

JOBSITE LOGISTIC SIMULATION IN MECHANIZED TUNNELING

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ABSTRACT

Projects in mechanized tunneling frequently do not reach their targeted production performance. Reasons are often related to an undersized or disturbed supply-chain management of the surface jobsite. Due to the sensitive interaction of production and logistic processes, planning and analyzing the supply-chain is a challenging task. Transparent evaluation of chosen logistic strategies or project setups can be achieved by application of process simulation. This paper presents the continued work of a simulation approach to analyze the complex system of mechanized tunneling. Special focus of this publication lies on the internal logistic as a part of the jobsite supply-chain. The generic implementation allows a flexible configuration of jobsite elements to compare possible setups. A case study demonstrates the approach and highlights the sensitive interaction of production and logistic processes under the influence of disturbances. Additionally, improvements to the original setup of the case study's construction equipment can be derived.

1 INTRODUCTION

The construction process of projects in mechanized tunneling is affected by various factors. Particularly, geology, water ground conditions, machine technology, surface constraints (e.g. available space, existing buildings) or the jobsite supply-chain management (SCM), to mention the most important factors, have strong influence on the project performance. Due to the high degree of individual project specifications, each Tunnel Boring Machine (TBM) design and project setup is unique (Maidl et al. 2012). The given boundary conditions are prone to uncertainty or may vary in the course of project progress. However, the project planning in mechanized tunneling is mainly based on experience, simplified static dimensioning models and theoretical assumptions. In many cases the attained project performance did not match the aimed performance given by the project planning (Osborne et al. 2013).

Mechanized tunneling is characterized as a complex and highly sensitive system of interactions and dependencies. Thuro and Plinninger (2003) summarized the influences on TBM performance as the interaction of machine parameters, geological conditions and logistic processes as shown in Figure 1. To analyze these dependencies, traditional planning methods are insufficient. Process simulation can overcome the limitations of traditional methods. Giving realistic forecasts of TBM performance and thus supporting the planning process is a challenging task. A detailed simulation-based analysis of the holistic TBM system including coupling effects of the different subsystems provides a difficult, yet promising, approach.

Recently, an extensive amount of research was conducted in the field of TBM-rock interaction with focus on the penetration rate and advancement speed. On one hand, many approaches for prediction of cutting tool conditions exist and are used to support the project performance using adjusted maintenance

strategies. But on the other hand, the wearing and failure of technical equipment, e.g. erector, grouting pump, etc., as well as deficiencies in the supply-chain are mostly disregarded due to their complex nature. However, a robust project schedule highly depends on an efficient and undisturbed construction process.

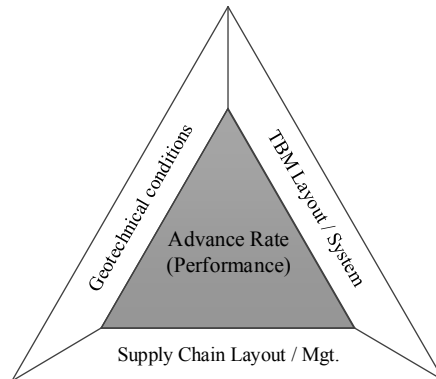


Figure 1: Influencing factors on TBM performance based on Thuro and Plinninger (2003).

In Rahm et al. (2012) we introduced a multi-method advancement simulation model of TBMs, combining process simulation with system dynamic formalism. The authors presented a formal TBM system description based on the System Modeling Language (SysML) (e.g. Friedenthal, Moore, and Steiner 2008). Processes are modelled and analyzed uniquely for each element by application of state charts. The approach focuses on the influences of technical disturbances on the project performance, but disregards the interaction between the ground and the cutting tools. Still not considered in detail is the logistic management, such as jobsite layout, construction equipment and the tunnel and surface supply chain. Based on this model, Rahm et al. (2013) presented a detailed simulation model including tool wear using Fuzzy Logic. The influences of uncertain geotechnical conditions on tool wearing are addressed by application of a fuzzy approach. With the combination of a multi-method advancement simulation together with tool wearing, a second essential performance factor is modeled in detail. Based on this pre-work, this paper presents a simulation model for the internal jobsite logistic in mechanized tunneling. The model allows analyzing the connected and dependent influences on TBM performance with respect to occurring disturbances and uncertain input data. Further, the identification of bottlenecks in the logistic chain is possible by analyzing the workload of surface construction equipment and warehouse utilization. Because of the holistic simulation approach, an accurate TBM performance prediction can be given to support the project planning and construction phase in mechanized tunneling.

