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Verifying complex microtunnelling construction simulation models using 3D visualization

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ABSTRACT

One of the primary impediments in the use of discrete-event simulation to 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 establishing the credibility of models and in obtaining valuable insight into subtleties of modeled operations that are otherwise no quantifiable and presentable. This paper presents a case study of a simulation model of a microtunnelling construction operation with fairly complex control logic that was verified and validated by visualizing the operation in 3D. The simulation module for the example was developed using AnyLogic simulation software.

1. Introduction

Nowadays, the use of process simulation methodology in construction is found as being one of the most effective methods for the modeling, analysis and understanding of processes related to analyzing, planning and scheduling of construction projects. Using process simulation, real operations can reasonably accurately be modeled and the whole construction process can be analyzed in depth, so that potential problems can be identified. Notwithstanding, there has been limited use of discrete-event simulation (DES) in planning and analyzing construction operations (Halpin and Martinez, 1999).

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 domain experts. 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 their results. This lack of credibility is a major deterrent hindering the widespread use of simulation as an operations planning tool in construction.

This paper illustrates the use of DES in the design of a complex dynamic tunnel construction with microtunnelling operation whose control logic was verified and validated using 3D animation. The model was created and animated using AnyLogic simulation software.

2. Verification, validation of simulated construction operations

Before using the simulation model, the model must be demonstrated to achieve simulation model credibility. The use of the validation and verification process is to gain the credibility. Therefore, in order to demonstrate the simulation model credibility, the validation and verification process are applied.

Verification is the process by which the model creator looks at what has been actually modeled, compares it to what was intended to be modeled, and updates the model to accurately reflect the intention (Kamat and Martinez, 2001). Verification has two aspects: design (all specifications and nothing else are included in the model or simulation design) and implementation (all specifications and nothing else are included in the model or simulation as built) (Pace, 2014). On the other hand, the aim of Validation 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 (Kamat and Martinez, 2001). Validation has two aspects: conceptual validation (when the anticipated fidelity of the model or simulation conceptual model is assessed) and results validation (when results from the implemented model or simulation are compared with an appropriate referent to demonstrate that the model or simulation can in fact support the intended use) (Pace, 2014).

Simulation models are increasingly being used to solve problems and to help in decision-making. The creators and users of these models, the decision makers using information obtained from the results of these models, and the individuals affected by decisions based on such models are all rightly concerned with whether a model and its results are “correct” (Law and Kelton, 2000). In the case of both Verification and Validation, the inner processing 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 (Oloufa & Ikeda, 1997).

Visualizing simulated operations can be an effective means of achieving this (Law and Kelton, 2000). 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.

Realistic 3D visualization can substantially help to communicate intricacies of simulation models. In addition, it can provide the behavior of graphically as the model moves through time. For instant the movements of parts through a factory during a simulation run are show graphically.

Visual communication can aid both verification as well as 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.

