AC 2012-4260: USING CONSTRUCTION EQUIPMENT SIMULATORS TO TEACH LEARNING CURVE THEORY

Dr. John Hildreth, University of North Carolina, Charlotte

Using Construction Equipment Simulators to Teach Learning Curve Theory

Abstract

Repetitive construction activities often experience a learning effect that cause the unit cost to decrease as the number of completed units increases. Construction engineering and management students must be able to model this effect to accurately estimate and schedule such operations. A course module including presentation of learning curve theory, an assignment requiring the repeated performance of a simulated operation, and analysis of the resulting performance data was designed to focus on the knowledge, comprehension, application, and analysis levels of Bloom's taxonomy of skills in the cognitive domain. The module resulted in excellent knowledge regarding learning curve theory and its application within the construction industry. A separate assessment vehicle revealed student proficiency at the highest levels of Bloom's taxonomy.

Introduction

Repetitive construction activities often experience a learning effect as a result of greater familiarity with the task, better coordination, increased effectiveness of tools and methods, and more attention from management and supervision[1]. The cost of completing each unit of such operations decreases as the number of units completed increases. An understanding of how cost changes is needed to accurately estimate and schedule the operations. A learning curve is a graphical representation of the relationship between unit cost and the number of units produced.

Learning curve theory states that when the production quantity doubles, the unit cost (measured in hours, man-hours, dollars, etc.) will decrease by a fixed percentage from the previous unit cost. A number of mathematical models have been used to describe the learning curve, including the straight line power model, Stanford "B" model, cubic power model, piecewise model, and exponential model[2]. The learning curve model most commonly applied to construction activities is the straight line power model[3,4,5]. Everett and Farghal[6] evaluated several models and found that such linear models provide the most reliable prediction of future performance.

Wright[7] originally developed the straight line learning curve model as:

$$\log Y = A + B \log X \text{ (or, equivalently } Y = aX^b \text{ in the power form)}$$

where, X is the cycle number, Y is the cost of performing cycle X, A is the cost to perform the first cycle, and B is a constant that describes the rate of learning. The constant B is related to the learning rate (ϕ) by:

$$B = \log \phi / \log 2$$

Oglesby et al.[8] report that the typical value of ϕ for repetitive construction operations ranges between 0.70 and 0.90. For ϕ = 0.70, the second unit will require 70 percent of the effort required for the first unit and the fourth unit will require 49 percent of the effort for the first unit.

American construction educators are responsible for providing a well-qualified cadre to serve the essential needs of the construction industry[9]. This requires educational techniques that produce student knowledge and provide authentic instruction that promotes transfer from the classroom to the outside world. Learning curve theory and its application to construction is typically taught using idealized data sets designed by faculty or found in a textbook. Such data can adequately demonstrate the effect of learning, but preclude student involvement and are often not authentic data from the construction operations. Student involvement in collecting authentic data requires extended time on site to observe and collect data regarding repetitive operations. Site access, safety considerations, and time constraints typically render this approach unavailable.

Construction equipment simulators have been developed by equipment manufacturers to train operators for the stressful and tough construction environments without the need to employ an actual machine. Equipment simulators present an opportunity for construction engineering and management students to operate equipment and repeatedly perform a simulated construction operation. As students become familiar with the controls and operation, they experience the effect of the learning on operational performance.

A graduate level course in construction planning and management techniques at the University of North Carolina at Charlotte included a course module on learning curves. The module included presentation of learning curve theory and an assignment requiring the repeated performance of a simulated operation and analysis of the resulting performance data. Student knowledge related to the application of learning curve theory to construction was assessed on the final course exam.

Bloom et al.[10] presented a six level taxonomy of skills in the cognitive domain as, proceeding from the lowest order processes to the highest:

1. Knowledge – memory of previously learned materials
2. Comprehension – understand facts and ideas
3. Application – use of new knowledge
4. Analysis – examine and break information into parts
5. Synthesis – compile information to make a new whole
6. Evaluation – present and defend judgments

The material presented in class and the assignments were designed to focus on the knowledge, comprehension, application, and analysis levels. The final exam problem was designed to assess student ability in the application, analysis, synthesis, and evaluation levels.