2 BACKGROUND

Simulation is being increasingly applied in the construction industry to support the decision making process. A detailed overview of approaches where simulation was applied to analyze production processes in mechanized tunneling can be found in Rahm et al. (2013). While simulations of construction processes are widely researched only limited research deals with the simulation of construction logistics. Most of these approaches deal with site layout applying different optimization methods to minimize travel time and costs of materials (e.g. Yeh 1995; Hyounseung 2002; Osman, Georgy, and Ibrahim 2003; Elbeltagi, Hegazy, and Eldosouky 2004; El-Rayes and Khalafallah 2005; Sanad, Ammar, and Ibrahim 2008; Zhang and Wang 2008; Easa and Hossain 2008; Zhou, AbouRizk, and AL-Battaineh 2009; Ning, Lam, and Lam 2011; Xu and Li 2012; Razavialavi and AbouRizk 2013). Furthermore, CAD-based models are available to support site layout planning (e.g. Ma, Shen, and Zhang 2005; Sadeghpour, Moselhi, and Alkass 2006). Additionally, few methods were developed to support the decision making process for site layout. Tommelein, Levitt, and

Hayes-Roth (1992) developed a knowledge-based approach using AI programming techniques. Zhang, Liu, and Coble (2002) combined Artificial Neural Networks with Expert Systems to support decision makers.

However, the interaction between production processes and logistic processes rapidly adds up to highly complex problems. Thus, most approaches consider production processes on a very abstract level or isolate them completely. Voigtmann and Bargstädt (2010) presented a simulation approach to analyze the influence of logistic strategies considering construction processes in detail. For the field of mechanized tunneling, two approaches explicitly deal with the interaction of logistics and production. Ebrahimi et al. (2011a) introduced the Symphony Supply Chain Simulator (SSCS). The SSCS is a special purpose simulation (SPS) for the Symphony framework to model the production, storage and transportation of liner segments from the factory to the construction site. The SSCS can be coupled with the SPS for Tunneling (AbouRizk et al. 1999 and Ruwanpura et al. 2001). By varying storage and transportation of the prefabricated liners, the authors identify a favorable setup (Ebrahimi et al. 2011b). Thus, the external supply with materials can be analyzed with this approach. However, interactions of jobsite logistics and production processes are not investigated in detail. Another approach should be mentioned that was presented by Liu, Zhou, and Jiao (2010). The authors developed a simulation model for hard rock TBM using the CYCLONE framework. The processes are modeled on a rather abstract level but nevertheless consider interactions between on-site logistics and production processes by considering the disposal of muck. The authors identify a suitable logistic setup through variation of three parameters: muck cars per train, number of trains and rail infrastructure. However, these approaches lack the possibility to alternate surface jobsite logistics and thus evaluate the impact of this part of the supply chain on the production performance.

Within this publication we will demonstrate the interaction of jobsite logistic processes and production processes and thus the need to model construction logistics in detail.

3 PROBLEM STATEMENT

Tunneling projects using the mechanized tunnel boring technique are very cost-intensive. In general, the use of a TBM becomes economically advantageous in projects with tunnel lengths greater than 1000m (Maidl et al. 2012). During project execution, project boundary conditions may change. An in-situ change of TBM setups or adaption of logistic concepts is often not possible or consequently leads to additional financial strains. Therefore, an accurate project planning is required to ensure a cost-efficient tunneling project.