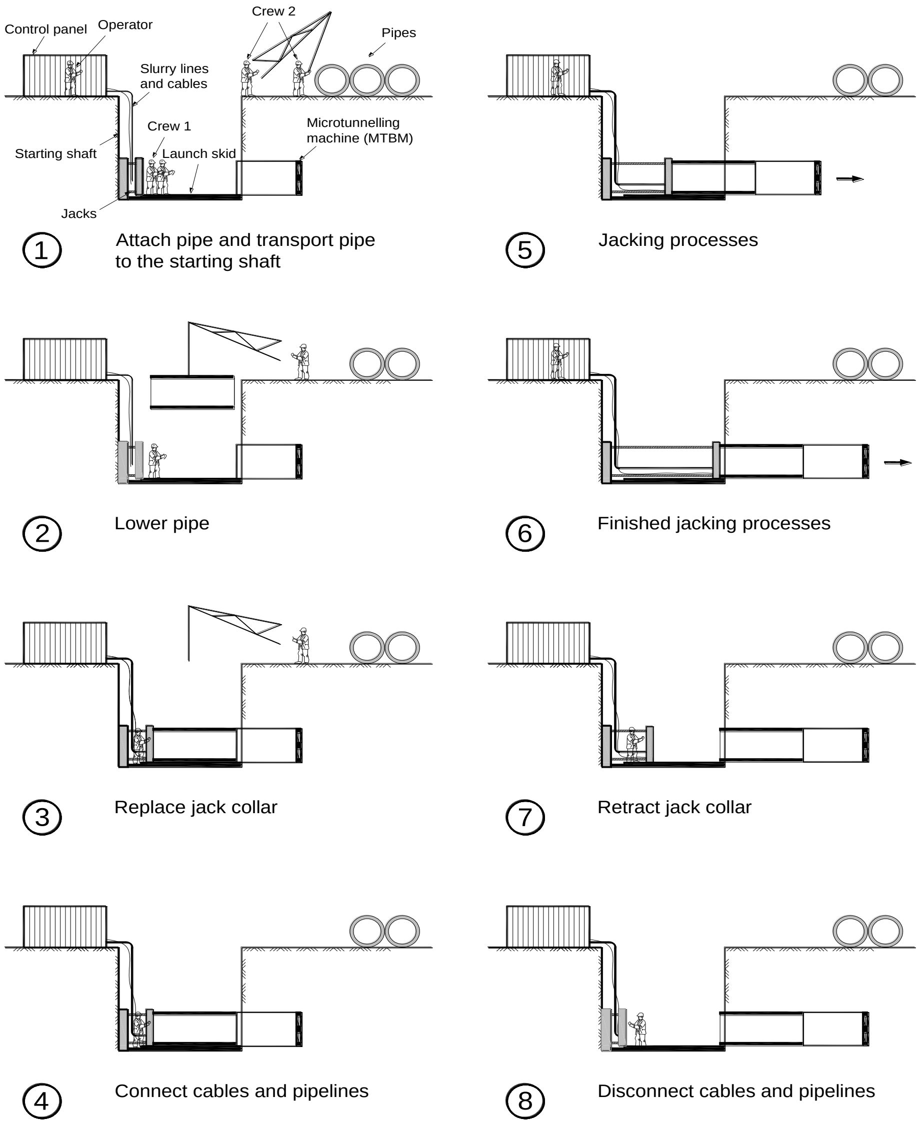
This is the process of validation, and can be significantly enhanced by animating simulated operations. Through visualization, the user can gain a better understanding of modeled systems.

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 tunnel construction with MTBM. Moreover, the paper also highlights how the improvement of the operation was facilitated due to the visual insights provided by realistic 3D visualization.

3. Microtunnelling process analysis

The basic principles of microtunnelling (Figure 1) are similar to other kinds of TBMs. The sequential concept of microtunnelling is can be summarized as follows: In this process, the pipe sections are brought to the construction site from the manufacturing company. At the construction site, they are unloaded from the truck by crane (or forklift) and stockpiled at a pipe storage near the top of the starting shaft. When the pipe is available, the Operator and Crew 2 (working on the surface) receive the signal from the shaft bottom, the crane is maneuvered, picks up a new pipe and lowers the pipe into the launch cradle. When the pipe is positioned on the launch cradle, the jack collar, cables and pipelines may be replaced and connected by Crew 1 (working in shaft) in order to prepare them for further operation. Subsequently, the pipe section may be jacked forwards. When the forwards pipe jacking is finished, the jack collar is retracted, cables and pipelines are disconnected. When the process is completed, the preparation for the next pipe is started and the sequence is repeated. The cycles repeat as required until the length of the tunnel is excavated. The summary of the tunnel construction with MTBM may be divided into two main processes, namely:

- **Preparation processes**: represent all activities required in order to prepare the excavation phase: lower pipe, connect jack collar, cables, pipelines, mix bentonite, retract jack collar, and disconnect cables and pipelines.
- **Jacking processes**: in this procedure the entire activities involved in excavation processes occur simultaneously: control the thrust load of the jacking frame, control the MTB, control the navigation system, and control the disturbances during excavation time.



① Attach pipe and transport pipe to the starting shaft

⑤ Jacking processes

② Lower pipe

⑥ Finished jacking processes

③ Replace jack collar

⑦ Retract jack collar

④ Connect cables and pipelines

⑧ Disconnect cables and pipelines

Figure 1. Microtunnelling principles (Dang, 2013)

4. Microtunnelling operation case study

The tunnel of the case study crossed the ”Baumstraße” in Recklinghausen City, Germany. The depth to axis was approximately 8.7 meters, grade 2,6 ‰ and the used type of pipe was DN1200. The pipe size was 1.2 meters internal diameter, 1.56 meters external diameter, 4.0 meters length. The position of the construction site was easily accessible. Excavation was carried out by microtunnelling machine AVN 1200T using hydraulic spoil removal. In Figure 2 a MTBM type AVN-T (Automatic tunneling machine with slurry material removal and an opening in the bulkhead partition door) is shown, which uses the same operation method and sequence as AVN 1200T. The AVN 1200T uses almost the same operating principles as MTBM, which is described in the last section. The whole 145.0 meters long drive of the tunnel of project will encounter types of soil conditions, which are marl, clay and fine sand. The soil condition of the project is not convenient for the jacking processes.

