Construction Process Simulation in Tunnel Construction – A Prerequisite for Automation

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Abstract

Construction process simulation allows producing a virtual copy of an existing or planned construction site. The detailed analysis of construction processes and construction logistics with the support of simulation models creates a better understanding of the performance defining aspects. In many construction sites, the actual performances lag behind the planned levels. This is due to the insufficiency of planning instruments. The authors have performed an in-depth analysis of the internal supply chain of an actual tunnel construction project. While the presented study has focused on the inner outfitting of the existing tunnel, similar work has been done for the excavation processes by the authors. The paper reviews the role, simulation plays for construction planning and investigates the benefits of simulation as a step towards increased automation levels.

Keywords –
Simulation; Tunneling; Process Modeling;

1 Introduction

Within the construction industry, tunneling is a highly specialized discipline due to its very strict spatial restrictions. Whether for the actual tunnel excavation itself or for the subsequent inner outfitting of the structures, delivery routes and workspace are limited. This poses challenges for the organization and execution of the supply chain processes that are necessary to keep work going. Often, different processes compete for space and must therefore be scheduled in such a way that they don't conflict with each other.

Since the involved capital cost and ongoing operating expenses of large civil engineering projects are very high, reducing execution duration is a key target of planners. Therefore, planning should allow for a maximum degree of parallelization of works. If this target can be reached, mainly depends on the possibility to deliver the required material to the worksites on schedule. The study presented by the authors uses process simulation to investigate the robustness of the supply chain concept for the inner outfitting of a railway tunnel in Germany. The study has been part of the bidding documents of a contractor for the execution of the works. The project owner's tender called for a verification of the bidder's logistic concept by simulation with particular consideration of the logistic restrictions, evacuation routes and all material transports. The tender requirements for the simulation study included:

- Core processes and work cycles with references for the underlying performance data.
- Possible interactions between system elements.
- Sensitivity analysis and study of alternative scenarios and their influence on the project completion.
- Mitigation strategies for bottlenecks shown by the evaluation.
- Description and explanation of the simulation study methods.

2 Process Simulation in Tunnel Construction

Although simulation studies have been used successfully in the planning of tunnel construction projects, the usage of simulation usually has been restricted to high level planning for strategic management purposes. The application of simulation as a tool for the improvement of work level processes has been rare. Nido et al. provided the planners of the Holes Creek Tunnel in Ohio, USA with a cycle time analysis based on the Cyclone simulation framework [1]. Liu et al. used a Cyclone model to evaluate the mucking system for a hard rock tunnel project in Xinjiang, China [2]. Ioannou et al. used Stroboscope to optimize resource allocation for the Hanging Lake tunnel project in Colorado, USA [3]. Fernando et al. used the Symphony simulation environment to evaluate different options regarding the use of one or several tunnel boring machines (TBMs) and their related logistic systems in the North Edmonton

Sanitary Trunk in Alberta, Canada [4]. For the Glencoe tunnel project in Calgary, Canada. Al-Bataineh et al. have used a Simphony model to investigate the influence of different geology scenarios and to determine the cost / time parameters for these different layouts [5]. The general-purpose simulation framework Anylogic has been used in several studies for a detailed analysis of work processes in tunneling [6] and [7]. One focus of these studies has been improved performance prediction for tunneling projects with regards to the influence of jobsite logistics on production rates [8] and [9].

3 Work and Transport Processes in Tunnel Outfitting

Once the excavation and structural construction of a tunnel is completed, the inner outfitting can be performed. The project which has been analyzed in this study consists of two parallel railway tunnels of 4km length in Germany. The bored tunnels are transitioning into a cut and cover structure of 1km length at each end. All sections are to be equipped with a slab track system as well as walkways and driveways at each side of the track. A drainage system and cable ducts are installed below these structures.

The construction process is separated into discrete process cycles. Within the schedule, these are defined by distinct construction stages which are executed along individual work sites. For each work site, the corresponding material requirements and delivery paths are defined by the contractor's logistics concept. The general construction schedule can be separated into the following stages which again make up the core processes:

1. Construction of drainage pipes and filler
2. Pouring of concrete invert
3. Installation of cable ducts
4. Concreting of side walkway and driveway
5. Construction profile concrete
6. Installation slab track and rail cover

Generally, the processes in the east and west tunnel are identical. To reach logistic independence, the work in the cut and cover sections is performed after completion of the works in the bored tunnel sections.