Finished projects show that unproductive timeshares frequently reach up to 60% of the overall working time. Hence, project performance is not only correlated with the advance rate but also affected by other, performance influencing parameters. Reasons for projects being unproductive often lie in an inaccurate planning of jobsite logistics. Due to the complex behavior and sensitive interactions of production and logistic processes, one single interrupted process can lead to disturbances in the whole process chain. For example a disturbed or undersized muck removal may force a slow down or standstill of the TBM. Since the backfilling grout has a limited processability and might harden throughout a standstill, the hardened grout has to be removed from the TBM. Furthermore, the grouting system must be cleaned and new grout has to be delivered again when needed. Such logistically caused cascading effects often lead to additional unproductive time periods.

Many TBM projects are located in urban and densely populated areas. Existing storage space on the surface jobsite is limited. Similarly, there are no capacities to use a large number of construction equipment e.g. cranes, trucks or tunneling vehicles. However, the jobsite logistics have to adapt its performance to the TBM construction process. Traditional planning methods and tools do not consider the logistical processes with a high level of detail. Thus, availabilities and workloads of engaged construction equipment is often unknown. The influences of changing project boundary conditions and the adaptation of the logistic chain to unexpected events are not regarded sufficiently in the project planning.

4 CONCEPT

In mechanized tunneling, the production processes *Advance* and *Ringbuild* are the performance-defining parameters. Disturbances within these processes automatically lead to longer project durations. The purpose of logistic processes is to support these production processes by delivering material and disposing excavated ground. The most important objective of logistic processes is to prevent disturbances of the production processes by missing capacities or material. The dependencies of these processes are bidirectional. For example, a rise of the advance speed leads to an increased amount of material. An undersized logistic chain cannot handle this requirement and the TBM has to reduce the advance speed or wait for material to be removed. To be able to give realistic forecasts of the TBM performance and support the planning process, a detailed analysis of the TBM system, including coupling effects of the ongoing processes, is needed.

Based on the existing process orientated simulation model introduced by Rahm et al. (2013), a logistic model has been developed and integrated into the existing model. All the logistical elements of the surface jobsite have to be identified and their dependencies analyzed. A formal system description with respect to the existing simulation approach, is presented in the SysML-Method. The model is implemented in a modular manner to ensure an easy and fast change of the simulation setup. Thereby, the model can be used in a vast range of tunneling projects and easily adapted to changing boundary conditions.

As mentioned before, the logistic aspect is one of the most important performance influencing parameter and projects often slow down due to insufficient logistic planning. Because of the bidirectional connection between production and logistic processes, a separate analysis of jobsite performance will not achieve practical results. To obtain sufficient performance evaluation a holistic process-orientated model regarding the detailed interactions of the logistic and production processes is needed. Further, the workload of a given setup can be analyzed and bottlenecks identified before a performance reduction occurs by modeling the surface construction equipment for mechanized tunneling projects.

5 FORMAL MODEL DESCRIPTION

The construction processes in mechanized tunneling are detached from the jobsite. Due to the continuously moving TBM, all materials needed for production must be delivered into the shaft and through the already existing tunnel to the TBM. This internal tunnel transport is typically performed by special tunnel vehicles. Surface jobsite logistics must be seen as the connection between the external logistics, delivering the material to the jobsite, and this internal tunnel logistic. To be able to deliver needed material to the TBM just in time, it is necessary to use the jobsite space and construction equipment as efficient as possible, since both are highly limited. Typical construction equipment for jobsites in mechanized tunneling are cranes, trucks, excavators and tunnel vehicles. To store needed material and excavated ground, the jobsite layout features several storage spaces. Furthermore, a selection of typical construction materials for tunneling jobsites is needed (e.g. pipes or segments).

To express this variety of elements and their connections transparently, the SysML-Methodology is applied. The formal system structure and hierarchy is shown in the SysML-Block Definition Diagram (bdd) in Figure 2. A detailed model of the TBM is given in Rahm et al. (2012). All system elements are connected to the surface jobsite, since this element manages all logistic processes. The materials needed for construction are predefined with variable parameters and belong to the type *Cargo*. Materials can be stored into *Storages* or can be moved by the existing *ConstructionEquipment*. Depending on the material parameters (e.g. weight) the construction equipment validates if a transport of this material is possible.