Learning Curve Course Module

The course module included lecture presentation of learning curve theory and the statistical methods to assess and develop the model, an example of operational analysis using learning curves, and a select review of literature pertaining to learning curves in construction. The presentation of theory focused on why cost decreases with repetitive performance and the mathematical models that have been used, as described by Thomas et al.[11]. The presentation of statistical methods focused on linear regression, the methods to assess the significance of model parameters, and developing confidence and prediction intervals.

The least squares method of linear regression is used to estimate the values of the A and B coefficients required to develop the straight line learning curve model. The B coefficient must be assessed using a t-test to determine whether the value is significantly different from 0, which would indicate that learning has no effect on performance and analysis based on learning curve theory is not appropriate. The developed learning curve model can be used to estimate the average cost of completing any specific unit. A confidence interval on this mean is used to provide an estimate range for this average cost at a specified level of confidence (α value). Similarly, prediction intervals provide a range of values for estimating the actual cost of completing any specific unit.

The example of operational analysis presented in class was based on generator installation data provided by Oglesby et al.[12]. The data was used to demonstrate learning curve analysis methods and showcase the ability to quantify the impacts of changes in site conditions (failure in material delivery, lack of site preparation, and personnel changes). Students were provided background scenario information and the performance data. Working together as a class, each student analyzed the data and quantified the impact.

Students then reviewed literature related to learning curves and their application to construction[13,14,15]. Everett and Farghal[16] studied the predictive ability of various learning curve models and presented data to support the conclusion that the straight line (linear log X, log Y) model is the single most reliable predictor. Farghal and Everett[17] evaluated the relationship between the amount of data available and the accuracy of forecasts based on this data. They concluded there is not a significant increase in accuracy after 25 to 30 percent activity completion. Hinze and Olbina[18] applied learning curve theory to analyze data regarding the prefabrication and driving of prestressed concrete piles. They provide an excellent example of analysis methods and discussion of the results.

An assignment was created to actively engage students in collecting operational performance data and using the data to predict future performance. Students were required to complete four a simulated crane-and-bucket concrete placement operations. The SimLog tower crane simulator was used, in which the students operated the simulated crane to place concrete from a bucket into wall forms of varying configurations as shown in Figure 1. The crane must be operated using standard joystick controls to move the bucket from one end of the wall forms to the other. Depending on the configuration of the wall forms, placing concrete in the forms requires the operator to rotate the crane, maneuver trolley, and control the bucket height.

From the simulated operations, the students were to collect performance data from the operation and apply learning curve theory to estimate the cost and time required to complete remaining concrete pours. For each pour, three buckets were emptied and performance data was collected in terms of the time required to complete the pour and the amount of concrete spilled outside of the forms (waste). Students were instructed to complete only one simulated pour per day to more accurately replicate the learning process.

