VALIDATING COMPLEX CONSTRUCTION SIMULATION MODELS USING 3D VISUALIZATION

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ABSTRACT

One of the primary impediments in the use of discrete-event simulation to plan and design construction operations is that decision-makers often do not have the means, the knowledge, and/or the time to check the veracity and the validity of simulation models and thus have little confidence in the results. Visualizing simulated operations in 3D can be of substantial help in the verification, validation, and accreditation of simulation models. In addition, visualization can provide valuable insight into subtleties of modeled operations that are otherwise non-quantifiable and presentable. This paper investigates the efficacy of 3D visualization in verifying and validating discrete-event construction simulation models. The paper presents a case study of a simulation model of an earthmoving operation with fairly complex control logic that was verified and validated by visualizing the operation in 3D. The simulation model for the example was developed using Stroboscope and was visualized using the Dynamic Construction Visualizer.

KEYWORDS

Construction Simulation, 3D Visualization, Verification, Validation, Credibility

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INTRODUCTION

Discrete-event simulation (DES) is a modeling technique that has been used to analyze and design many construction operations. DES is particularly beneficial for modeling complex dynamic systems that are intractable to other modeling approaches. The state-of-the-art construction simulation systems allow the modeling of complex construction operations in great detail and with utmost flexibility. Notwithstanding, there has been limited use of DES in planning and designing construction operations.[1, 2]

Construction simulation tools typically provide results in the form of numerical or statistical data. However, they do not illustrate the modeled operations graphically in 3D. This poses significant difficulty in communicating the results of simulation models, especially to persons who are not trained in simulation but are nevertheless involved in making decisions. The resulting “Black-Box Effect” is a major impediment in verifying and validating simulation models. Decision makers often do not have the means, the training and/or the time to verify and validate simulation models based solely on the numerical output of simulation models and are thus always skeptic about simulation analyses and have little confidence in the results.[3] This lack of credibility is a major deterrent hindering the widespread use of simulation as an operations planning tool in construction.

This paper investigates the efficacy of 3D visualization in verifying and validating discrete-event construction simulation models. The paper illustrates the use of DES in the design of a complex dynamic earthwork operation whose control logic was then verified and validated using 3D animation. The simulation model was created using Stroboscope and animated using the Dynamic Construction Visualizer.

VERIFICATION AND VALIDATION OF SIMULATED CONSTRUCTION OPERATIONS

Discrete-event modeling is an inherently complex activity that is both a science and an art. The modeling of a construction operation requires the description, in the language of the simulation modeling system, of mental plans that are often complex and elaborate. Differences between the mental plan and the operation actually modeled in a first attempt are ubiquitous. *Verification* is the process by which the model creator looks at what has been actually modeled, compares it to what was intended, and updates the model to accurately reflect the intention.

The developer of the computer simulation model, however, may have misconceptions about how the actual operation will take place in the field. Thus, a model may not be an accurate representation of reality despite proper verification by its developer. Such errors cannot be discovered by verification because the model indeed reflects what the model creator intended. The aim of *Validation* therefore is to determine whether simulation models accurately represent the real-world system under study. This is typically carried out by consulting people who are intimately familiar with the operations of the actual system, but who are not necessarily proficient in simulation. Figure 1 schematically presents the processes of verification and validation that lead to accreditation of the model and the use of its results in implementing the actual operation at the jobsite.

