Simulation-based Analysis of Surface Jobsite Logistics in Mechanized Tunneling

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ABSTRACT

The construction procedure in mechanized tunneling is affected by a complex interaction of logistic processes. Due to restrictive factors, like limited space on construction sites, a just in time delivery of material is required for production purposes. Slight differences of the production rate of a Tunnel Boring Machine (TBM) have huge impacts at the logistical chain. Therefore, the logistic management is one of the key factors responsible for the success and profitability of tunneling projects. In this paper, a discrete event simulation model is presented that supports tunneling experts in the planning process and that can be applied in the construction phase as a tool for decision analysis. Since each TBM is unique, it has a unique demand for logistic solutions. Therefore, the simulation model is implemented in a modular manner such that it can be applied for a vast number of different projects in mechanized tunneling. The properties of the construction site and the TBM are freely configurable. To show the functionality of the model a fictive demonstration model was conducted. It illustrates the influence of different logistic processes on the production rate of a TBM as well as the complex interactions of single logistic processes in the supply chain of a construction site.

INTRODUCTION

In mechanized tunneling each TBM features special equipment according to the geotechnical formations. Additionally the boundary conditions of each project are also unique or can change continuously during the construction phase. Today the planning of logistic concepts for tunneling projects is based on past experience of the project engineers on uncertain performance forecasts. However, the productivity of the logistical chain must match the excavation rate to ensure productivity during the project phase. As an example an increase in excavation rate leads to an increased demand of material for the TBM and therefore and provides additional requirements for the construction equipment on the jobsite.

Equally, changes in the jobsite setup or disturbances of construction equipment can reduce the productivity of the TBM. For these reasons an efficient planning of the logistic chain and the needed construction equipment for tunneling projects is complex and hard to manage with standard planning tools.

STATE OF THE ART

Due to the various sources of uncertainty regarding the geotechnical formations, geomechanical behavior or ground water table, mechanized tunneling represents one of the most difficult and complex areas in engineering. The lack of information and uncertainties affects the project planning, project schedules and project costs. To handle these uncertainties is one of the most challenging tasks for the project management of tunneling projects. In the past two decades, the TBM technic was successfully established in the whole spectrum of soils, in hard rock and all kinds of geotechnical boundary conditions (Maidl et al. 2012). A common way to analyze different aspects of TMB and tunneling projects in the planning phase or during the construction phase is the use of simulation models.
To estimate the performance of TBM M. Alvarez Grima et al. (2000) and Pham et al. (2011) combine fuzzy logic (FL) and artificial neural networks (ANN) methods. With the use of real TBM project data for training the ANN the authors make a forecast for the penetration rate and advancement speed of TBM's. Rock mass properties, geometry and machine characteristics are used as the main factors influencing the penetration rate. The limitation of this approach with respect to the project planning is the disregard of the ringbuilding process and the whole supply chain management as elementary aspects for mechanized tunneling projects. Additionally the jobsite setup and the layout of temporary facilities (TF) like warehouse, maintenance shops ore storage spaces can have large impacts on the project performance (Zhou et al. 2009). Cheng und O'Connor (1996) and Sebt et al. (2008) developed GIS technology based approaches to estimate the optimal layout of temporary facilities for construction jobsites. All of these approaches are using the geometry of the TF, facility relationships and the existing amount of space for the site layout planning. Complete project planning and construction process simulation is not considered within these purely geometry based methods. To forecast and analyze the efficiency, of the TBM and of the whole tunneling project, combination of different simulation strategies with respect to the special characteristics of the TBM technique is required. Rahm et al. (2012) provide a multi method simulation model combining a discrete event process simulation (DES) of the TBM and a system dynamic (SD) material flow model. The performance prediction of the project is identified considering technical disturbances but with disregard to the jobsite layout and the influence of the logistic chains. Some holistic simulation models and sensitivity analysis of tunneling construction projects were developed by AbouRizk et al. (1999) and Ebrahimy et al. (2011). The main disadvantage of these holistic approaches is the project-specificity of the simulation template. Each TBM in mechanized tunneling is unique and therefore needs special unique templates.