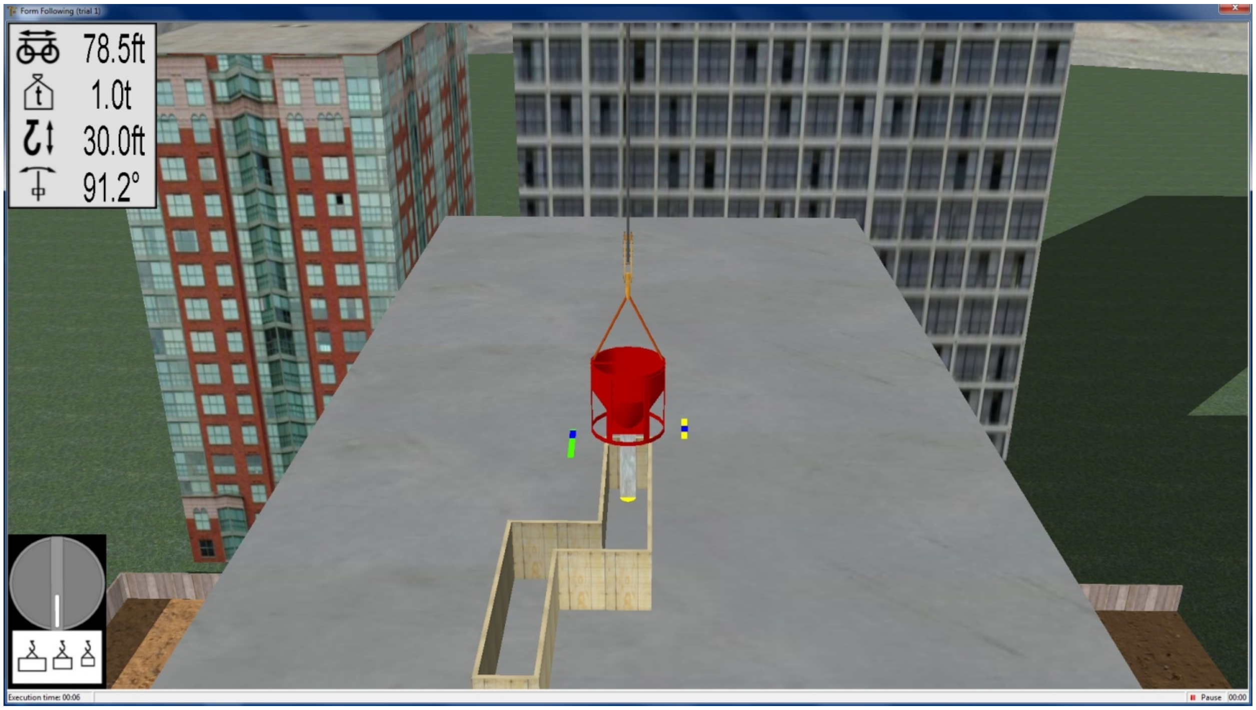

Figure 1: Simulated Crane and Bucket Concrete Placement

For each simulated pour, the average time required to complete the operation and the average waste quantity was calculated. This data was combined with data provided regarding the bucket and pour quantities, crane cycle time, crew composition, and resource rates. The number of buckets required, total duration, production rate, and unit cost was calculated for each pour. Learning curve analysis was applied to the results to estimate the duration, total cost, and unit cost for 12 remaining concrete pours.

Performance of the operation could be increased by learning efforts focused on decreasing either the time required or the amount of concrete wasted. Guidance was not provided regarding where improvement efforts should be focused, rather it was assumed that efforts would be first focused on time and then waste. However, students focused primarily on reducing waste. This is likely because feedback regarding was immediately available, as students could see when concrete was falling outside of the forms and feedback regarding time was available only after concrete placement was complete.

As a result of focusing learning efforts on reducing waste, the amount of wasted concrete decreased as the number of completed pours increased, while the time to complete the pours remained nearly unchanged. The learning rate for both concrete waste and performance time were calculated and tested using a t-test to determine if they were statistically different, at the 5 percent level of confidence, from a value of 1 (no learning occurred). Each student found that there was a statistically significant reduction in waste with an increasing number of pours, but that the number of pours was not a statistically significant predictor of performance time. Thus, the learning curve should be used to predict waste and time should be predicted as the average performance time for the first four pours. Examples of student results are shown in Figures 2 and 3.