The device site layout is considered a critical factor defining simulation module, due to the fact that it reflects the resource cycle patterns of the project. Project site layout should provide adequate space for the microtunnelling operation, ease of material delivery, and the equipment arranged reasonably to minimize any waste of time of the resources cycle. In order to generalize the site layout for the simulation module, the site layout of microtunnelling project is slightly modified based on the site layout observed in the job-site. Figure 3 shows the common site layout of the project.

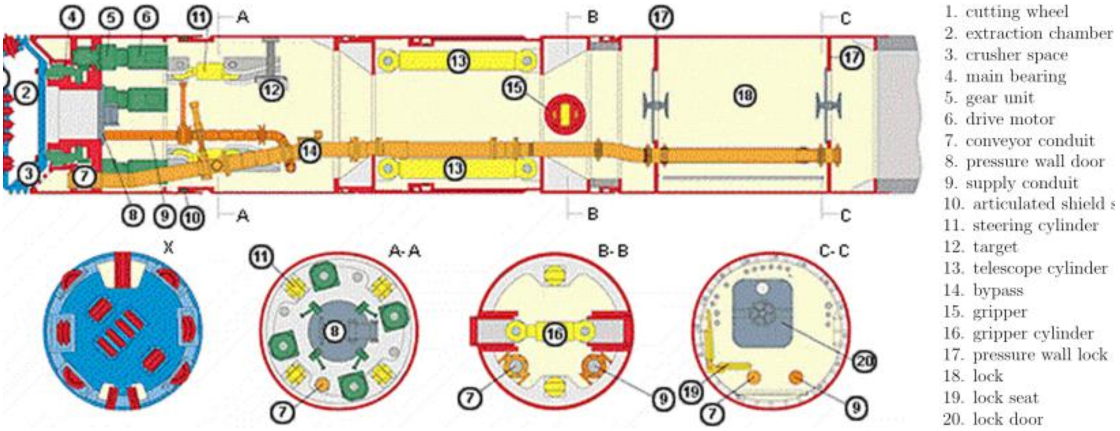


Figure 2. Longitudinal section of a microtunnelling machine AVN-T [6]