4 Simulation Modeling

The simulation model has been implemented in the commercial simulation framework Anylogic. Anylogic supports the integration of different simulation paradigms in a single model. This includes system dynamics, discrete event and agent-based modelling approaches [10]. Furthermore, embedded object libraries allow efficient modeling of vehicles, road networks and railway systems. In the presented study, the individual construction processes have been modeled by statecharts, using the discrete event approach. A road network which is dynamically adjusted to the respective situation, especially the changes in the logistics restrictions in each construction stage has been used to model the vehicles of the supply chain within the construction site. The embedded road library of the Anylogic software has been used to implement the road network. The system boundaries have been set to the physical boundaries of the cut and cover sections. Figure 1 shows the jobsite layout and the model boundaries.

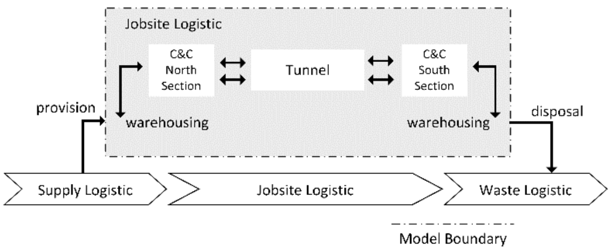

Figure 1 System- and Model Boundaries

It is assumed, that the external supply chain is always able to deliver the required performance. As an additional abstraction, the transport required for material disposal are ignored as they are minimal during the outfitting stage of construction. As construction only proceeds during dayshifts, transports during nightshifts are not modelled as well. Furthermore, personnel transport is assumed to take place between the material transports without disturbing them.

4.1 Modeling of Core Processes

The overall completion duration of the project is defined by its core processes and the resulting process chain. Each core process is defined by a set of properties which uniquely identify it and set its behavior within the overall model. The parameters are:

- Process Name
- Requirements for starting (logical or date)
- Separation into production intervals or sections
- Location of start and endpoints
- Required resources for execution
- Productivity per unit
- Material requirements (type and amount)
- Process related logistic restrictions
- Process related waiting durations

Due to slight differences in the execution logic, the processes for the outfitting of the bored tunnels and each cut and cover section are defined separately.

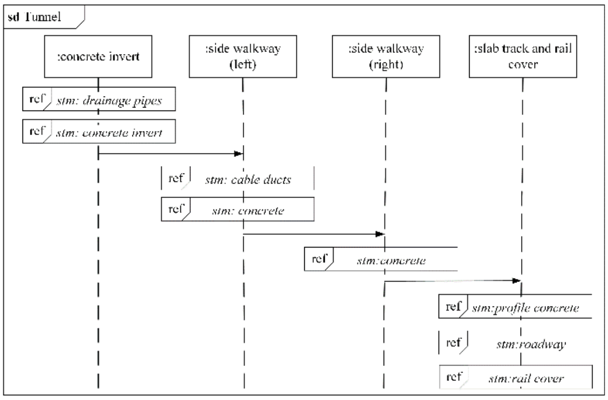

Figure 2 Logical order of process execution in the bored tunnels

Figure 2 shows the logical order of the process execution for different core processes as a SysML Sequence Diagram. Each of the core processes is implemented by a generic state chart. Functions, parameters and variables are used to customize the generic model to each respective process.

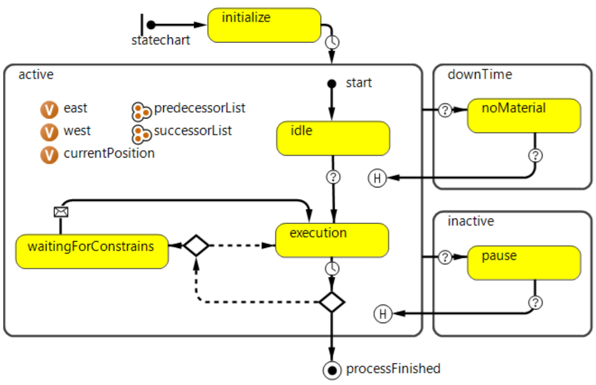

Figure 3 Generic statechart for work process modelling

The state chart shown in Figure 3 is used generically to model all work processes. For each work process, an individual instance of the state chart is generated. Within the chart, each rectangle reflects a particular state of the system. At any given moment, the system is on one particular state.