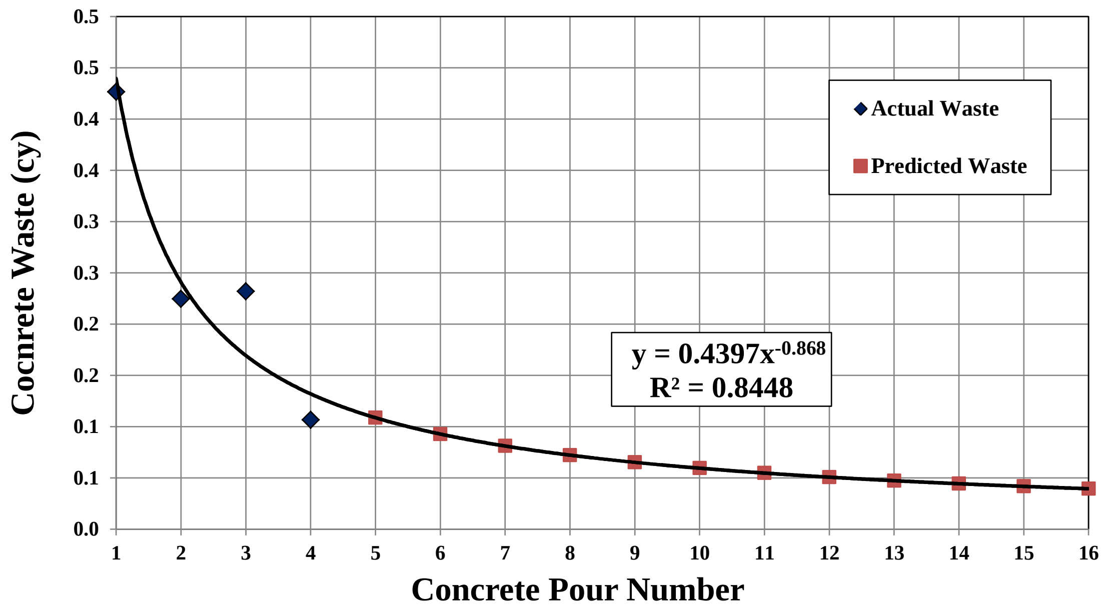

Figure 2: Actual and Predicted Concrete Waste Volume

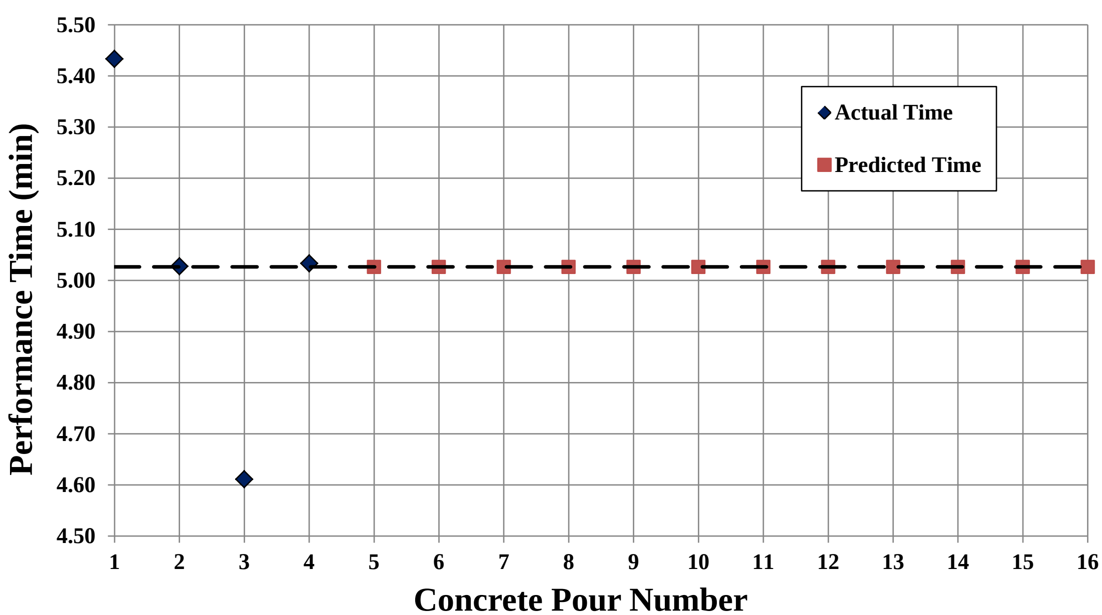

Figure 3: Actual and Predicted Performance Time

Using the measured and predicted values, the duration, total cost, and unit cost for 12 remaining concrete pours were predicted. Student performance on the assignment was very good. All students were able to:

- apply learning curve theory to determine the appropriate prediction methods,
- analyze their measured data and develop an appropriate model, and
- predict operational performance.

Thus, the students were able to demonstrate proficiency at the application, analysis, and synthesis levels of Bloom's taxonomy.

Learning Assessment

The course final exam question included a problem that was designed to assess student ability regarding learning curves in the application, analysis, synthesis, and evaluation levels of Bloom's taxonomy. Students were provided performance data from a prestressed concrete pile driving operation to provide foundational support for a highway bridge. The actual unit cost of installing the piling was provided for 10 bridge bents. During the course of the project, the owner suspended work for a period and the contractor was forced to relocate the original piling crew and complete the work with a different crew. Students were required to analyze the cost data, estimate any additional costs incurred as a result of the work suspension, and write a brief report describing the analysis and results.

The problem required students to:

- evaluate whether learning curve theory is an appropriate analysis technique (analysis)
- apply learning curve theory to model and evaluate the data (application)
- calculate additional construction costs (synthesis)
- argue in support of a claim for additional costs (evaluation)

A straight line learning curve was fit to the data prior to the suspension to evaluate whether learning curve theory should be applied, as shown in Figure 4. The slope of the best fit learning curve was -0.324, which corresponds to an approximately 80 percent learning rate. To assess the significance of this value, a t-test was used to test the null hypothesis that the slope was equal to zero (no learning). The resulting p-value was 0.005, which is significantly less than the 0.05 level of confidence. Therefore, the null hypothesis was rejected and it was concluded that learning occurred and learning curve theory should be applied.