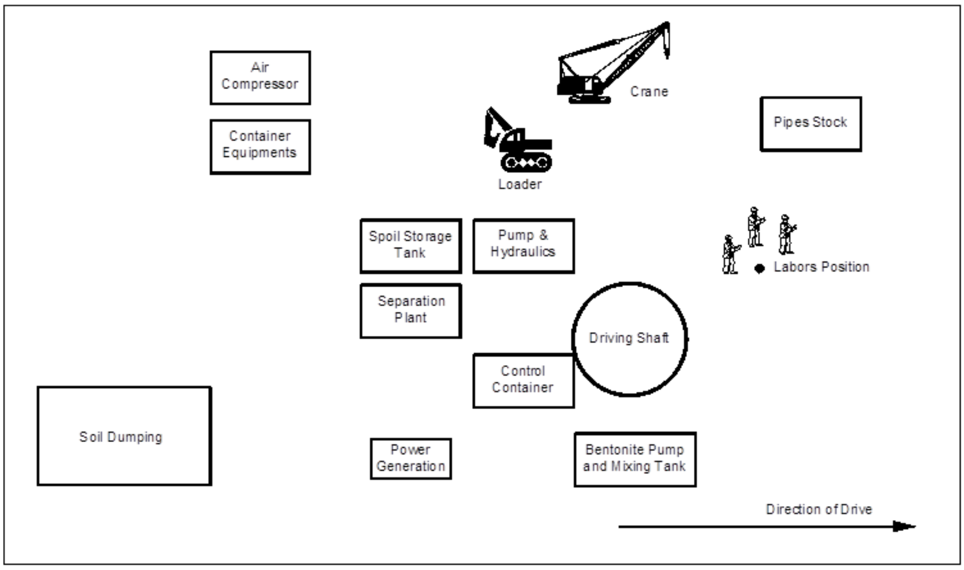


Figure 3. Site layout of microtunnelling project

5. Discrete event simulation model

The DES paradigm is typically used in simulation studies to model and analyze construction sequences. It is an old method created in the 1960s by Geoffrey Gordon when he conceived and evolved the idea for GPSS (General Purpose Simulation System) and brought about its IBM implementations (Gordon, 1962). The method is the most commonly used one for modeling sequences of a system, e.g. construction sequences (Koenig, 2011). The entities (transactions in GPSS) are passive objects that represent people, parts, documents, tasks, messages, etc. They travel through the blocks of the flowchart where they stay in queues, are delayed, processed, seize and release resources, split, combined, etc (Borshchev and Filippov, 2004). Each event occurs at an instant in time and marks a change of state in the system (Robinson, 2004).

The common technique is called flowcharts and state-charts (state-machines) that uses the DES concept to graphically illustrate the application of the paradigm. Normally, one state-charts is integrated by two major elements - namely states and transitions (Rahm et al., 2012). The states represent the behavior of a system. The transitions describe the movement between different states as time passes (Object Management Group, 2007).

A simple example is provided for the use of state-machines (stm) in order to explain the application of the discrete event modelling in the simulation model. Figure 4 represents the stm of MTBM. The initial state of the system is inactive. When the event evStart is active, the system changes to the state excavating. The excavating state is finished when the transition evCompleted occurs, the system changes to the state inactive again.

6. The dynamic MTBM construction visualizer

The Dynamic Construction Visualizer (DCV) of MTBM is implemented in AnyLogic simulation software. The most common simulation methodologies today: Discrete Event Simulation (DES), System Dynamics (SD) and Agent Based Modeling (ABM) have been integrated in AnyLogic software (Figure 5).

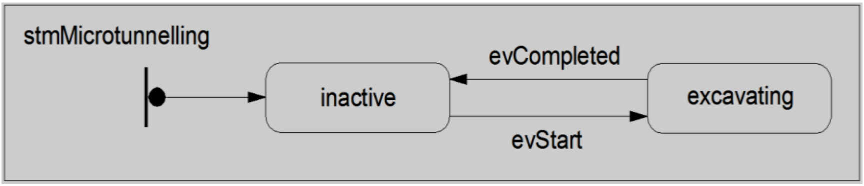


Figure 4. Discrete event description of MTBM operation

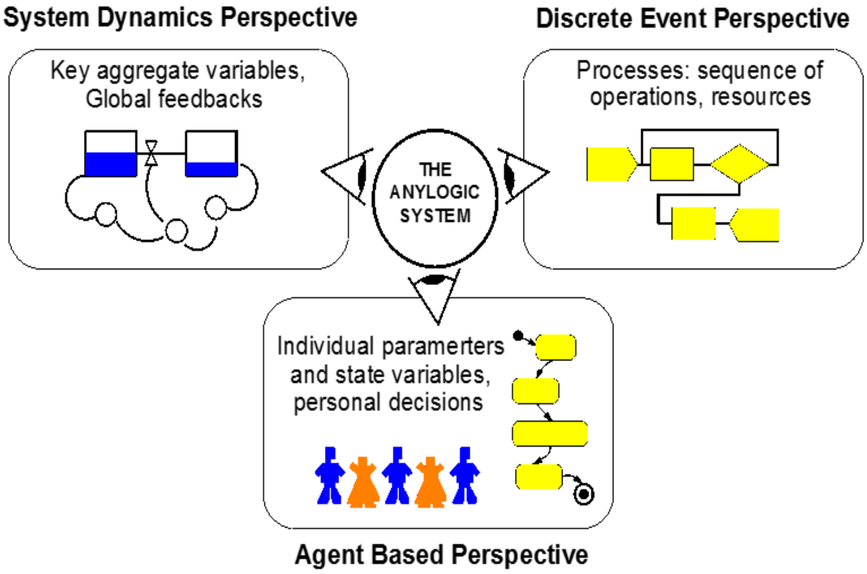


Figure 5. The methodologies applied in AnyLogic (AnyLogic Company, 2012)

The AnyLogic simulation software is especially useful regarding the simulation of large and complex operations. With this software, almost all corporate fields of application can be represented, e.g. production, logistics, business processes, market and competitors, supply chain and construction sequences (AnyLogic Company, 2012). The AnyLogic simulation software is able to break the simulation model down into different parts, and analyze them individually. Dividing the entire simulation model into different parts also reduces the complexity of the simulation model, because it makes the model more orderly and therefore easier to understand. Thereby, modelers can combine different simulation approaches within the same model.