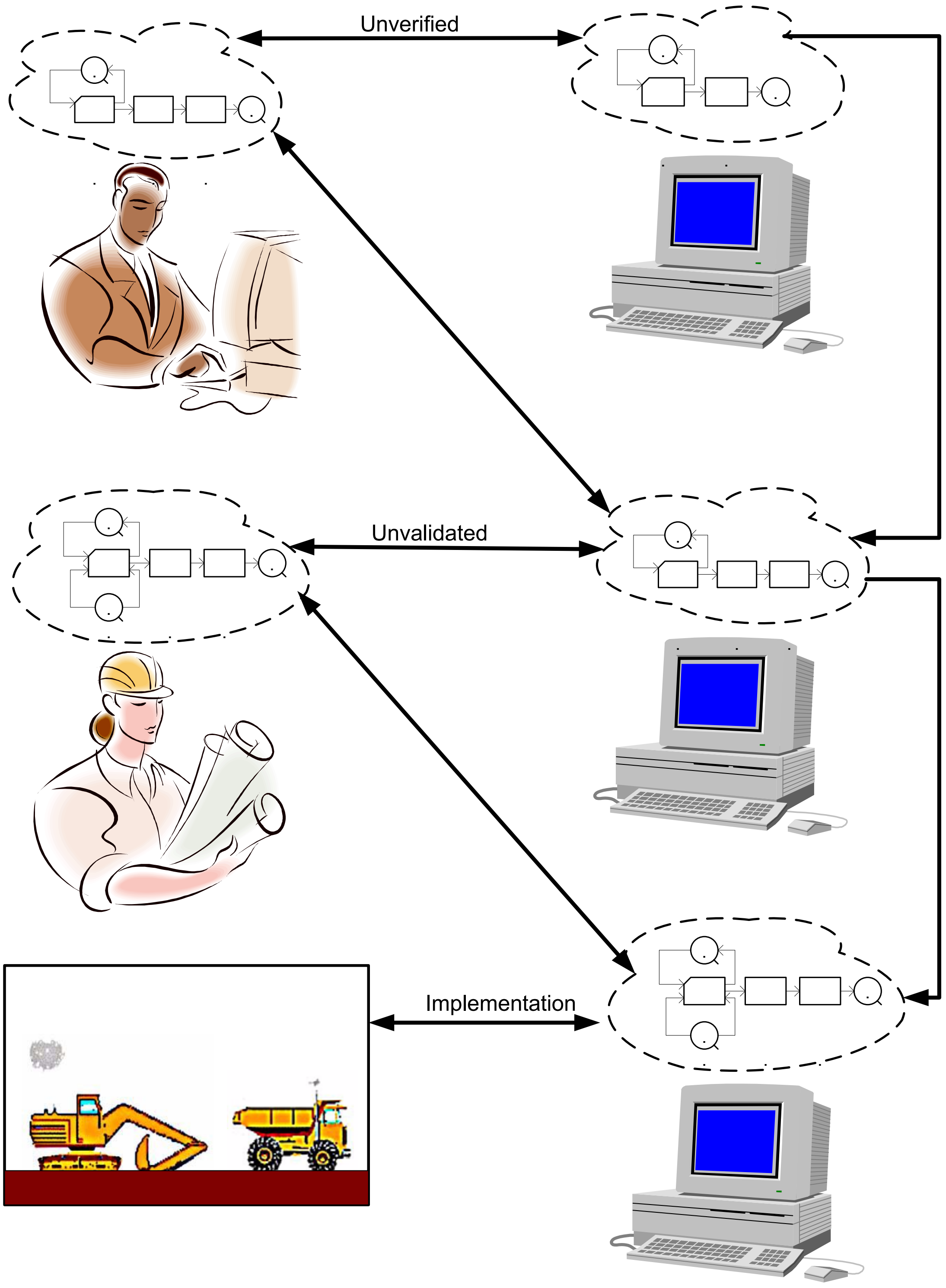

Figure 1. Process of Verification and Validation

Simulation models are termed as *Credible* when the models and their results are accepted as being valid, and are used as an aid in making decisions.[4] In the case of both Verification and Validation, the inner workings of a model and its output need to be communicated to others for discussion and input, in a way that is both comprehensive and comprehendible.[5]

Visualizing simulated operations can be an effective means of achieving this.[4, 6, 7] It is a generally accepted fact that visually presented information is understood and grasped more easily than any other form of communication. The need to visually communicate simulated operations is more relevant in the context of construction because construction operations analysts (e.g., superintendents) typically do not have the necessary training in simulation to allow them to validate simulation results based on numerical analysis.