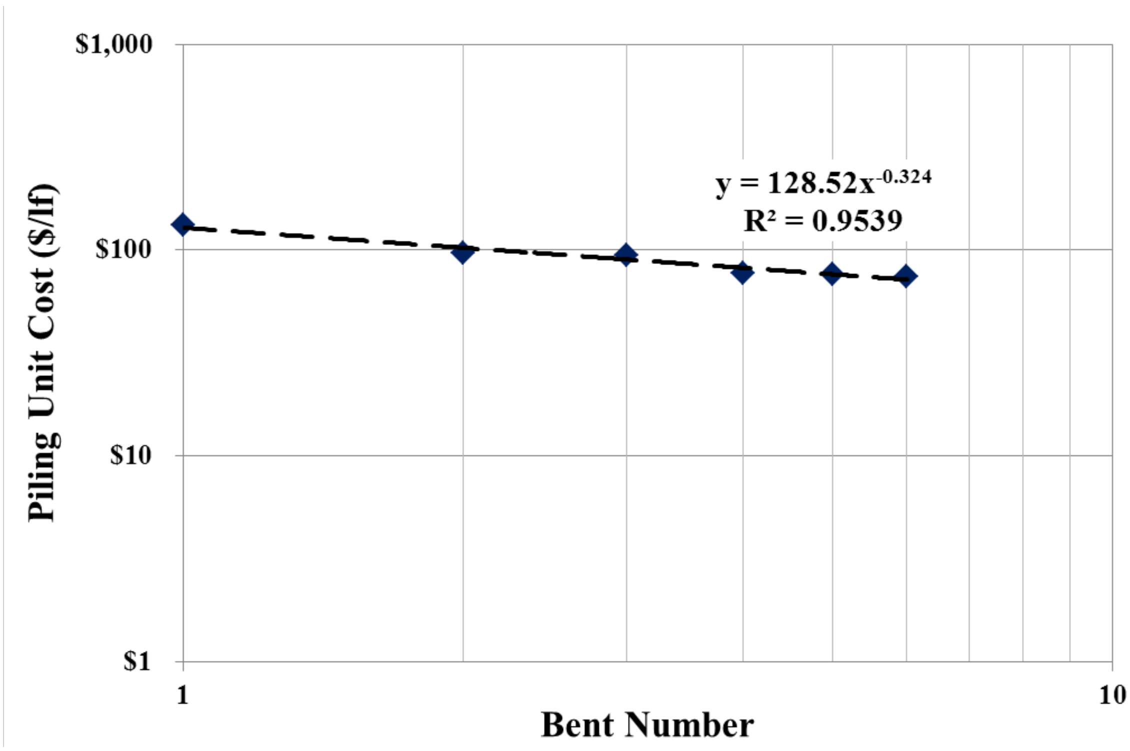

Figure 4: Learning Curve for Piling Operation

The determined learning curve model was used to estimate the unit cost that would have been achieved had the work not been suspended and develop prediction intervals at a 0.05 level of confidence level. The additional costs incurred as a result of the suspension, and the compensation due to the contractor due as a result, were calculated as the difference between the unit cost expected to be achieved by the original crew and the actual unit cost experienced by the replacement crew. The prediction bands delineate the range of unit costs predicted to be achieved by the original crew with a 5 percent level of confidence. The actual unit costs were evaluated with respect to the prediction intervals to determine whether the actual costs were significantly greater than would be expected from the original crew. As can be seen in Figure 5, the actual cost fell above the upper prediction band.