In case a TBM is requesting material, the internal jobsite logistic management has to ensure that this request will be performed as soon as possible. Assuming that the requested material is available in one storage unit and a tunnel vehicle is waiting in the shaft to get loaded, a delivery order is created and sent to the construction equipment. To manage requests and navigate and select construction equipment, a priority-based ordering system is implemented. All system elements containing graphical representations

and can be instantiated in a varying number of entities. Graphical representations are necessary to consider influences of the jobsite layout. Furthermore, the storage capacities are calculated according to the storage and material geometry.

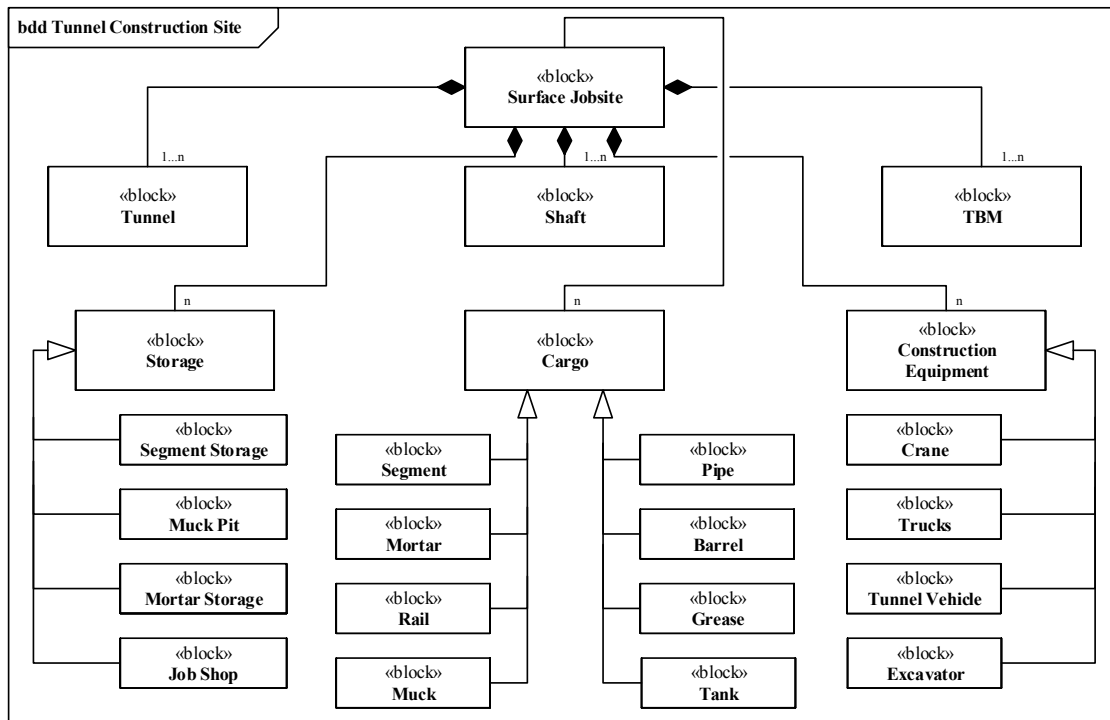


Figure 2: SysML-Block definition diagram for mechanized tunneling construction jobsite logistics.

6 IMPLEMENTATION

The presented approach is implemented using the commercial simulation software AnyLogic. AnyLogic enables the usage of State Chart to model processes for discrete event simulation. Each bdd-Block displayed in Figure 2 is represented by an Anylogic-ActiveObject. A sample of the implemented ActiveObjects is shown in Figure 3. All elements are specified by easily accessible parameters, such as velocity or maximum lifting capacity. These element specifications and their corresponding graphical representation are used to calculate the duration of transportation processes.