Accurate 3D visualization can substantially help to communicate intricacies of construction simulation models. It can provide valuable insight into details of construction operations that are otherwise non-quantifiable and presentable. It has the potential to enable the extraction of knowledgeable information from simulations. Visualization can be of help in verification as well as in validation of simulation models. Volumes of data that take hours to review can be communicated in a few seconds. For instance, many techniques are available to simulation analysts to perform verification (e.g., looking at simulation logs). However, a visualization of what occurred in the simulation model can reveal such errors very quickly. Similarly, communicating the working of simulation models to domain experts through visualization can allow errors in logic to be easily identified and corrected. This is the process of validation, and can be significantly enhanced by animating simulated operations. Through 3D visualization, more people can gain a better understanding of the modeled operations.

The remainder of this paper describes how 3D visualization was used to verify and validate the control logic of a simulation model of a complex earthmoving operation. In addition, the paper highlights how the improvement of the operation was facilitated due to the non-quantifiable and otherwise presentable visual insights provided by accurate 3D animation. The tool used in animating the operation, the Dynamic Construction Visualizer, is also briefly described.

EARTHMOVING OPERATION CASE STUDY

The case study presented here is a combination of two separate operations that took place in the states of Virginia and North Carolina. These two operations have been combined to make it possible to illustrate two separate but interesting issues of relative complexity in a single exposition.

The presented operation involved moving 975,000 bank m3 of material in 75 workdays (16 work hours each) from two possible sources to a common dumpsite as shown on the plan view in Figure 2. The two sources are located towards the bottom left part of Figure 2 and are labeled MLA (main loading area) and ALA (alternate loading area). The dumpsite is towards the top right part of Figure 2 and is labeled DumpArea. The haul distances from the main and alternate loading areas to the dump area were 1,670 meters and 1,920 meters. Both haul routes shared 1,370 meters and included a narrow segment 470 meters in length.

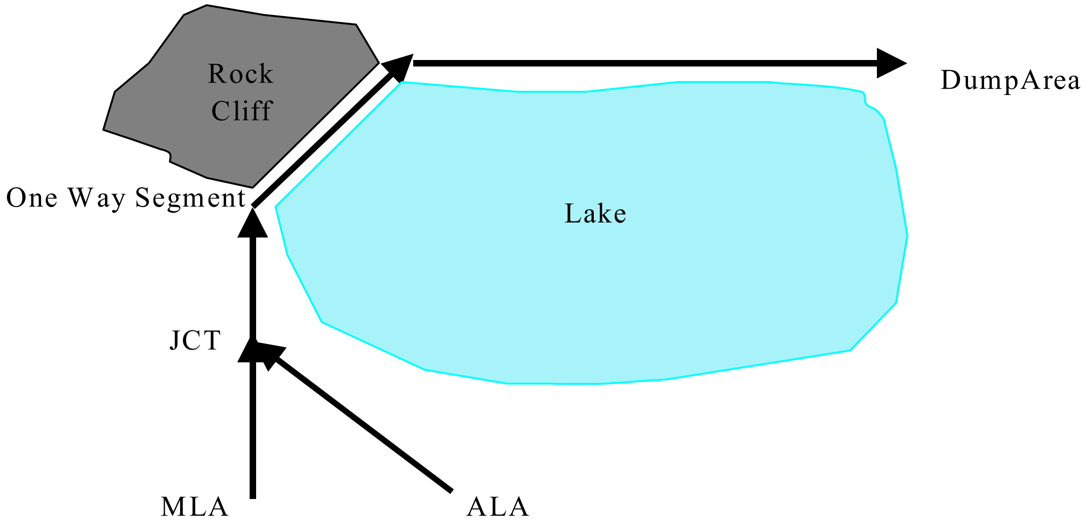

Figure 2. Plan View of the Earthwork Operation Jobsite

The narrow portion was not wide enough to allow simultaneous traffic in both directions. Due to the obstruction shown on Figure 2 and other site constraints, it was not feasible to widen the curve. The dump area was 42 meters above the main loading area and 68.5 meters above the alternate loading area. The underfooting in several parts of the haul routes was soft. The maneuvering space at the load and dump areas was limited.

