Allyn and Bacon.
- Duffy, T. M., and D. J. Cunningham. 1996. "Constructivism: Implications for the design and delivery of instruction." In *Handbook of research for educational communications and technology*, edited by D. H. Jonassen. New York: Macmillan Library Reference.
- Dweck, C. S. 1986. "Motivational processes affecting learning." *Am. Psychologist* 41 (10): 1040. <https://doi.org/10.1037/0003-066X.41.10.1040>.
- Eiris Pereira, R., and M. Gheisari. 2019. "360-degree panoramas as a reality capturing technique in construction domain: Applications and limitations." In *Proc., 55th ASC Annual Int. Conf.* Cheyenne, WY: Associated Schools of Construction.
- ElGawely, M., and W. Nadim. 2020. "Immersive virtual reality environment for construction detailing education using building information modeling." In *Proc., 10th Int. Conf. on Engineering, Project, and Production Management*, 101. Berlin: Springer.
- Garris, R., R. Ahlers, and J. E. Driskell. 2002. "Games, motivation, and learning: A research and practice model." *Simul. Gaming* 33 (4): 441–467. <https://doi.org/10.1177/1046878102238607>.
- George, A. K., M. L. McLain, K. Bijlani, R. Jayakrishnan, and R. R. Bhavani. 2016. "A novel approach for training crane operators: Serious game on crane simulator." In *Proc., 2016 IEEE Eighth Int. Conf. on Technology for Education (T4E)*, 116–119. New York: IEEE.
- Goedert, J. D., R. Pawloski, S. Rokooeisadabad, and M. Subramaniam. 2013. "Project-oriented pedagogical model for construction engineering education using cyber infrastructure tools." *J. Civ. Eng. Educ.* 139 (4): 301–309. [https://doi.org/10.1061/\(ASCE\)EI.1943-5541.0000165](https://doi.org/10.1061/(ASCE)EI.1943-5541.0000165).
- Guerra, M., and T. Shealy. 2018. "Teaching user-centered design for more sustainable infrastructure through role-play and experiential learning." *J. Civ. Eng. Educ.* 144 (4): 05018016. [https://doi.org/10.1061/\(ASCE\)EI.1943-5541.0000385](https://doi.org/10.1061/(ASCE)EI.1943-5541.0000385).
- Hargis, J. 2001. "Can students learn science using the internet?" *J. Res. Comput. Educ.* 33 (4): 475–487. <https://doi.org/10.1080/08886504.2001.10782328>.
- Holzmann, V., H. Weisz, and D. Zitter. 2018. "Simulating advanced project management decision making processes with PMZONE board game." In *Proc., ECGBL 2018 12th European Conf. on Game-Based Learning*, 240. Reading, UK: Academic Conference & Publishing International.
- Ilbeigi, M., D. Bairaktarova, and A. Morteza. 2023. "Gamification in construction engineering education: A scoping review." *J. Civ. Eng. Educ.* 149 (2): 04022012. [https://doi.org/10.1061/\(ASCE\)EI.2643-9115.0000077](https://doi.org/10.1061/(ASCE)EI.2643-9115.0000077).
- Jonassen, D. H., and J. Strobel. 2006. "Modeling for meaningful learning." In *Engaged learning with emerging technologies*, 1–27. Dordrecht, Netherlands: Springer.
- Josiek, S., S. Schleier, T. Steindorf, R. Wittrin, M. Heinzig, C. Roschke, and M. Ritter. 2020. "Game-based learning using the example of finanzmars." In *Proc., 2020 6th IEEE Congress on Information Science and Technology (CiSt)*, 7–14. New York: IEEE.
- Jumaat, N. F., Z. Tasir, N. D. A. Halim, and Z. M. Ashari. 2017. "Project-based learning from constructivism point of view." *Adv. Sci. Lett.* 23 (8): 7904–7906. <https://doi.org/10.1166/asl.2017.9605>.
- Kerka, S. 1997. *Constructivism, workplace learning, and vocational education*. ERIC Digest No. 181. Columbus, OH: ERIC Clearinghouse on Adult, Career, and Vocational Education.
- Khah, F. S., Z. K. Rybkowski, A. R. Pentecost, J. P. Smith, and R. Muir. 2019. "Development and testing of an innovative architectural programming simulation as a precursor to target value design." In *Proc., 27th Annual Conf. of the Int. Group for Lean Construction (IGLC)*. Dublin, Ireland: International Group for Lean Construction.
- Kiili, K. 2007. "Foundation for problem-based gaming." *Br. J. Educ. Technol.* 38 (3): 394–404. <https://doi.org/10.1111/j.1467-8535.2007.00704.x>.
- Kiili, K., and H. Ketamo. 2007. "Exploring the learning mechanism in educational games." *J. Comput. Inf. Technol.* 15 (4): 319–324. <https://doi.org/10.2498/cit.1001139>.
- Kolb, D. A. 2014. *Experiential learning: Experience as the source of learning and development*. Upper Saddle River, NJ: Pearson Education.
- Kuh, G. D., J. Kinzie, J. H. Schuh, and E. J. Whitt. 2011. *Student success in college: Creating conditions that matter*. Somerset, UK: Wiley.