At the time of project start, all processes are in the state "initialize". The state "execution" is initiated, once the defined conditions are fulfilled (for example completion of the predecessor). Based on the process performance, the current position of the worksite is permanently updated. The variables "east" and "west" indicate in which tunnel the process takes place. The remaining available construction material are determined based on the processes consumption data. If the material is used up completely, the "working" state is interrupted and the system transitions into the "noMaterial" state. An underlying shift schedule defines when the system moves into the "pause" state. A history function "H" allows resuming work at the point where it stopped after an interruption. By using the "predecessorList" and "successorList" elements, the logical order of execution is defined. Communication functions organize the interaction with other model elements.

4.2 Modelling Transport Processes

The transport processes are modelled by the Anylogic embedded road traffic library. It uses movement processes and queues through which objects are moving according to a defined set of rules. The traffic model is separated into distinct sections that reflect the road sections that vehicles must pass through. For each section, different traffic conditions such as one-way traffic, two-way traffic and waiting points are defined. This allows modelling bottlenecks and passing locations for trucks.

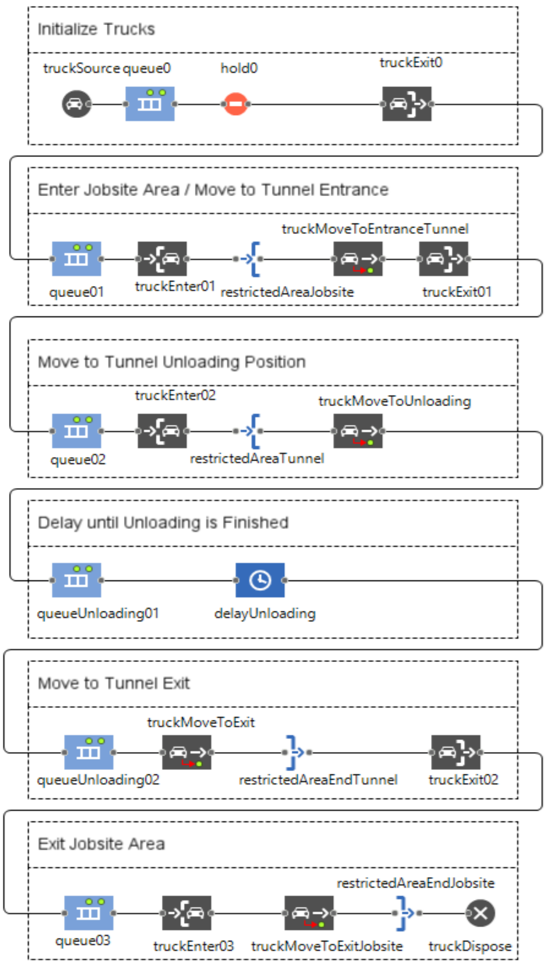

Figure 4 Dynamic traffic model for the site logistics

Figure 4 shows the logic structure of the road traffic model. The underlying logic of the model and its visualization are implemented separately. Figure 5 shows a screenshot of the traffic visualization within the simulation model. The driving paths are idealized as straight sections in the view. Inclination and curves are reflected by their effect on the driving speed of the vehicles.

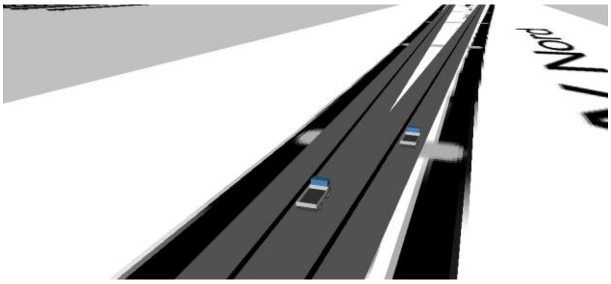

Figure 5 Visualization of traffic processes

The key information for the transport processes are the following:

- Transport batch sizes
- Driving speed (full and empty) in different sections
- Driving routes / supply strategy
- Unloading durations

To deliver material to the different work sites, four different supply strategies can be distinguished:

1. Drive through from north to south. The full trucks enter the tunnel on the north side, unload the material at the work site and once empty, they drive out to the south.
2. Drive through from south to north. The full trucks enter the tunnel on the south side, unload the material at the work site and once empty, they drive out to the north.
3. Delivery from North. Trucks drive into the site backwards from the north side and after unloading dive out forwards to the north again.
4. Delivery from South. Trucks drive into the site backwards from the south side and after unloading dive out forwards to the south again.