DISCRETE EVENT SIMULATION MODEL

The simulation tool used to design this operation, STROBOSCOPE, is a programmable and extensible general-purpose system that is designed to model complex construction operations with utmost flexibility.[8] STROBOSCOPE modeled in detail the transport portion of the operation, including dynamic truck routing strategies and the one lane (but bi-directional) haul road segment.

The primary control logic components, combinations of which were to be tested in the simulation model were:

- Truck Routing Strategy to main and alternate loading areas
- Traffic Management on the narrow one-way segment

In the initial routing strategy, trucks returning after dumping were routed to the main and alternate loading areas with likelihoods of 8 and 4 respectively, indicating a 66.7% probability that a returning hauler would go to the main loading area, and a 33.3% probability that the hauler chose the alternate loading area. This initial truck routing strategy was rather naïve but was the easiest to set up in an initial simulation model. Based on the insights gleaned from visualization, subsequent stages of the operation design explored more sophisticated truck routing strategies by using dynamic formulas to define likelihoods.

The default operating logic for the one-way segment marked for travel in either direction was defined such that a truck arriving to the empty segment established the current direction of travel. This direction was maintained as long as trucks kept arriving at the same end of the segment. Trucks eventually stopped arriving at that end and the segment cleared as the last truck exited. At that point direction of travel reversed if trucks arrived and were waiting at the other end. Otherwise it was again established by the next truck to arrive. In this study, it was necessary to analyze and optimize the transport capacity of the narrow segment, as it was the most constrained control parameter.

THE DYNAMIC CONSTRUCTION VISUALIZER

The Dynamic Construction Visualizer (DCV) is implemented as a virtual environment application that can process ASCII text files (trace files) written in the DCV language to accurately describe the spatial and temporal characteristics of simulated operations.

The trace file driven approach allows its seamless integration with numerous process modeling tools that are capable of generating formatted text output during a simulation run. The required trace file consists of sequential animation command statements such as CREATE, DESTROY, PLACE, and MOVE. In addition, the file also contains statements such as PATH and NONDIRECPATH that define resource movement paths during the animation. The statements in the input file are then processed sequentially to visualize the modeled operations in 3D virtual space.

This is accomplished using 3D CAD models of the involved system resources (e.g. Trucks and Loaders) and other model entities. The result is in essence a “motion picture” of the actual operations being carried out in the virtual environment. This “motion picture” can be replayed at varying speeds depending on the viewer’s preferences. In addition, the system also allows users to jump ahead or back to any point in simulation time which is fairly analogous to being able to instantaneously rewind and fast forward a motion picture tape to a desired location. The user is able to navigate easily in 3D virtual space and hence can position himself/herself at any vantage position he/she desires at any time during the visualization process.

Realistic animations can be created using 3D CAD models from supported data file formats such as .3ds (3D Studio™), .iv (Open Inventor™), and .wrl (VRML). Practically every CAD modeling program can export data files in VRML format. Thus, the DCV is practically independent of any CAD modeling software as well.

The DCV is designed to allow simulation model developers to accurately convey the essence of their simulation models in 3D. Doing so facilitates the verification and validation of simulated operations, and helps establish credibility. In addition, it provides valuable visual insights into the modeled system that are difficult to be quantified and depicted numerically or by any other form of visualization.

VISUALIZATION OF THE MODELED EARTHMOVING OPERATION

STROBOSCOPE produces static output in the form of tables and charts. In addition, STROBOSCOPE models can be instrumented to generate animation trace files conforming to the syntax of the DCV language during simulation runs. The trace files are then processed by the DCV visualization engine to depict dynamic 3D output in the form of animations.

Simulation models need to be instrumented to generate DCV animation commands during a simulation run. The following line of code, for example, tells STROBOSCOPE to add two lines of text to the DCV trace file (named ATF in this case) every time a truck starts to haul.

```
ONSTART Haul PRINT ATF
"TIME %.2f\059
MOVE Truck%.0f HaulRoute %.2f\059\n"
SimTime Haul.Truck.ResNum Haul.Duration;
```

These two lines will be written to the DCV trace file numerous times, each of which will look similar to:

```
TIME 423.86;
MOVE Truck1 HaulRoute 83.21;
```

The time, truck number, and the duration to haul will of course be different each time. The DCV trace file will contain other lines of text that will be written out when other parts of the modeled operation take place. Thus, the time-ordered sequence of animation statements written out by all the activities in the model during a simulation run constitutes the trace file necessary to visualize the modeled operations.