All approaches for simulation models in mechanized tunneling focuses on different aspects of the tunneling project but disregard the coupling effects of the TBM advance process, jobsite layout planning and supply chain management. Furthermore a free configurable simulation template allows analyzing the effects of the logistic processes on the project process for a large number of tunneling projects.

OBJECTIVE

Logistic processes and the understanding of the supply chain management is a key factor for the success of tunneling construction projects. To analyze the influences of the logistic chain on the project performance a discrete event logistic simulation model can be used. All influential factors of the logistic chain on the advance rate of the TBM, and therefore on the project performance, have to be identified and considered. The coupling of a process orientated simulation model, the jobsite layout and the logistic chain allows an accurate forecast of required resources and materials on the jobsite. These informations can be used to achieve a just in time delivery without losses of performance due to missing material. Additionally, the efficiency of the construction equipment can be improved.

CONCEPT

In order to implement a logistic simulation model, first step is to identify and abstract the elements of a tunneling jobsite influencing the performance of the TBM from logistical point of view. In this paper, the *System Modelling Language* (*SysML* (Object Management Group 2010)) is used to describe the implemented elements and their couplings. Figure 1 shows the *block definition diagram* (*bdd*) of the model for the simulation-based analysis of surface jobsite logistics in mechanized tunneling. In the *bdd* the basic structure, hierarchy and relationships between the shown elements are described. Because of the combination of production and logistic processes in one simulation model, it is necessary to define boundary conditions and an objective function. In this case the TBM is modeled as the element that requests the overall requirements and defines the performance of the jobsite. The construction time of the project is chosen as objective function which has to be minimized. Model boundaries are chosen according to jobsite geometry and defined storage places.

The *Construction Equipment* elements (Figure 1) can be understood as the connection between the external and the internal jobsite logistic system. All elements shown in Figure 1 are predefined and freely configurable in technical specifications. This concept offers an easy and efficient way change simulation setup, to compare different scenarios and therefore to analyze the logistic processes and to identify bottlenecks or spare production capacity.
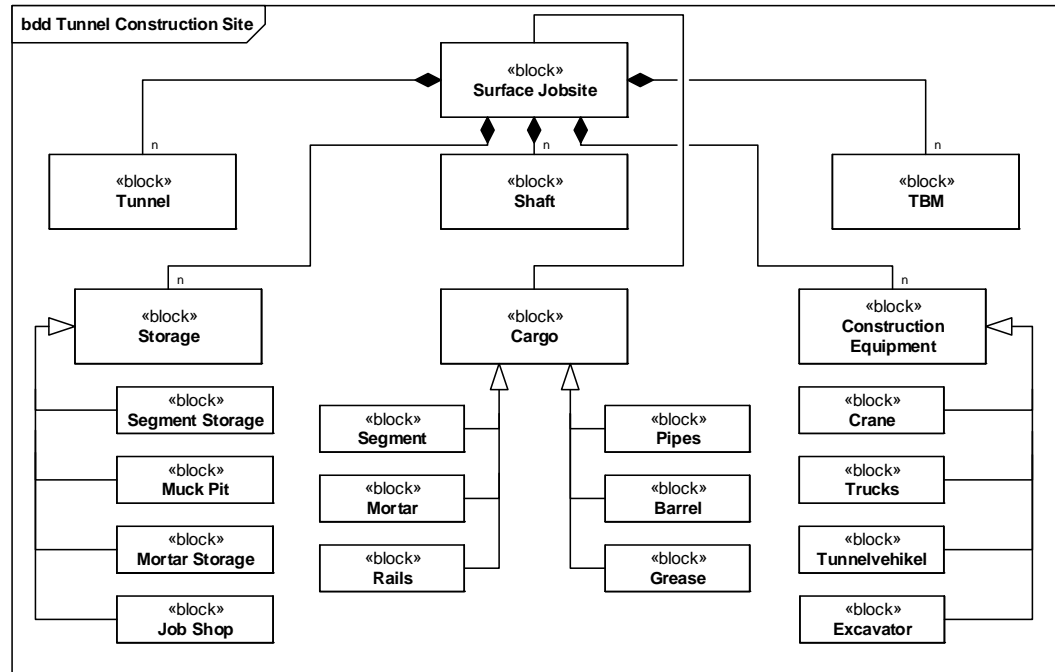
**Figure 1. bdd-diagram for tunnel construction site in logistic simulations**