For each work process, one particular supply strategy is defined in the simulation model. Once material is ordered by a work process, the associated transport strategy is assigned to the vehicle.

4.3 Interaction of System Elements

With regards to the logistic processes that supply the inner outfitting of the tunnels, especially the implementation of material orders and deliveries is of importance. The interaction of the individual construction processes is based on the embedded lists of predecessors and successors that define the possible execution order. Thus, the current state of all processes is permanently communicated between model elements to check if any process reached its requirements for work start or completion.

The transport processes are coupled with the construction processes by a material ordering system. For each work process, a set of variables and parameters defines the execution of material orders. Figure 6 shows this element within the simulation model. The element defines the required material type, its consumption rate, delivery batch size, performance rate and remaining material amount. The process “invert concreting” in the east tunnel requires for example the material invert concrete which is of the class “material” and is represented by the generic agent “agent material”. The required material is permanently compared to the available material. As soon as it becomes visible that the available material does not suffice for the completion of the current work section, a material order is triggered. This is executed within a defined time buffer to avoid downtime due to lack of material. The time buffer reflects the lead time for the order.

Each material order triggers a delivery process. With consideration of the information contained in the order, a suitable vehicle (truck / mobile mixer) is provided and starts driving to the work site which placed the order. The driving duration depends on the vehicle type, the transport route, transport strategy and interaction with other vehicles which could cause waiting durations at bottlenecks along the way. Upon arrival at the work site, a certain duration is needed for unloading after which the vehicles drive back out.

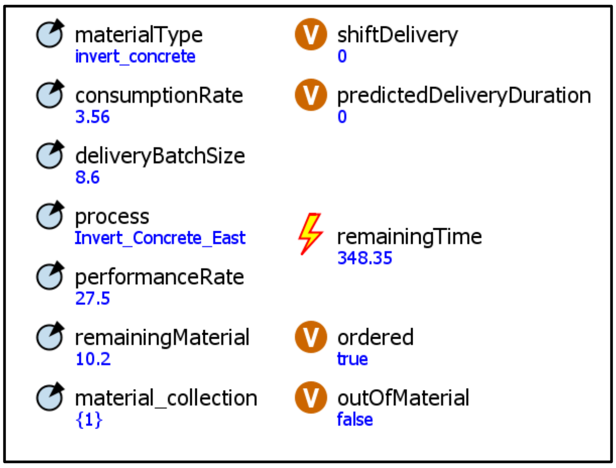

Figure 6 Control variables for the ordering process

4.4 Model Verification

Simulation models must be verified to ensure the correctness of the conclusions drawn from their results. A number of verification techniques are employed either during modeling or after completion of the model. The following methods have been used throughout the presented study:

- Completeness has been ensured by comparing all work processes from the project execution schedule with the event logs of the simulation model execution.
- The consistency of the model has been reviewed by checking the logical order and relation of all work processes in the simulation model and comparing them to the technical requirements defined in the project planning documents.
- The suitable level of detail has been confirmed as no performance relevant processes take place below the level of detail that has been modeled.
- To evaluate the plausibility of the results, the process logs during model execution and the material consumption patterns have been checked and compared to the planned amounts.

5 Simulation Results

The simulation model has been created based on the project execution schedule and the logistic concept that have been prepared by the bidder. The main purpose is the validation of the chosen logistics strategy. To evaluate the simulation results, construction performance with consideration of the supply chain simulation has been compared to the progress rates which have been assumed in the construction schedule. This comparison has been performed for different scenarios to determine sensitivity to varying progress rates. The first scenario is "standard", with all performance values and transport capacities assumed as in the planning documents. The second scenario is "fast completion" with increased construction performance rates (+10%) and the third one "reduced transport capacity" with reduced transport speeds (-10%) for all trucks. Figure 7 shows that even in the second scenario under aggravated circumstances, all work processes can be executed with an acceptable performance rate. Consequently, the same results could be verified for the other two evaluated scenarios. The results show, that the capacity of the proposed logistical system provides adequate buffers in the process chain to ensure an undisturbed construction progress even under hindered boundary condition. Thus, the simulation study verifies the bidder's logistics concept as sound and robust.