The size of the generated trace files depends on the amount of detail modeled and the length of the simulation. The size of typical trace files will vary from a few hundred lines for simple models to several thousand lines for detailed and complex models that simulate operations over long periods of time. The trace file for visualizing 8 hours of the discussed earthwork operation is, for example, 36400 lines long. The STROBOSCOPE model required 44 animation-specific commands to do this. There is no limit on the size of the trace files that can be processed and is therefore not a constraining issue.

In the current visualization, the observer was able to examine the presented operation in a very realistic manner. In addition, the observer could “see” all the characteristics of the terrain such as gradients of the routes, the limited maneuvering spaces at the loading areas, the configuration of the one-way segment, and the limited visibility (due to steep grades) available to truck drivers approaching the junction from the loading areas (point JCT in figure 2). At all times, the observer could “move” to any desired location on the virtual jobsite using keyboard keys to steer. The level of detail at which the operation was visualized comprehensively established the veracity and the validity of the simulation model.

Verification

Differences between the mental plan of the modeler and the operation modeled in a first attempt are ubiquitous. The model of the presented operation was no different. The initial STROBOSCOPE model contained various coding errors. Some of these errors drastically altered the logic of the modeled operation. For instance, the most conspicuous of these errors altered the logic of the model to allow bi-directional traffic through the narrow one-way segment. This meant head-on collision between trucks traversing the segment. Figure 3 depicts an animation snapshot of the scenario.

Another error created discrepancies in the resolution of the right-of-way among trucks arriving at the Y-intersection (Point JCT in Figure 2). This allowed trucks arriving from either direction to traverse the intersection regardless of other present traffic. Figure 4 presents a snapshot of a near miss when an empty truck heading towards the alternate loading area suddenly cut across a loaded truck emerging from the main loading area.

Figure 3. Modeling Flaw: Bi-directional Traffic in One-way Segment

Yet another modeling flaw allowed an empty waiting truck to start taking position under the main excavator even before the loaded truck ahead had cleared the loading area. Figure 5 depicts this scenario wherein the empty truck almost runs into the exiting loaded truck.

Figure 4. Modeling Flaw: Near Collision at the Y-Intersection

Visualization revealed all these errors in a few minutes. It took an equally negligible time to fix the coding errors in the STROBOSCOPE model. Some of these errors could have been detected using traditional verification techniques, albeit with a lot more time investment. For instance, we could have identified after some inspection of the logs that trucks traversed the one-way segment simultaneously in either direction. With a little more effort, we could also have predicted some confusion at the Y-intersection. It would, however, have been very difficult to identify the discrepancy that caused an empty truck's early intrusion into the loading area.

Figure 5. Modeling Flaw: Rear-end Collision at the Main Loading Area

The reason for this can be explained by looking at the portion of the initial stroboscope model presented in Figure 6. The activity LoadTruck was immediately followed by the activity Haul. The activity Maneuver was programmed not to take place while the activity LoadTruck was in progress. At the instant at which LoadTruck ended and Haul commenced, however, a waiting truck would start to Maneuver. This seemed perfectly logical by looking at the model. The slow speed of the exiting loaded trucks and the relative agility of the empty trucks were, however not apparent by looking at the model or its trace. As Figure 5 presents, the faster speed of the empty trucks would almost cause them to hit the rear end of the exiting loaded trucks.