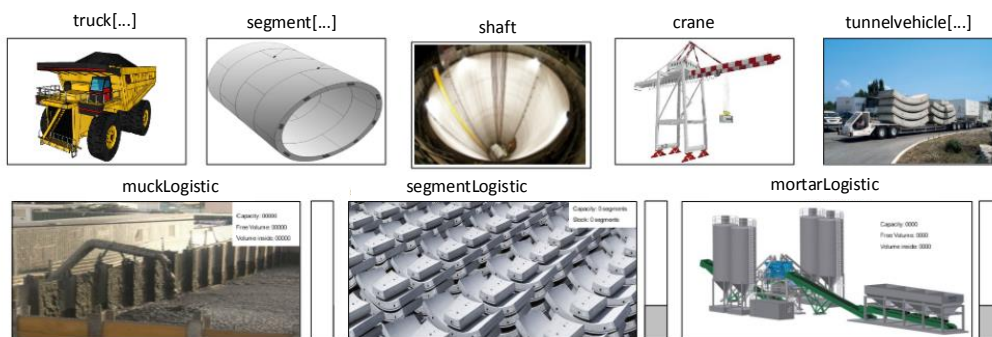


Figure 3: Screenshot of the logistic model part of the simulation model implemented in AnyLogic.

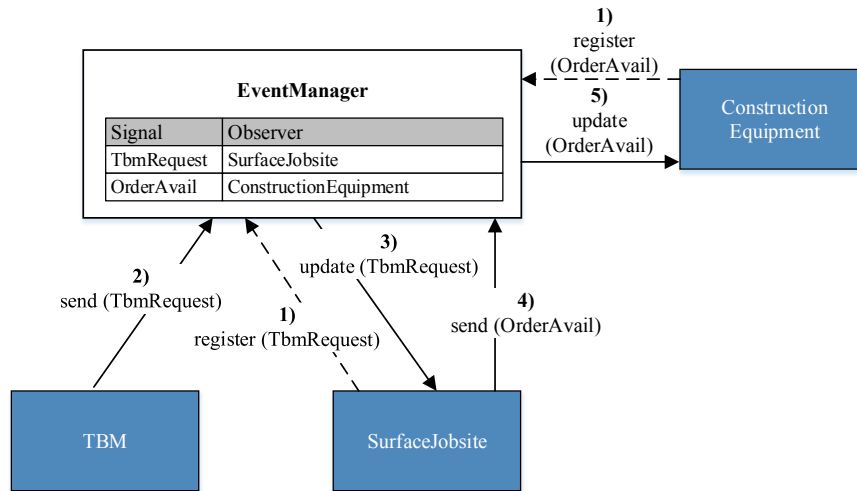


Figure 4: Conceptual drawing of the *EventManager* for a *TbmRequest*.

The communication between different system elements is implemented within the Observer-Observable design pattern. Therefore, we avoid hard structures and enable the easy exchange of system elements in order to simulate different project setups. An example of element communication is displayed in Figure 4. Every element registers itself at the implemented event manager as a listener for predefined signal types (1). In case the TBM requests material, a *Signal* is sent to the *EventManager* (2) and transmitted to the *SurfaceJobsite* (3). This element, responsible for logistic management, analyzes the *Signal* and generates an *Order* with a *SignalType* depending priority value. If the requested material is available on the jobsite, the *Order* becomes executable and a *Signal* is sent back to the *EventManager* (4). Otherwise, the *Order* is saved and will be executed as soon as material is available. Ongoing *ConstructionEquipment* is receiving and analyzing the generated *Order* (5). If it is possible to transport the material and if the storage is reachable for the single *ConstructionEquipment* the *Order* will be executed. The formal description of this procedure is based on the SysML Block Definition Diagram, Sequence Diagram and State Chart paradigm. For the sake of simplicity a pseudo code, representing the order generation and the construction equipment management for the described case, is shown in Algorithm 1 and Algorithm 2.

```

Data: Signal.TBMRequest
analyze TbmRequest;
generate new Order(TbmRequest.Type);
set Order.Priority according to request type;
if required Material available in storage
then
    add storage to Order;
    send Signal.OrderAvail;
else
    save nonexecutable order and wait for
    supply of material;
end