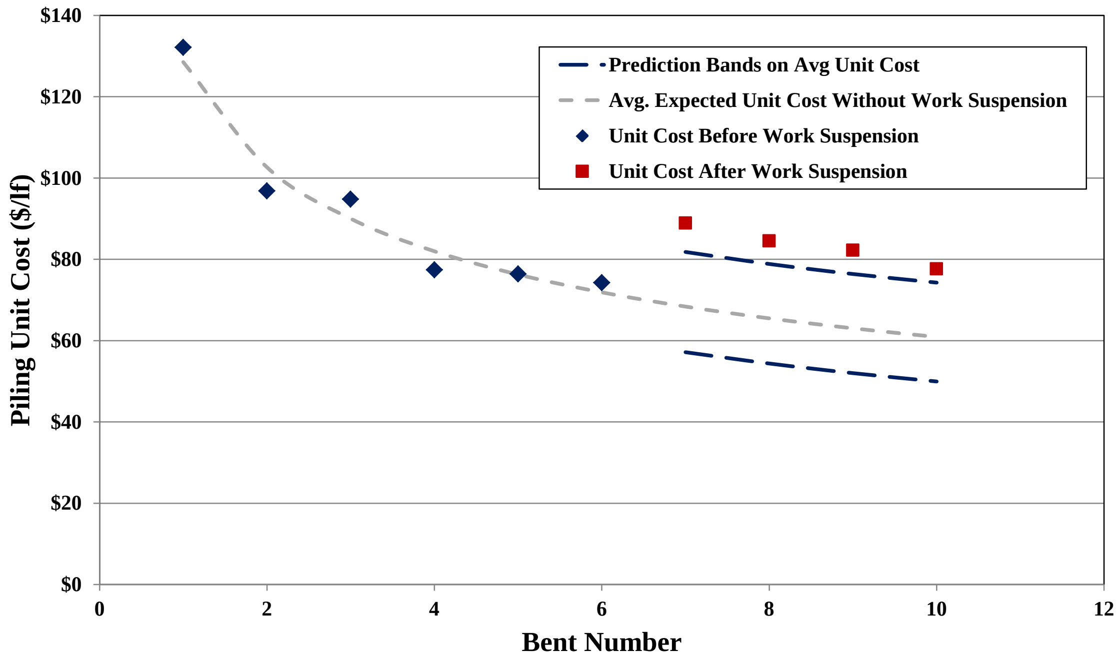

Figure 5: Estimated Unit Cost for Original Crew with Prediction Intervals

Assessment Results

The final exam assessment results indicate that the students possessed excellent knowledge regarding learning curves. There were nine students enrolled in the course and the vast majority were able to evaluate and apply learning curve theory, and to develop an argument based on the results. The results of proficiency at the tested taxonomy levels are presented in Table 1.

Table 1: Assessment Results for Proficiency at Tested Bloom's Taxonomy Levels

Bloom's Level	Task	Portion Demonstrating Proficiency
Analysis	evaluate whether learning curve theory is an appropriate analysis technique	66%
Application	apply learning curve theory to model and evaluate the data	89%
Synthesis	calculate additional construction costs	89%
Evaluation	argue in support of a claim for additional costs	89%

Interestingly, the portion of students demonstrating proficiency at the lowest level of Bloom's taxonomy tested, the analysis level, was the lowest. Only 66 percent of students adequately calculated the learning rate and statistically tested the significance of the result. Another 22 percent calculated the learning rate, failed to test the significance, but proceeded assumed learning curve theory was appropriate. These students based their decision to proceed with learning curve analysis on the obvious difference in unit costs before and after the work suspension. While their observation and conclusion were correct, learning rate statistical significance testing was required for proficiency at the analysis level.

For each of the application, synthesis, and evaluation levels, 89 percent of students demonstrated proficiency at these higher levels of Bloom’s taxonomy. This large portion of students were able to apply learning curve analysis methods to estimate the unit costs that would be expected from the original crew and calculate the additional construction costs incurred by the contractor as a result of the work suspension. They were also able to formulate an argument for equitable adjustment in contract price based on the results of their analyses.

Conclusion

The concept of learning effect and the analytical methods based on learning curve theory are important for construction engineers and managers to accurately estimate and schedule repetitive construction operations. Traditional instructional methods based on idealized sets of operational data do allow students to experience the learning effect. Involving students in the collection of authentic data requires extended time on site and is often prohibited by site access restrictions, safety considerations, and time constraints. Construction equipment simulators, such as the SimLog tower crane simulator, permit students to actively participate in a virtual construction operation and provide firsthand learning effect experience.

In the presented case study, a course instructional module combining traditional lecture and classroom examples with an active learning assignment. Students actively participated in a virtual construction operation, collected the data necessary for analysis, and predicted future operational performance. The module resulted in excellent knowledge regarding learning curve theory and its application within the construction industry. The value of the innovative instructional approach employed was evident from the assessment of student knowledge that revealed the vast majority of students were able to demonstrate proficiency at the highest levels of Bloom’s taxonomy of skills in the cognitive domain.

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