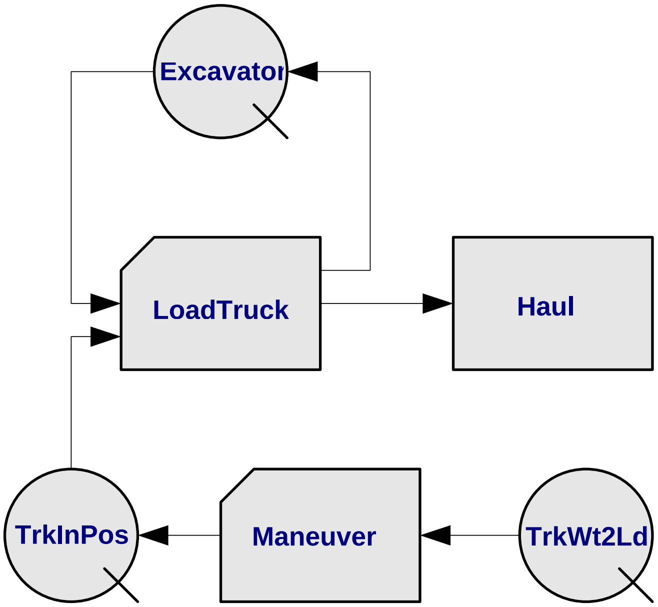

Figure 6. Portion of the Initial STROBOSCOPE Model

This immediately suggested the need for an additional activity, ExitLoadArea, between LoadTruck and Haul that would also block the instantiation of the Maneuver activity. Such subtle errors, although not apparent using traditional verification techniques, are easily noticed by looking at a visualization for a few seconds.

Validation

The developer of a computer simulation model may be inexperienced or have misconceptions about how the actual operation will take place in the field. Thus, a model may not be an accurate representation of reality despite proper verification. A verified model accurately reflects what the model creator intended. The aim of validation therefore is to determine whether a simulation model accurately represents the real-world operation. This is typically carried out by consulting people who are intimately familiar with the operations of the actual system, but who are not necessarily proficient in simulation.

Due to our background in construction engineering and general knowledge of earthmoving operations, we were competent enough to validate the presented simulation model to a large extent. However, for the purpose of completeness in the investigative exercise, we presented the simulation model and the visualization to an experienced local earthmoving contractor.

The contractor, looking at the visualization of the digging excavator (main loading area) contended that it (the excavator) appeared to be digging too fast for the type of terrain it was operating on. To our surprise, subsequent careful examination of the underlying data used in the simulation model confirmed that the data used to establish the probability distribution came from a different study. The fit of the distribution to the data had been validated through all appropriate statistical methods; the fit was indeed good and proper. It was, however, a fit to data for a different job study. The experienced contractor was able to recognize this immediately by looking at the visualization.

Visualizing the operation that was modeled using bad data provided a tangible opportunity for the domain expert to notice this discrepancy during visualization. It would have been very difficult indeed for the contractor, who was not proficient in simulation, to notice this flaw had he been told that the probability distribution for the loading time of the main excavator was a Normal with a mean of 48.5 seconds and a standard deviation of 7.25 seconds. Visualization made all the difference.

Insightful Visual Details

In addition, visualization provided several non-quantifiable and otherwise presentable details that were critical in making decisions. The basic problem with the narrow one-way segment was that loaded trucks, traveling uphill, were very slow. They arrived at the curve at such an interval that they entered when a previous truck was almost exiting. The direction of travel was thus maintained in the loaded direction for very long periods, during which empty trucks arrived and bunched at the other end. When empty trucks entered the curve, however, they traversed and cleared it very quickly.

The dynamic output produced by the DCV provided a much better picture of the truck bunching and additionally revealed strategies that could be used to improve the operation. Figure 7 shows a snapshot of the animation with 5 empty trucks bunched up waiting to enter the big one-way segment; one loaded truck about to enter the curve before another loaded truck finishes traversing it; and one loaded truck heading towards the dump area. The slow speed of the loaded trucks and the fast speed of the empty trucks as they traverse the curve cannot be seen on the snapshot. Only the animation can convey that information.