```

Algorithm 1: update(TbmRequest)

```

Data: Signal.OrderAvail
for Existing Construction Equipment do
    if Equipment can transport Material
    then
        if Equipment can reach storage
        then
            add Order to OrderList with
            respect to priority;
            executeOrder();
        end
    end
end

```

Algorithm 2: update(OrderAvail)

7 EXAMPLE

The following example visualizes the presented approach by showing the simulation results of an artificial tunneling project of 4500 meter length using a six meter diameter TBM. As mentioned before, an holistic simulation needs a logistical input data as well as TBM performance parameter. Even if the data is not connected to a real tunneling jobsite, all assumed parameters are based on experience gained by the evaluation of completed projects. The project setup demonstrates a jobsite with dramatic logistic problems due to an undersized logistic setup. Furthermore, the TBM performance is influenced by technical failure, modeled with triangular distributions for the mean time between failures (MTBF) and the mean time to recover (MTTR), as parameterized in Table 3. The assumed disturbances already reduce the performance and thus decrease the demands on the logistic chain. The TBM advance speed and the ringbuild process time are assumed to follow a Weibull distribution. The distribution parameters are not displayed explicitly. As soon as the TBM finishes ringbuilding, the external logistic sends a truck loaded with 7 segments and one smaller key stone (7+1). Subsequently, a truck arrives on the jobsite with a uniform distributed delay of 30 to 120 minutes. One gantry crane, with the technical specifications shown in Table 2, is available on the jobsite and solely responsible for unloading the segment trucks as well as loading segments on the vehicle waiting in the shaft. Furthermore, the excavated ground is transported to the surface by a muck tank attached to the tunnel vehicles. Thus, the gantry crane is additionally used to unload the filled muck tanks from the tunnel vehicle and to dispose the removal in the muckpit. Due to the vehicle-based muck disposing, some TBM advancement is only possible when a tunnel vehicle is located at the TBM. There are two tunnel vehicles used on the jobsite with the technical specification shown in Table 1.

Table 1: Parameters for the Tunnel Vehicles.

Tunnel Vehicle	v [km/h]	capacity [pcs]
velocity (empty)	15	-
velocity (full)	10	-
muck tank	-	2
mortar tank	-	1
segments	-	7+1

Table 2: Parameters for the Gantry Crane.

Gantry Crane	v [km/h]	capacity [pcs]
velocity (empty)	2.25	-
velocity (full)	1.5	-
max. lift	-	1

Table 3: Parameters for the triangular distribution representing the mean time between failures (MTBF) and the mean time to recover (MTTR) for the system elements directly influencing the production processes.

Element	MTBF [min]			MTTR [min]		
	min	mean	max	min	mean	max
Cutting Wheel	1000	1800	2800	30	90	300
Screw Conveyor	120	540	1000	50	90	360
Erector	1000	1800	4000	15	75	300
Thrust Cylinder	1200	4800	15000	30	60	300
Grouting System	240	1900	2800	15	90	300

The given jobsite layout is demonstrated in Figure 5. Setup 1 represents the originally planned situation. Within the first layout, the segment storage has a capacity to store up to 72 segments, while the parking space for segment trucks is located to the left of the muckpit. Because of this, the segment storage is maximized, but the gantry crane must cover longer distance to unload the incoming segment trucks. Setup 2 provides an alternative jobsite layout, where the parking space for segment trucks is right next to the segment storage. This setup entails a smaller segment storage with space for only 48 segments.