- Lynch, D. R., and J. S. Russell. 2009. "Experiential learning in engineering practice." *J. Civ. Eng. Educ.* 135 (1): 31–39. [https://doi.org/10.1061/\(ASCE\)1052-3928\(2009\)135:1\(31\)](https://doi.org/10.1061/(ASCE)1052-3928(2009)135:1(31)).
- Maturana, H. R. 2006. "Self-consciousness: How? When? Where?" *Constructivist Found.* 1 (3): 91–102.
- Montgomery, D. C., and G. C. Runger. 2010. *Applied statistics and probability for engineers*. Hoboken, NJ: Wiley.
- Newstetter, W. C., and M. D. Svinicki. 2014. "Learning theories for engineering education practice." In *Cambridge handbook of engineering education research*, 29–46. New York: Cambridge University Press.
- Nicholson, S. 2012. "Completing the experience: Debriefing in experiential educational games." In *Proc., 3rd Int. Conf. on Society and Information Technologies*, 117–121. Winter Garden, FL: Florida International Institute of Informatics and Systemic.
- Obikwelu, C., and J. C. Read. 2012. "The serious game constructivist framework for children's learning." *Procedia Comput. Sci.* 15 (Jan): 32–37. <https://doi.org/10.1016/j.procs.2012.10.055>.
- Patil, Y. M., and P. D. Kumbhar. 2021. "Learning by gamification: An effective active learning tool in engineering education." *J. Eng. Educ. Transform.* 34 (Sep): 447–453. <https://doi.org/10.16920/jeet/2021/v34i0/157194>.
- Pelling, N. 2011. *The (short) prehistory of gamification. Funding Startups (& other impossibilities)*, August 9, 2011.
- Piaget, J. 1952. *The origins of intelligence in children*. New York: W. W. Norton.
- Pietrafesa, E., R. Bentivenga, P. Lalli, C. Capelli, G. Farina, and S. Stabile. 2020. "Becoming safe: A serious game for occupational safety and health training in a WBL Italian experience." In *Proc., Int. Conf. in Methodologies and intelligent Systems for Technology Enhanced Learning*, 264–271. Berlin: Springer.
- Pütz, C., C. Heins, M. Helmus, and A. Meins-Becker. 2020. "Gamification and BIM: Teaching the BIM method through a gamified, collaborative approach." In *Proc., Int. Symp. on Automation and Robotics in*

- Construction*, 272–277. Washington, DC: International Association on Automation and Robotics in Construction Publications.
- Rogora, A. 2021. “New proposals for sustainable design: The imitation game as an experience of shared co-design.” In *Sustainability in energy and buildings 2020*, 527–537. Singapore: Springer.
- Sharma, P., and M. Hannafin. 2005. “Learner perceptions of scaffolding in supporting critical thinking.” *J. Comput. Higher Educ.* 17 (Sep): 17–42. <https://doi.org/10.1007/BF02960225>.
- Smith, K. A., S. D. Sheppard, D. W. Johnson, and R. T. Johnson. 2005. “Pedagogies of engagement: Classroom-based practices.” *J. Eng. Educ.* 94 (1): 87–101. <https://doi.org/10.1002/j.2168-9830.2005.tb00831.x>.
- Statista. 2022. “Value added by the construction industry as a share of gross domestic product in the United States from 2000 to 2021.” Accessed March 4, 2022. <https://www.statista.com/statistics/192049/value-added-by-us-construction-as-a-percentage-of-gdp-since-2007/>.
- Tagliabue, L. C., S. M. Ventura, J. Teizer, and A. L. Ciribini. 2021. “A serious game for lean construction education enabled by internet of things.” In *Ludic, co-design and tools supporting smart learning eco-systems and smart education*, 225–233. Berlin: Springer.
- Tobias, S. 2010. “Generative learning theory, paradigm shifts, and constructivism in educational psychology: A tribute to Merl Wittrock.” *Educ. Psychologist* 45 (1): 51–54. <https://doi.org/10.1080/00461520903433612>.
- Torrente, J., E. J. Marchiori, and A. Blanco. 2011. *Production of creative game-based learning scenarios: A handbook for teachers*. Brussels, Belgium: European Commission.
- US Bureau of Labor Statistics. 2023. “Economic News Release: Employees on nonfarm payrolls by industry sector and selected industry detail.” Accessed March 4, 2023. <https://www.bls.gov/news.release/empsit.t17.htm>.
- Violatti, C. 2018. “Neolithic period. Ancient history.” Accessed October 14, 2023. <https://www.ancient.eu/Neolithic/>.
- Weimer, M. 2013. *Learner-centered teaching: Five key changes to practice*. San Francisco: Wiley.
- Werbach, K., and D. Hunter. 2012. *For the win: How game thinking can revolutionize your business*. Philadelphia: Wharton Digital Press.
- Zidane, Y. J. T., and B. Andersen. 2018. “The top 10 universal delay factors in construction projects.” *Int. J. Managing Projects Bus.* 11 (3): 650–672. <https://doi.org/10.1108/IJMPB-05-2017-0052>.