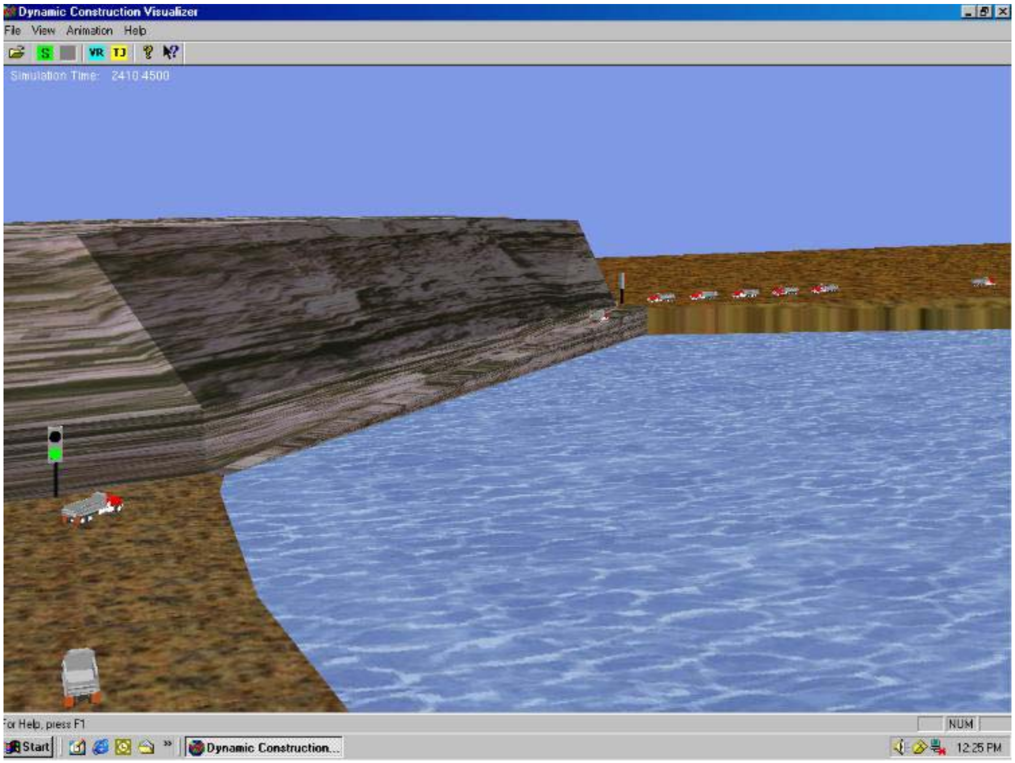

Figure 7. Bunched up Trucks Waiting to Enter the Narrow Segment

Figures 8 and 9 show snapshots of the animation a while later, when the trucks that had bunched up have arrived almost together to the main and alternate loading areas. A few trucks are out of view in the snapshot but will arrive soon to the loading areas. The visualization provided clear indications that the entry of loaded trucks to the segment had to be controlled so that empty trucks could traverse it in smaller bunches.

The visualization also revealed the ineffectiveness of the probabilistic (but random) truck routing policy; at times trucks were routed to an excavator that was busy and had a long queue of trucks waiting to be served even though the other excavator was free. Visualizing the operation clearly indicated that the percentages naively used in the preliminary design were not a bad choice, although the routing method itself was.

Figure 8. Bunched up Trucks at the Main Loading Area

Simulation Time: 2640.4600

Figure 9. Bunched up Trucks at the Alternate Loading Area

CONCLUSION

The purpose of using simulation to model construction operations is to test and obtain insights into the consequences of using various construction alternatives. The results of simulation are expected to help the planner in making the most advantageous decisions. It is of utmost importance, however, that simulation models be credible if they are to be accepted and used as a decision-making aid.

The presented research investigated the effectiveness of dynamic 3D visualization in the verification and validation of discrete-event construction simulation models. The paper demonstrated, with the help of a case study that visualizing simulated operations in 3D can be an effective means of accurately communicating modeled operations, especially to decision makers who are not necessarily proficient in simulation. This is of significant help in verifying and validating simulation models thus establishing their credibility.

The paper also demonstrated that the dynamic visual output provided by 3D visualization can provide several subjective details about the operations that can be of immense help in decision-making. In addition, the reader was briefly introduced to research being conducted at Virginia Tech to enable smooth dynamic animation of discrete-event construction simulations.

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