The first example demonstrates the negative influences of the logistic chain on the TBM performance. For both setups, 1000 simulation runs were conducted to eliminate freak-values possibly caused by the use

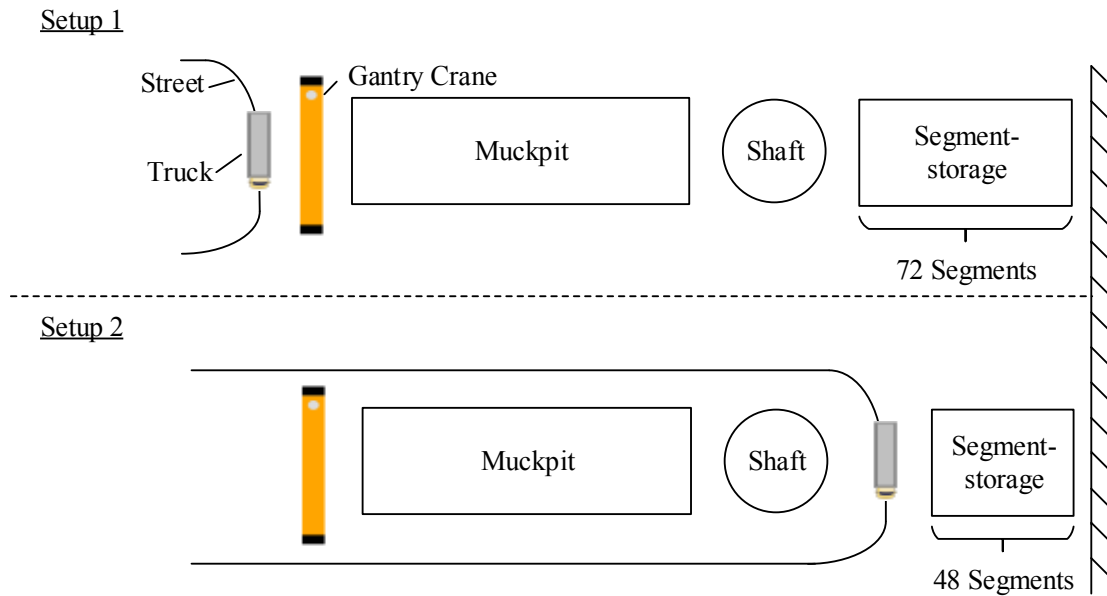


Figure 5: Different jobsite layouts for simulation experiments.

of probability distributions. The final results for the overall project duration of the first setup are displayed in Figure 6. The computed project duration is around 321 days. The unproductive time related to logistic processes is around 57% of the project duration, as shown in Figure 7. This time share mainly correlates to the undersized surface logistic setup, which is too slow to handle all loading and unloading processes of the trucks and tunnel vehicles. Especially, the long distance between the segment storage and the segment truck parking slot can be identified as a bottleneck when regarding the workload of the gantry crane, which is near to 81%.

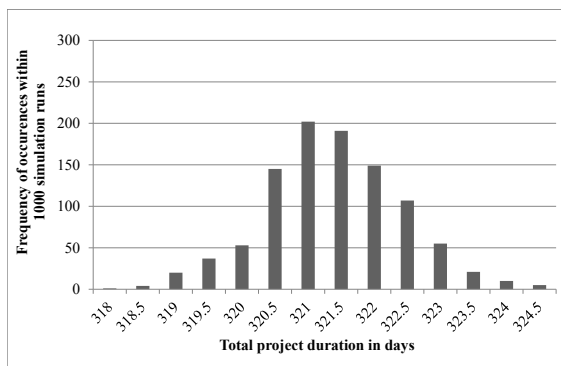


Figure 6: Total project duration of 1000 simulation runs for the jobsite setup 1.

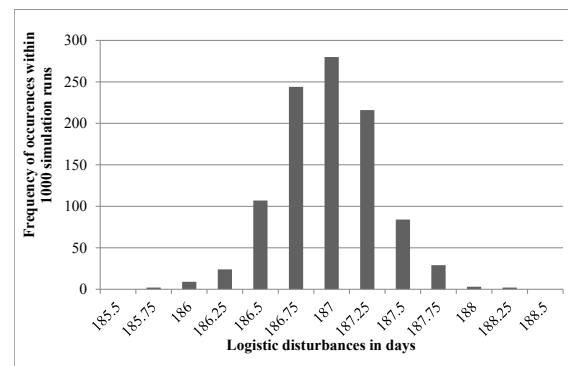


Figure 7: Total disturbances duration related to logistic issues of setup 1.