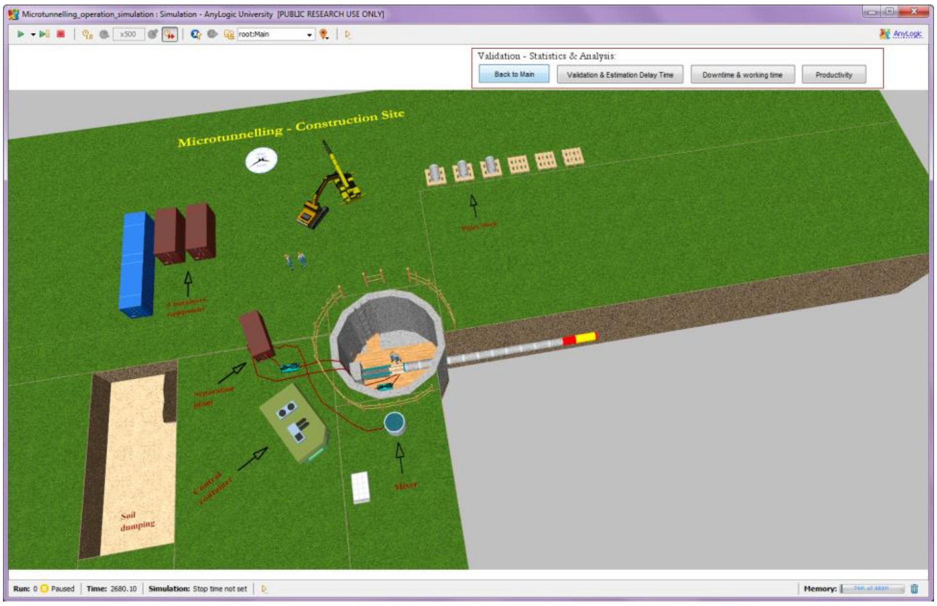
Realistic animations can be created using libraries, namely: The enterprise library, the pedestrian library and the rail library. The aim of each library is (AnyLogic Company, 2012):

- **The enterprise library** is a library designed to support the discrete event modeling. Using the enterprise library, modelers can for example simulate the manufacturing, logistics or supply chain. The user can use the enterprise library in order to model real world systems or the operation processes of systems or construction.
- **The pedestrian library** is a library to support the simulation of pedestrian flows in a *"physical"* environment. For example, using the pedestrian library, the developer can create the model of pedestrian intensive buildings (e.g. subway stations, security checks, etc.).
- **The rail library** is a library developed for modeling, simulating and visualizing operations of a rail yard of any complexity and scale. The rail yard model can be merged with multi - method simulation modeling such as: discrete event or agent-based in order to model e.g. loading, unloading, resources, maintenance etc.

7. Visualization of the modeled operation

In order to verify the computer program of a dynamic system, the analysts may use animation. The users then see dynamic displays (moving resources, cartoons) of the simulated system. Since the users are familiar with the corresponding real system, they can detect the conceptual errors (Kleijnen, 1995). Therefore, the simulation module is verified for the 3D animation.

Figure 6 shows a 3D graphic screenshotted from the simulation module during the run. The 3D animation describes the information about the internal behavior of the resources during the excavation of MTBM in a graphical way. All actions and behavior of the resources during running the simulation module are observed. The results indicate that the structure and logics of each stage in the simulation module are similar to the practical results.



Run: 0 Paused | Time: 2680.10 | Simulation: Stop time not set | Memory:

Figure 6. 3D animation of MTBM operations

Based on the analysis above, it can be concluded that the simulation module can represent the logic and structure of the MTBM. In addition, it also represents an indirect evidence that the simulation module may be used to evaluate and analyze the factors that affect the productivity in MTBM operations.

8. Conclusion

The purpose of using simulation to model tunnel construction with MTBM is to obtain insights into the consequences of using different techniques and strategies and thus helping the planner in making the most advantageous decisions. This paper demonstrated that visualizing simulated operations in 3D enhances the credibility of simulation models by realistically communicating the modeled operations. In addition, it also demonstrated that the dynamic visual output provided by 3D visualization can provide subjective details about the operations that can be of immense help in decision-making. The paper also introduced the simulation models is developed by AnyLogic software, which provides the most common simulation languages and packages with the support necessary to visualize the simulated operations in 3D, enabling planners and designers to obtain a more realistic and comprehensible feedback from simulation analyses.

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