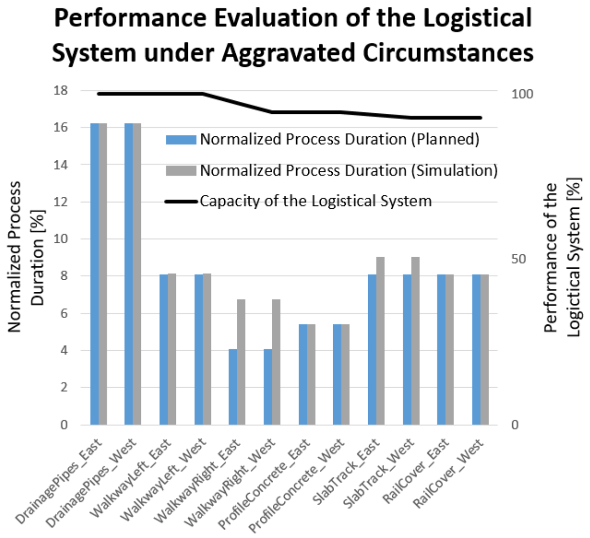

Figure 7 Simulation results for the second scenario with increased construction performance rates

Additionally, to the verification of the supply chain strategy, the simulation model can be used to derive valuable information on the expected traffic volume during different stages of project execution. Figure 8 shows the summary of required transports from and to the jobsite throughout the project. Such information is especially relevant to authorities if projects are located in congested urban areas.

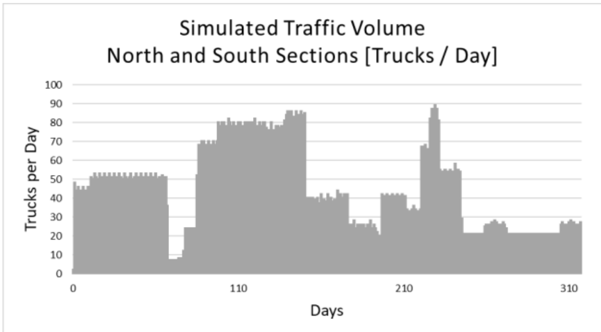

Figure 8 Traffic volume for standard scenario

6 Other Simulation Applications in Tunneling

While the study presented here is focusing on the inner outfitting of tunnels, much value can be added to tunneling projects by supporting their planning with simulation studies during planning the actual drilling. During this stage, large amounts of material are moved, and often special constraints highly restrict the available options for logistics. Cranes, trains, trucks and storage areas compete for scarce space. Figure 9 shows a 3D model of an urban tunneling jobsite on which two tunnel boring machines have to be supplied through a small shaft. In such conditions, the performance of the jobsite is often severely limited by logistic bottlenecks. Simulation studies help estimating these effects and assist the development of counter strategies.

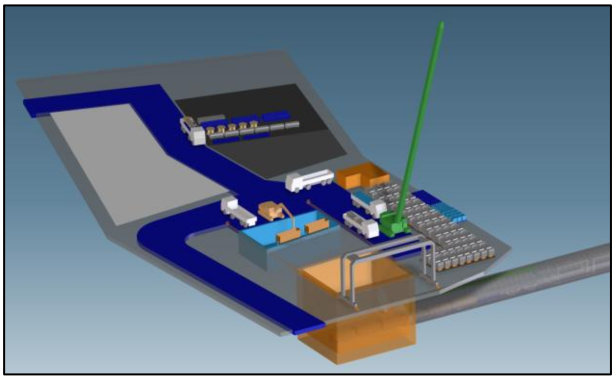

Figure 9 Screenshot of a simulation model for a tunneling site

7 Conclusion and Outlook

Simulation studies have helped dramatically increasing the productivity in the manufacturing sector. As currently the construction sector moves towards higher productivity rates and fields such as automation and robotics are entering the industry, simulation becomes an increasingly important factor in planning. The underlying knowledge about the interaction of processes is crucial for finding ways to automate them. The authors are confident that the construction industry bears great potential for productivity gains in the future.

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