In mechanized tunneling the construction process does not take place on the jobsite. All materials needed for the construction of one segment ring must be transported from storage places into the shaft and through the excavated tunnel sections to the TBM. These logistic processes are coordinated by an integrated, priority-based order system. Once the TBM consumed material, e.g. the segments during the ringbuilding process, a delivery order will be generated. If the segment storage contains enough segments, the order is sent to the construction equipment e.g. surface crane to transport the segments into the shaft. An important goal is to prevent downtime of the TBM. Therefore all available equipment and material is primary used to support the excavation process. The external logistic, e.g. segment delivery, has a lower priority and is executed afterwards.

IMPLEMENTATION

During the last years the discrete-event simulation is a common way to analyze logistic chains or different logistic scenarios. The formal model is implemented in the simulation software AnyLogic 6.9.0. AnyLogic is using the statecharts paradigm for the simulation of discrete events. The described blocks of the *SysML – bdd* are represented by *Active Object Classes* (*AOC*) in the simulation software.

Each block is implemented in an own *AOC* with freely configurable properties. **Error! Reference source not found.** shows the drag and drop approach to create the simulation model using the presented elements. With this method it is possible to create a unique simulation just by selecting the required elements and

bring them together in the development environment. Second step is to modify the element properties e.g. the technical specifications of the TBM or the maximum load of   the   crane.
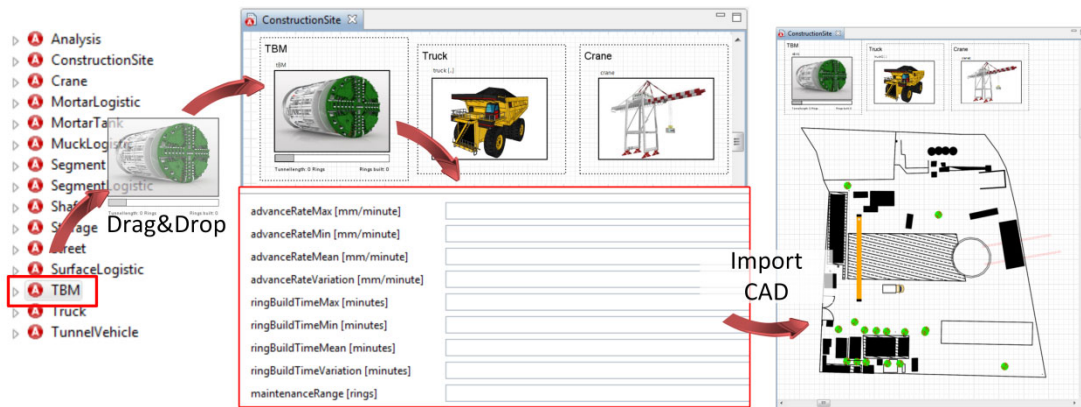
Figure 2. Configuration of the simulation model

Afterwards CAD drawings are used to define the jobsite layout. All embedded elements are automatically identified and will be used for the simulation of the logistic chain. The layout of the jobsite and the available storage spaces constitute the maximum stock of material on the jobsite. Process times are calculated with respect to the element properties and the jobsite layout.

The implemented approach is very versatile in use. All element interactions and dependencies are predefined. With the use of the SysML model and the shown hierarchy the extension of the model is possible with minimum effort.