The model with the alternative jobsite layout was also simulated 1000 times. Here, the distance between segment storage and parking position is shorter, but the storage capacity is reduced. Storages can be seen as a buffer for fluctuating truck delivery and TBM requirements. Thus, an undersized storage capacity can lead to disturbances when the TBM advancing speed is high but the truck delivery is delayed. However, the simulation results displayed in Figure 8 and Figure 9 show a reduction of project duration as well as a reduction of logistical disturbances. This setup reduces the logistical disturbance to only 30% of the

first setup. Also, the workload of the gantry crane can be reduced to 60%. The reasons for the remaining disturbances can be found by analyzing the segment storage utilization. The number of segments stored is constantly close to zero. Frequently, a request of the TBM cannot be executed due to missing segments on the jobsite. But nonetheless, this setup leads to a substantially improved project performance and should be the preferred project implementation. The investigation of possible alternatives in the delivery pattern seems promising to find even lower downtimes.

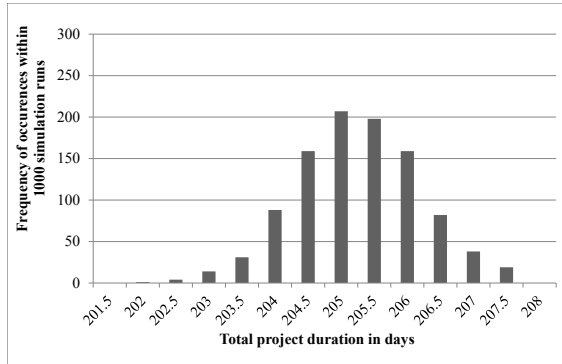


Figure 8: Total project duration of 1000 simulation runs for the jobsite setup 2.

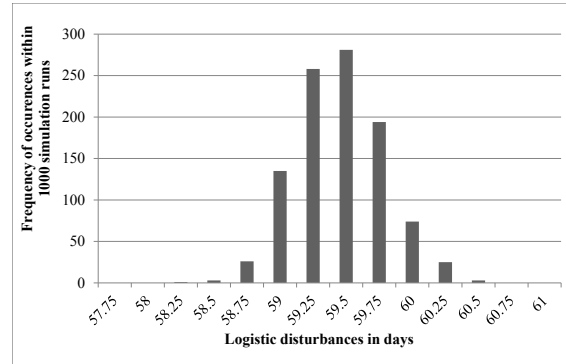


Figure 9: Total disturbances duration related to logistic issues of setup 2.

8 CONCLUSION

This paper presents the ongoing work of a holistic simulation model for construction projects using the mechanized tunneling technique. Based on an existing process simulation model for mechanized tunneling, this paper presents the combination of production and logistic processes influenced by technical disturbances. The approach focuses on the internal jobsite logistic as a main factor affecting TBM performance. To support the project management to achieve a fast and undisturbed project execution, the introduced model helps to understand the complex system behaviour and various different system dependencies. With the use of discrete event simulation logistic processes become more transparent and analyzable. Thus, the decision process is supported throughout the whole planning and implementation phase.

The described approach allows a fast and accurate change of project setups, such as alternative surface layout or construction equipment. To manage jobsite logistic processes, a priority-based order system combined with the Observer-Observable design pattern is used. Each system element can be analyzed uniquely in order to identify bottlenecks and develop alternative setups or strategies. The improved understanding of the holistic system behaviour, especially the bidirectional dependencies between production and logistic processes, enables planners to modify and compare different project setups.

A virtual example illustrates the influences of an undersized logistic on the TBM performance and project duration. Respecting the prevailing boundary conditions, the jobsite layout is modified in a second example to visualize the crucial impact of the logistic chain on the overall project performance.

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