Example

To show the benefit of the simulation for the planning process of the logistic and the success of tunneling projects, a demonstration model is presented. The model shows the influences of three different logistic scenarios on the TBM performance and thus the project duration of a fictitious jobsite. A tunnel of 12000 meter length has to be driven with the use of a TBM (Ø 8.0 meter). The jobsite layout allows storing 32 rings of segments (7+1) and 2400m³ of excavation material (≈ 32 advances). Table 1 shows the important time parameter of the logistic simulation. Three different soil layers are visible with different excavation speed represented by a truncated normal distribution. The normal distributions are stretched by the value of σ and truncated to fit in [min, max]. In all sections the time to build one ring is adopted with a normal distribution with mean value 15 minutes. Maintenance work on the TBM is planned every 200 rings with a duration of 24 hours.

Table 1. Time parameter setup of the simulation model

Parameter	Value [min]			
	μ	σ	min	max
Advancement rate				
Section 1 - 2250 m	30	5	15	80
Section 2 - 5250 m	50	10	15	80
Section 3 - 4500 m	20	5	15	80
Ringbuilding	25	10	15	30

During the planning phase three different alternative jobsite setup alternatives were identified. In the first setup one gantry crane type 1 is installed to transport the segments delivered by trucks to the segment storage and from the segment storage into the shaft. It is assumed that there will be no disturbance due to the external delivery logistic. As long as there is free storage space, there are trucks delivering segments to the jobsite. That means that TBM downtime is caused by problems in the jobsite logistic.
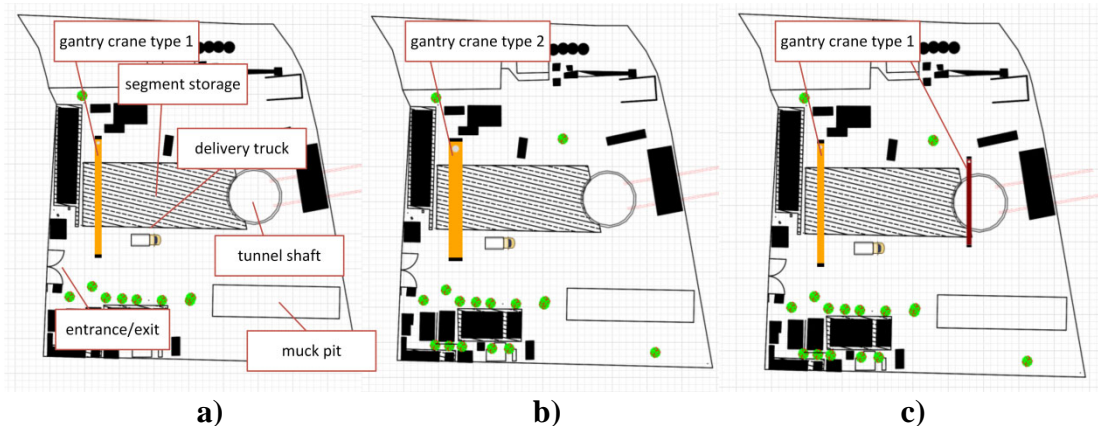
Figure 3. Simulation scenarios

The second scenario simulates the use of a more powerful gantry crane type 2. This crane features twice the maximum load as type 1. That allows the crane to lift up two segments at the same time.

In the last setup two cranes of type 1 are installed. That leads to a split of the logistic processes. One crane executes the unloading of the delivery trucks while the second one is responsible for segment transportation into the shaft. Both cranes can lift one segment at a time. The aim of the simulation is to analyze the performance of the jobsite setups and identify the best one with respect to their ability to support the anticipated TBM performance and thus reduce the project duration.

The simulations experiments are executed with fixed seeds to get reproducible results. The results of the simulation runs are shown in Figure 4. Without any disturbances due to the jobsite logistic, the project duration of this setup is the summation of the maintenance, advance and ringbuild time. In the first scenario severe downtimes of the TBM occur and the simulated project duration increases

from 357 days to 803 days. To analyze the reasons for these downtimes the utilization of the gantry crane is shown. It is obvious that the gantry crane operates at full capacity. Therefore the bottleneck of the logistic system is detected and the setup of the construction equipment must be changed. Figure 4(a) and (b) illustrate the comparison of the two alternative setups. The use of a gantry crane type 2 reduces the project duration by over 468 days (42%). But the utilization of the crane is still close to the limit. Especially the comparison of the gantry crane's inactive time and the maintenance durations of the TBM indicate that this setup is still not sufficient for the performance of the TBM. A more efficient alternative is the use of two gantry crane type 1 and the division of the logistic workflow. The downtime is reduced to 29 days. Compared to the initial setup this entails a reduction of above 93%. The project duration can be shortened to 386 days. In order to further reduce the downtime of the project, increasing the segment storage might provide a possible strategy. However, this is not conducted in this publication.
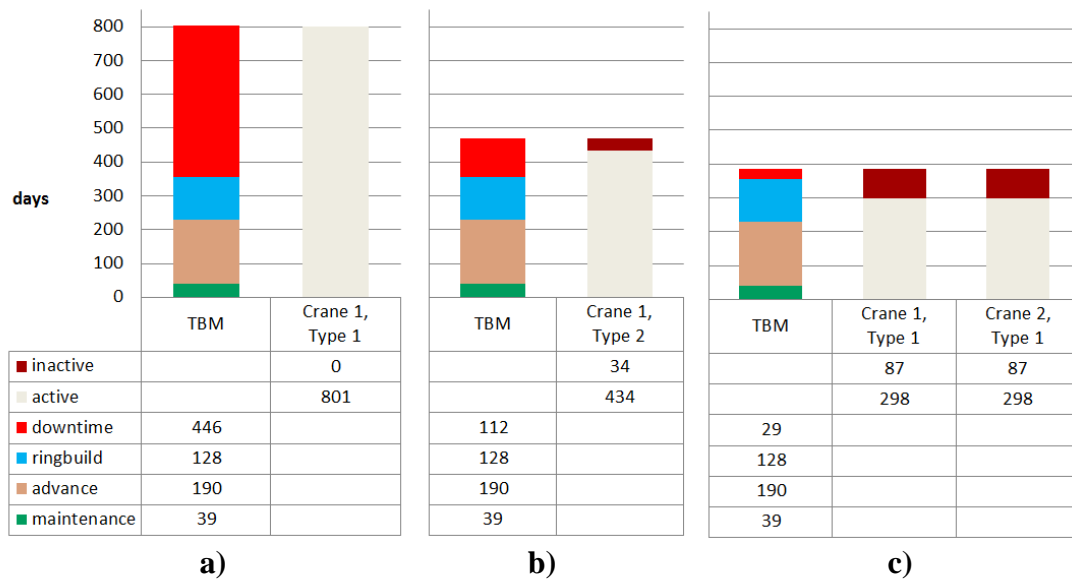
	a) TBM	a) Crane 1, Type 1	b) TBM	b) Crane 1, Type 2	c) TBM	c) Crane 1, Type 1	c) Crane 2, Type 1
inactive		0		34		87	87
active		801		434		298	298
downtime	446		112		29		
ringbuild	128		128		128		
advance	190		190		190		
maintenance	39		39		39		

a)   b)   c)

Figure 4. Project duration and crane utilization

CONCLUSION AND OUTLOOK

In this paper an innovative and freely configurable concept for surface jobsite logistic simulations in mechanized tunneling is presented. The benefit of the described approach is that there are two analyses possible. On the one hand, the simulation can be used to identify the parts of the logistic system responsible for performance losses resulting in an increased project duration. Each element of the construction equipment can be evaluated by analyzing their utilization. Secondly, after identification of the inefficient elements, additional resources can be added or alternatives can be defined. This supported by the flexible configurability of each element. Thus the best setup for the given jobsite boundary conditions can be identified.

Due to the formulation of the model in SysML and the modular implementation the extension of the simulation model is not limited. In the next step the presented logistic simulation will be coupled to other existing simulation models in mechanized tunneling. This approach will extend the simulation with a system dynamic material flow model and a disturbance analysis of the TBM. The shown simulation model can be executed as a Monte Carlo experiment and therefore analyze the sensitivity of different logistic processes on the performance of the TBM. Further research must address the sensitivity of logistical bottlenecks and validate the shown approach with real data of tunneling projects.

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